Synergies in Oscillation Searches

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NOW 2006

September 9-16, 2006
Conca Specchiulla, Italy

Theree Flavour Oscillations

Future precision oscillation experiments:

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\theta_{23}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{S_{13} \rightarrow \text{3 flavour effects} \rightarrow S_{13} \rightarrow \delta} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\theta_{12}}$$

x Majorana-CP-phases

matter effects

<u>Aims:</u> ➔ **improved precision of the leading 2x2 oscillations**

➔ **detection of generic 3-neutrino effects: θ_{13}, CP violation**

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**

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

Cervera et al.
Freund, Huber, ML
Akhmedov, Johansson , ML, Ohlsson, Schwetz

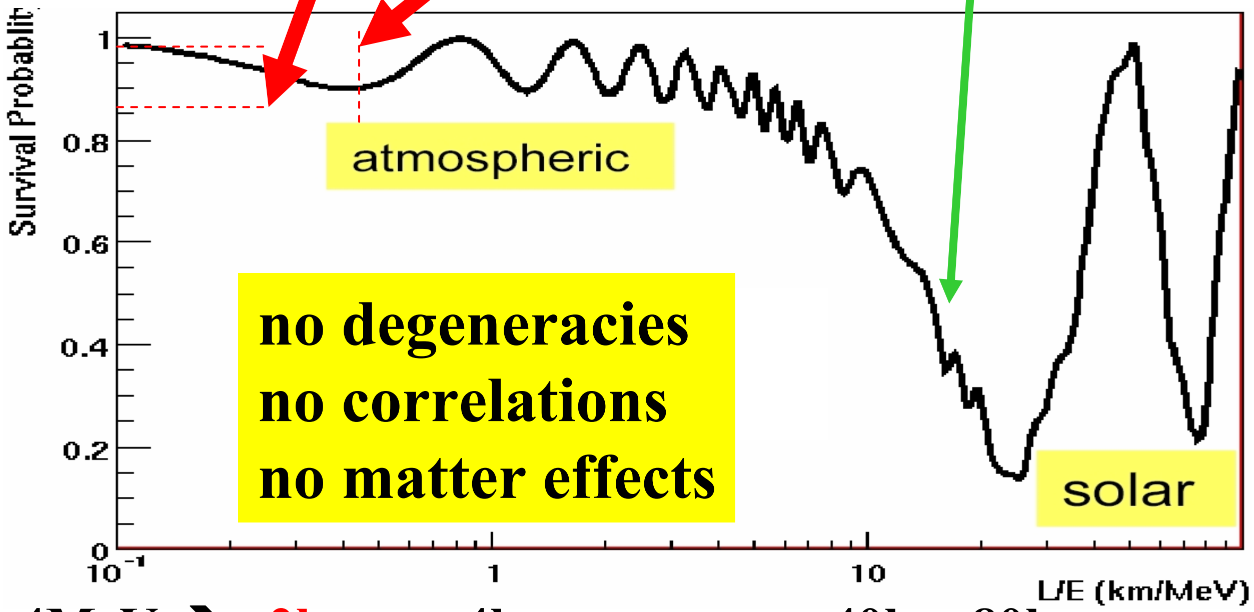
↳ **$(\sin^2\theta_{13})_{eff}$ *or* correlations & degeneracies**

Precision with New Reactor Experiments

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

identical detectors → many errors cancel

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



no degeneracies
no correlations
no matter effects

E=4MeV → 2km 4km 40km 80km

- → **Double Chooz**
- → **KASKA**
- → **Daya Bay**
- → **Reno, Angra,**

…

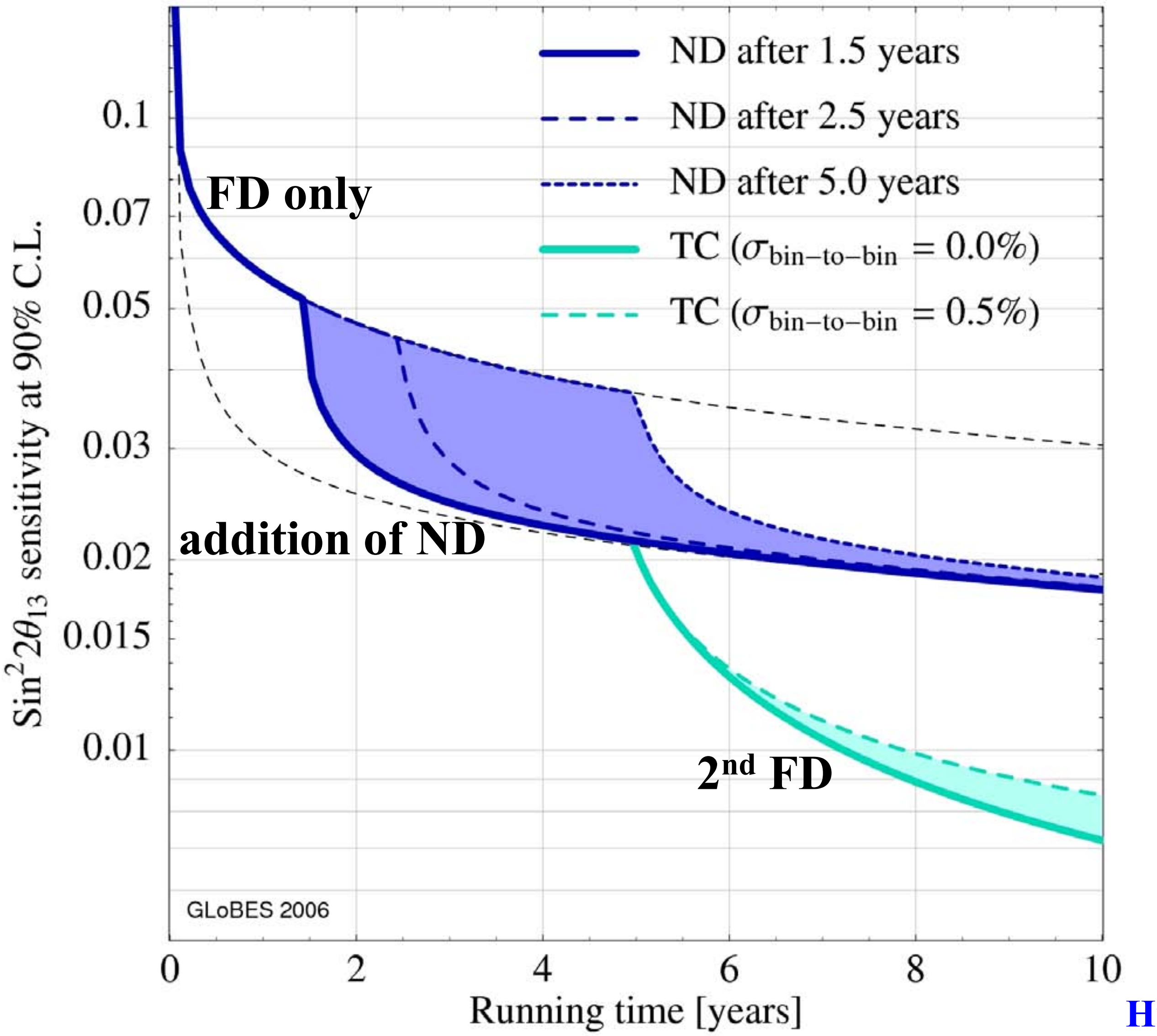
See talk by A. Cabrera

Double Chooz

existing far detector hall

… + another
existing big hall!

Double Chooz and Triple Chooz

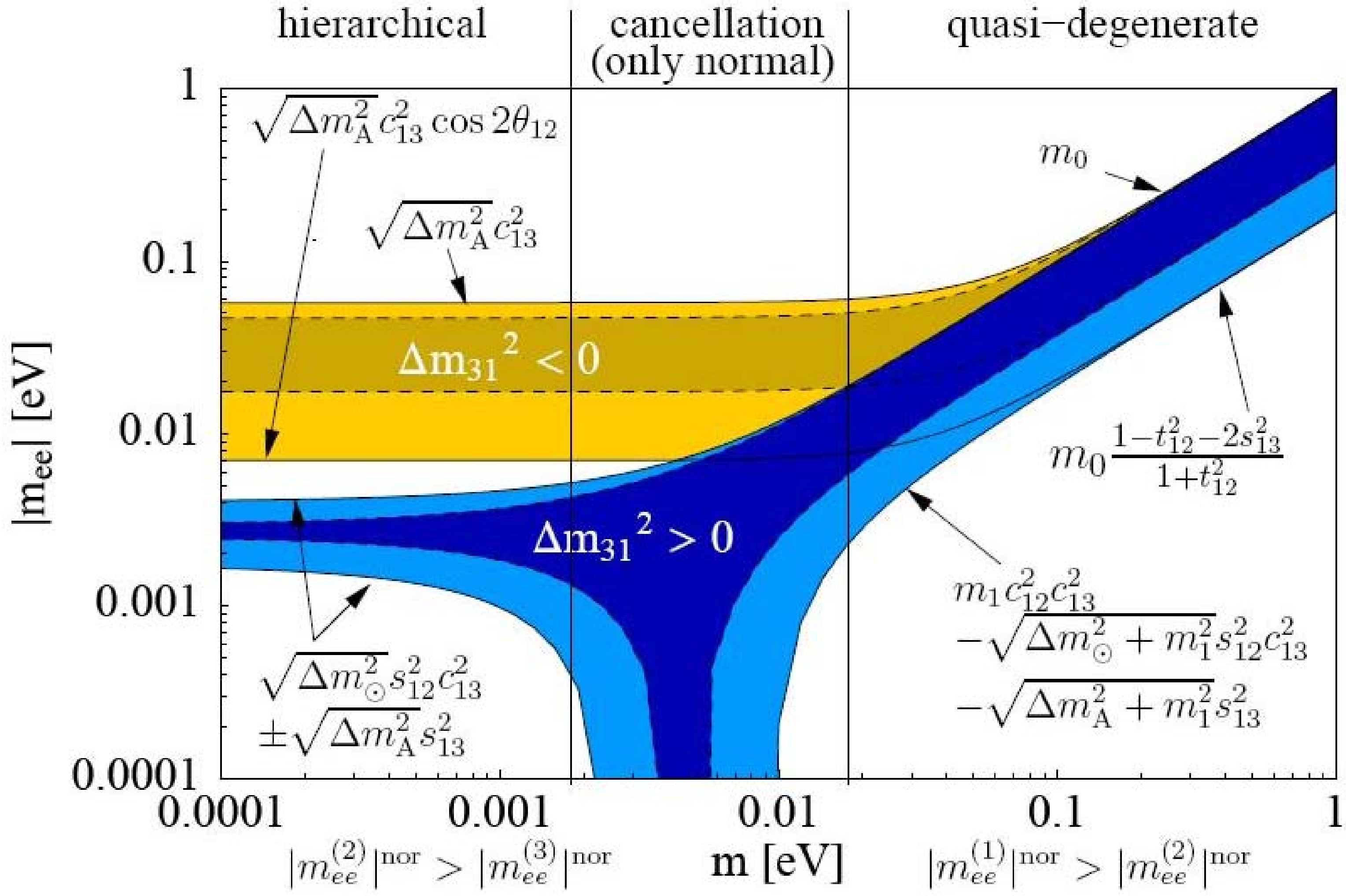


$\sin^2 2\theta_{13}$ sensitivity

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

Huber, Kopp, ML, Rolinec, Winter

Impact of $\sin^2\theta_{13}$ on $0\nu2\beta$ Mass Plot



Double Chooz and 0ν2β

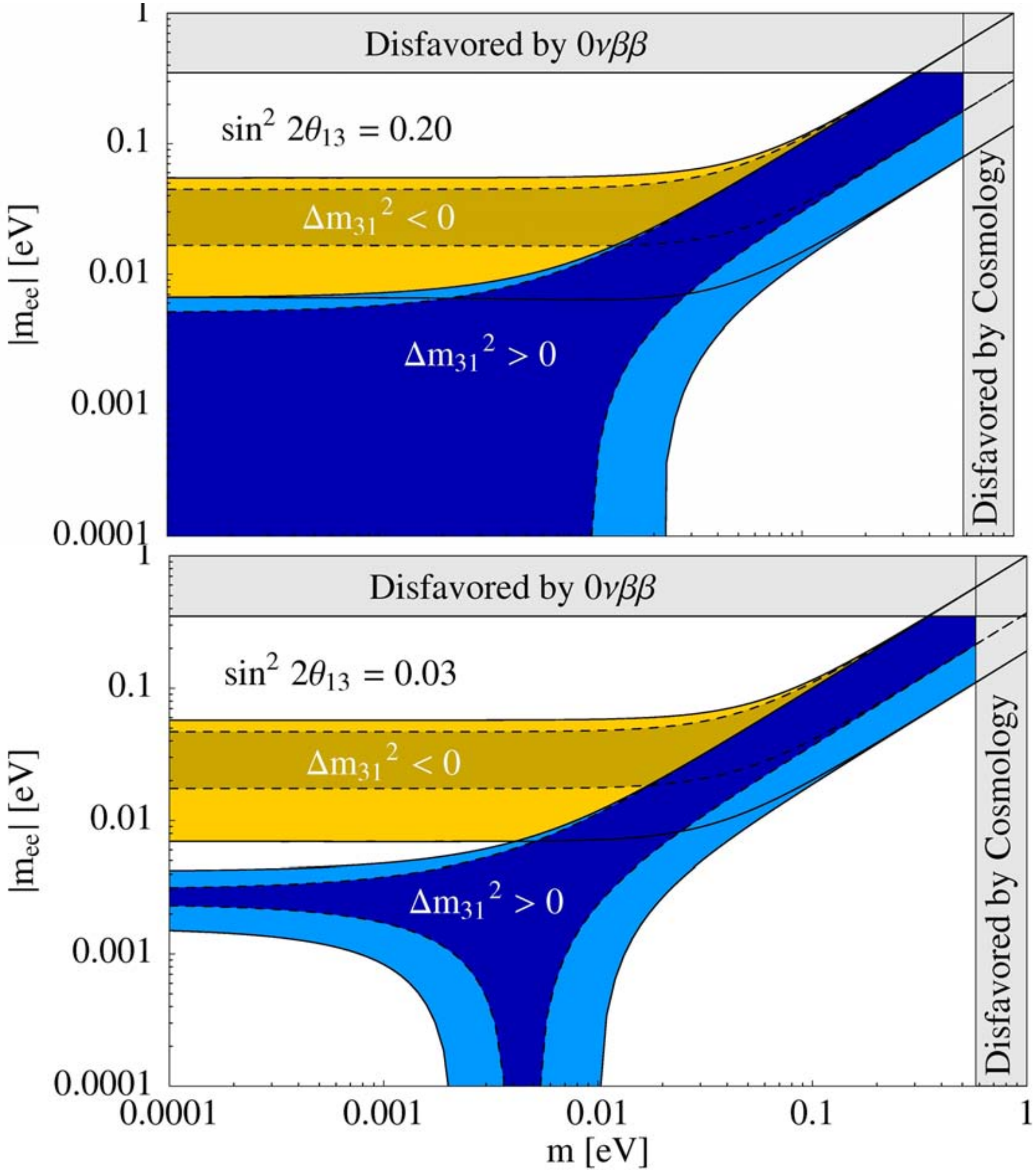
- **m_{ee} versus m_1**

  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

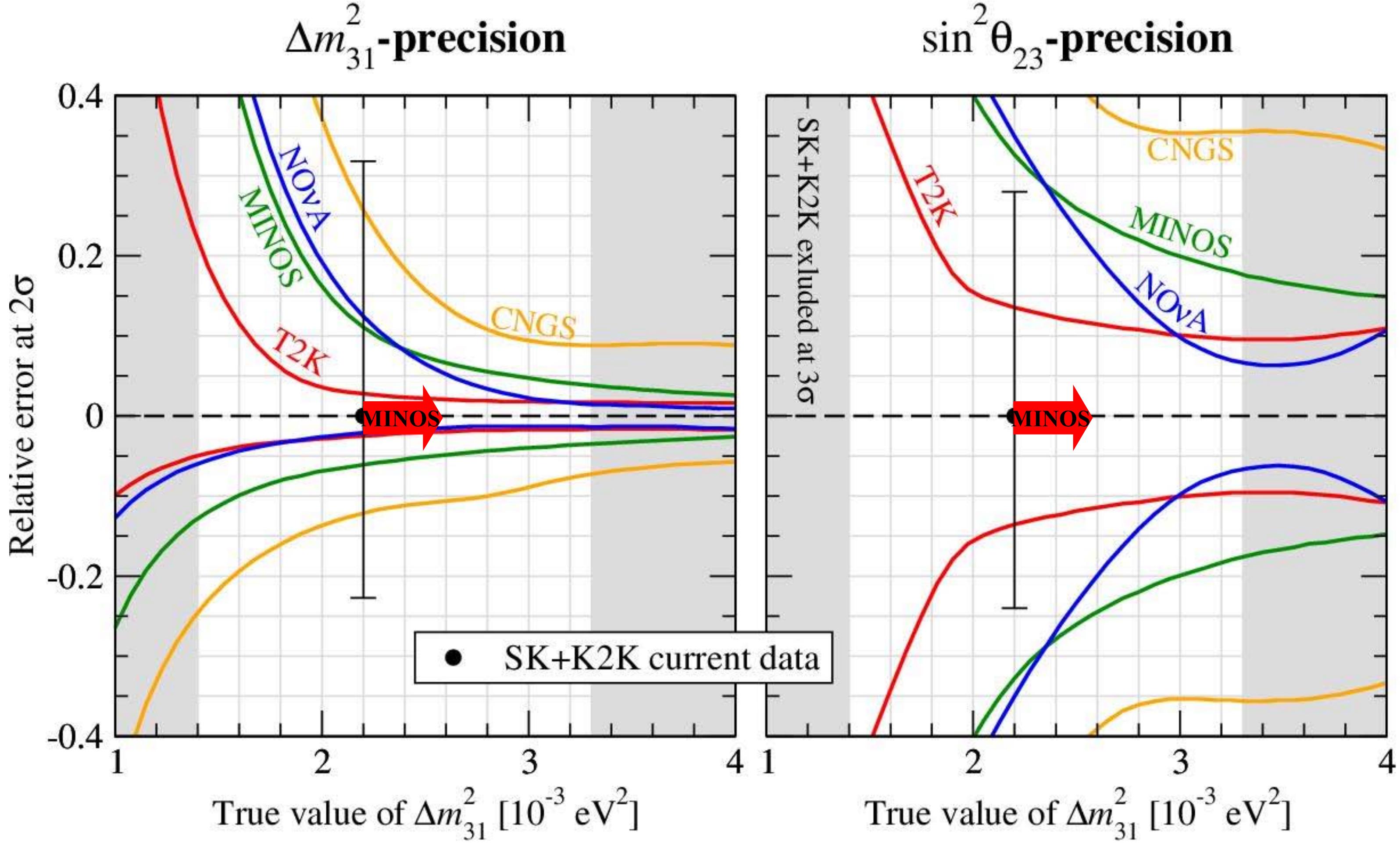


Future Long Baseline Experiments

K2K	**analysis**	**establish atmospheric oscillations with beam**
MINOS	**running**	**expected precision:**
OPERA	**almost running**	**8% for Δm^2_{13} , 25% for $\sin^2\theta_{23}$, θ_{13} ?**
T2K	**construction**	**4% for Δm^2_{13} , 15% for $\sin^2\theta_{23}$, ➔ θ_{13}**
NOνA	**pre-approved**	**3% for Δm^2_{13} , 15% for $\sin^2\theta_{23}$ (combined with T2K) , ➔ θ_{13} , ➔ δ ? , ➔ $\mathrm{sgn}(\Delta m^2_{13})$**
T2KK, T2H, …	**R&D**	
β-beams	**R&D**	**precision neutrino physics**
neutrino factory	**R&D**	
...muon collider	**…**	

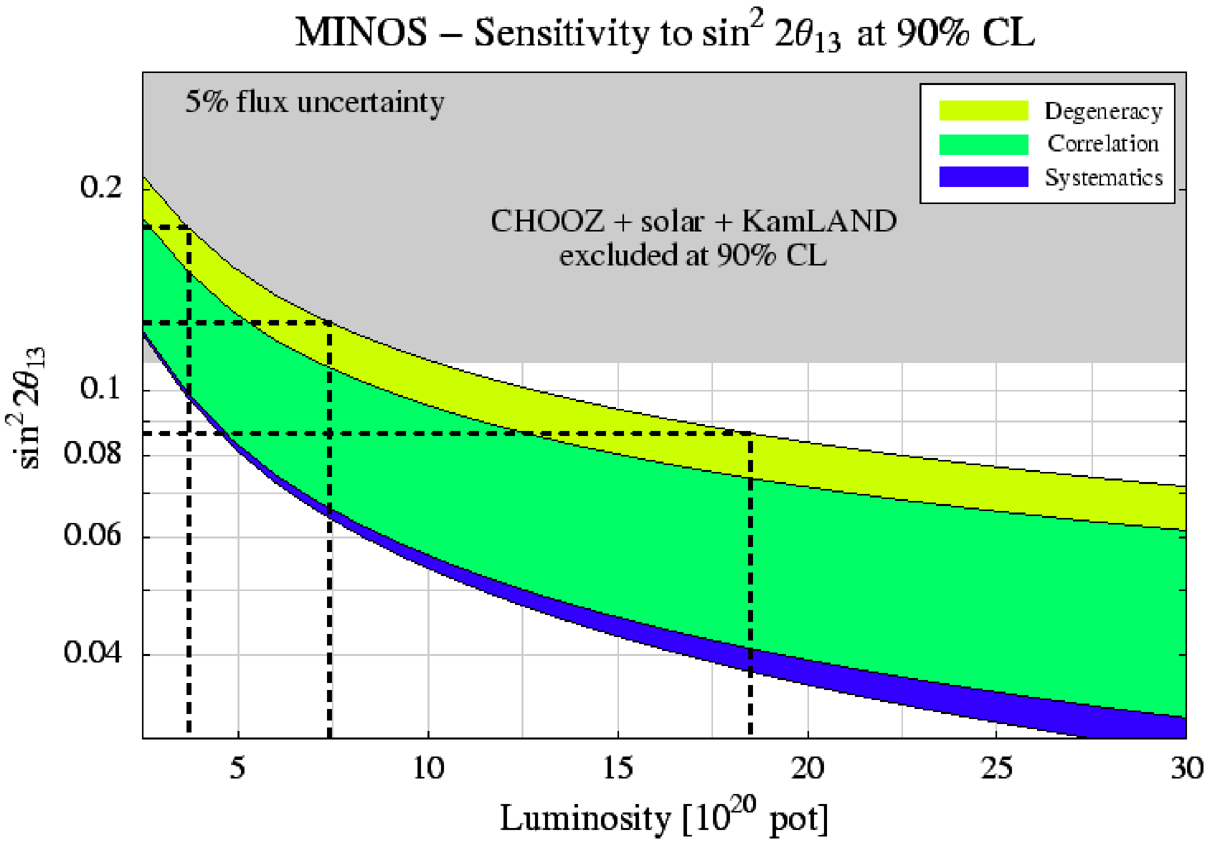
- **every stage is a necessary prerequisite for the next**
- **continuous line of improvements for beams, detectors, physics**

Improvement of Δm^2_{31} and $\sin^2\theta_{23}$



Huber, ML, Rolinec, Schwetz, Winter

θ_{13} in the Coming LBL Generation



MINOS sensitivity as a funtion of time:

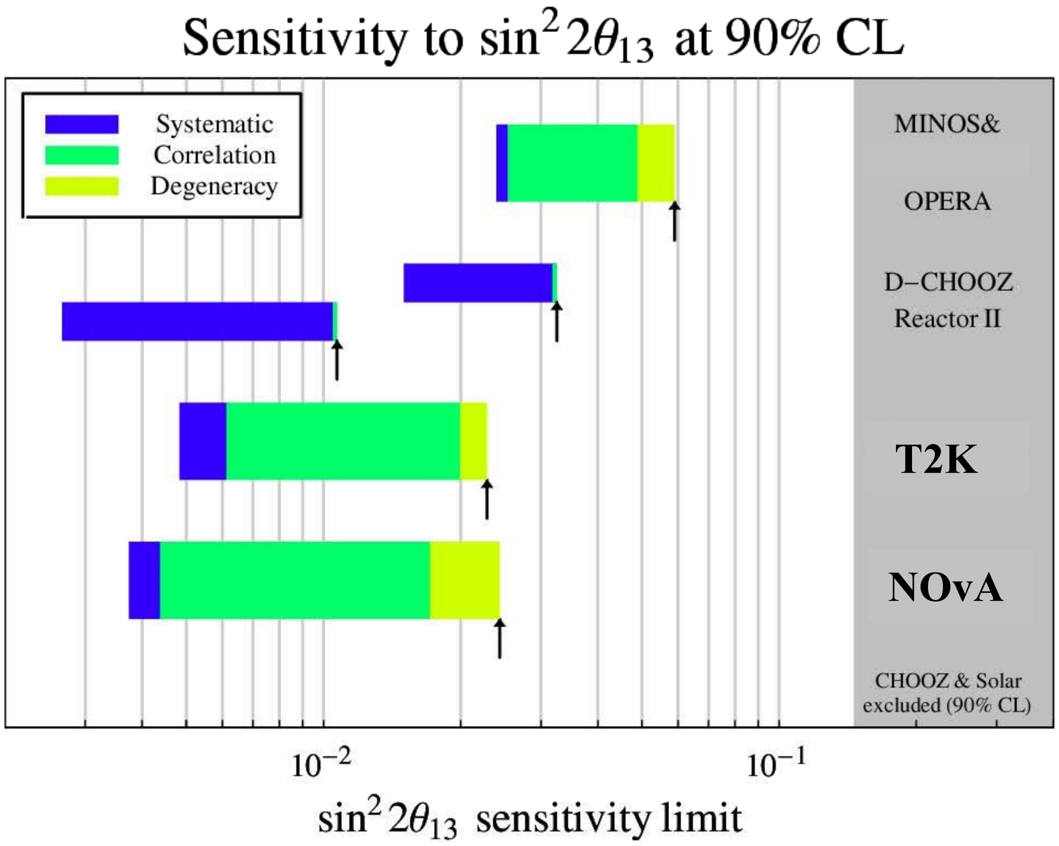
– MINOS: $3.7 \cdot 10^{20}$ pot/y

– 1,2,5 years

➔ **modest improvements**

➔ **other objectives**

θ_{13} Sensitivity in the Next Generation



coming long baseline experiments

1 reactor +2 detectors

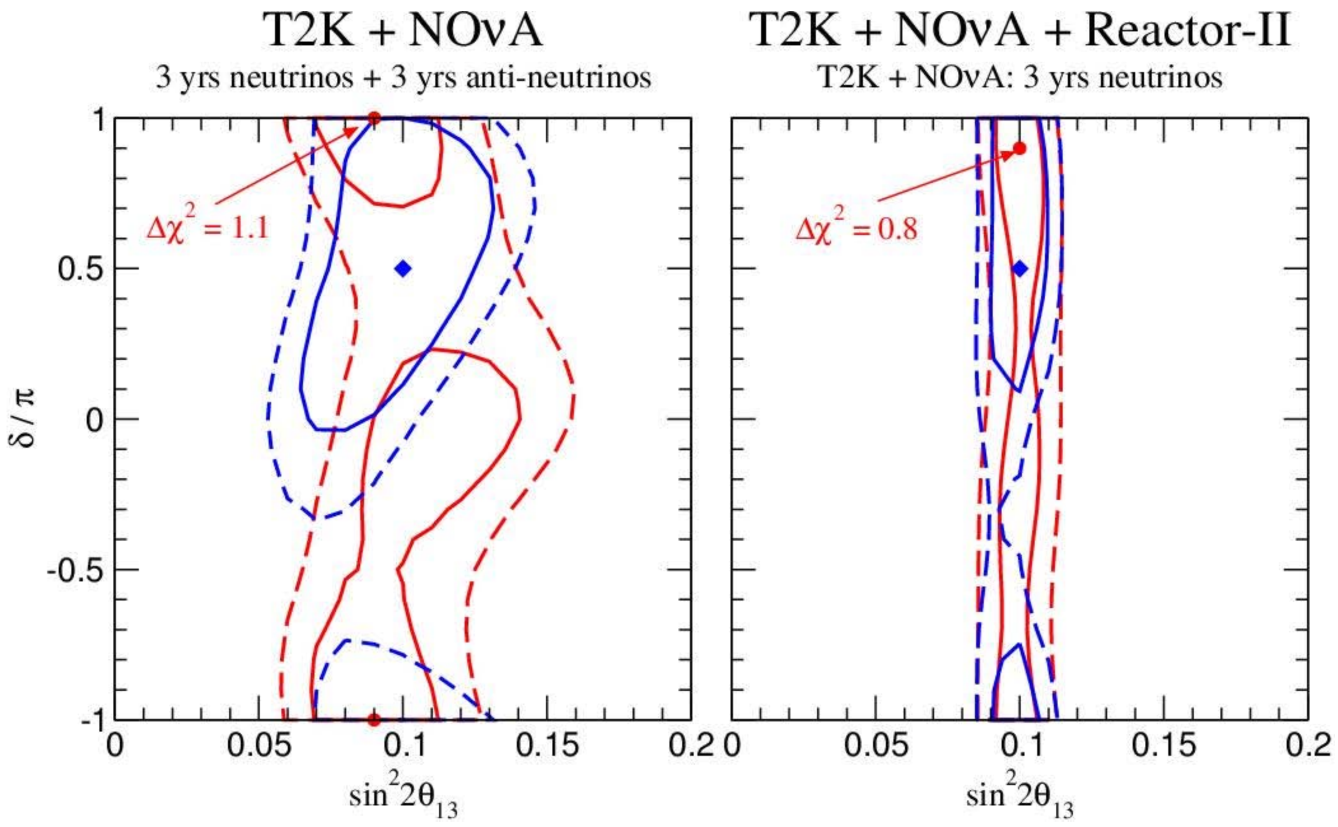
next generation long baseline experiments

Compare:
- **5 years each**
- **5% flux uncertainty**

- one order of magnitude improvement for θ_{13}
- synergies between reactor and accelerator experiments
  - reactor anti-neutrinos ⇒ only neutrino beams (x-section)
  - reactor: uncorrelated θ_{13} ⇒ combine with beams & resolve correlations
- synergy between beams ⇒ NOνA at larges baseline ⇒ matter effects

Leptonic CP Violation – Best Case

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



$\Delta m^2 > 0$

$\Delta m^2 < 0$

— 90%CL

···· 3σ

➔ limits or measurement of leptonic CP violation

(… and sgn(Δm^2) for sizable $\sin^2 2\theta_{13}$)

Huber, ML, Rolinec, Schwetz, Winter

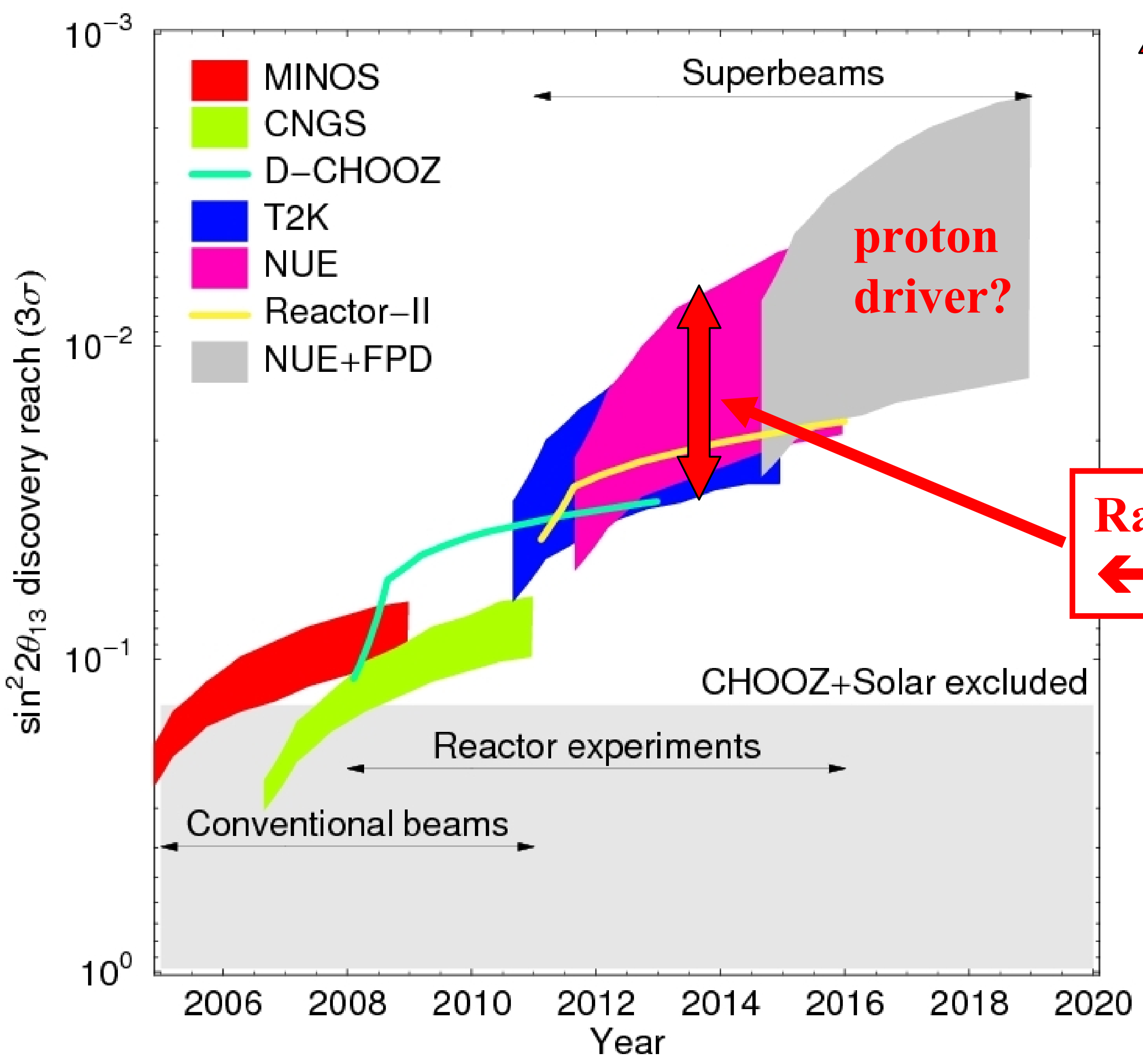
Long Term Perspectives

- **superbeams: $E_\nu \approx$ GeV** ➔ Totally Active Scintillator Detector ≈ 30 kt
- **superbeams, β-beams: $E_\nu \approx$GeV** ➔huge Cerenkov detectors ≈ 1000 t
  ➔huge liquid Ar detectors ≈ 100 kt
  ➔huge scintillator detectors ≈ 30 kt
- **neutrino factory: $E_\nu \approx$20-50 GeV** ➔large magnetized iron Calorimeters ≈ 40kt
  ➔large magnetized liquid Ar detectors ≈20kt
  ➔large OPERA-like emulsion detectors ≈5kt

L=3000km, magnetized iron ➔ wrong sign muons

	P(MW)	**μ‘s/year**	**$T_\nu+T_{\bar\nu}$ (y)**	**M(kt)**
Neutrino factory I:	**0.75**	**10^{20}**	**5**	**10**
Neutrino factroy II:	**4.00**	**$5.3*10^{20}$**	**8**	**50**

Sensitivity Versus Time



proton driver?

β-beams
neutrino factory

Range
⇔ ~unknown CP phase

See talks by

P. Huber

T. Schwetz

H. Nunokawa

I. Kato

…

How to Break Degeneracies & Correlations

Rates only ➔ degeneracies ...broken by

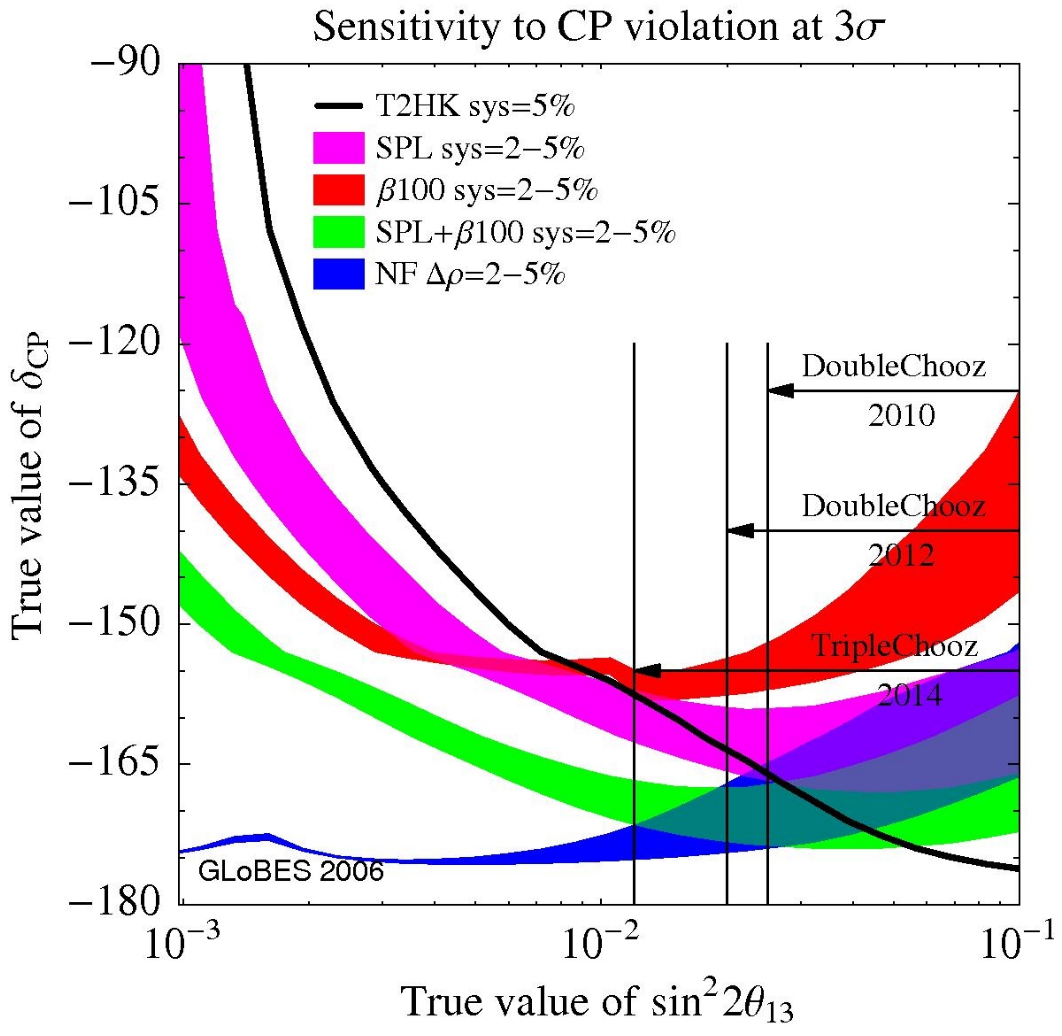
➔ Combine different osc. channels (golden, silver, platinum)
➔ use different baselines
➔ combine different energies
➔ use energy spectrum
➔ go to „magic baseline“

All degeneracies can in principle be broken
Optimal strategy (physics output / time, money, feasibility)
depends on further R&D…

… and intermediate results

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

The Importance of θ_{13} for Road Maps



Huber, ML, Rolinec, Winter

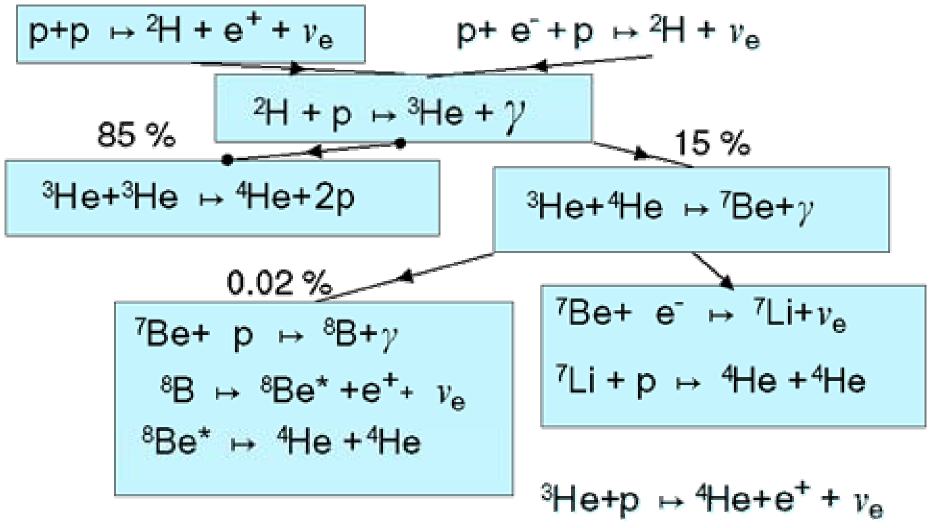
- ➔**result of reactor experiments crutial for future steps**
- ➔**unexpected results crutial for future steps (MiniBooNE, …)**

The Value of Future Precision Experiments

Solar Neutrinos: Learning About the Sun

Observables:

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



$p+p \mapsto {}^2H + e^+ + \nu_e$

$p+ e^- + p \mapsto {}^2H + \nu_e$

$^2H + p \mapsto {}^3He + \gamma$

85 %

15 %

$^3He+{}^3He \mapsto {}^4He+2p$

$^3He+{}^4He \mapsto {}^7Be+\gamma$

0.02 %

$^7Be+ p \mapsto {}^8B+\gamma$

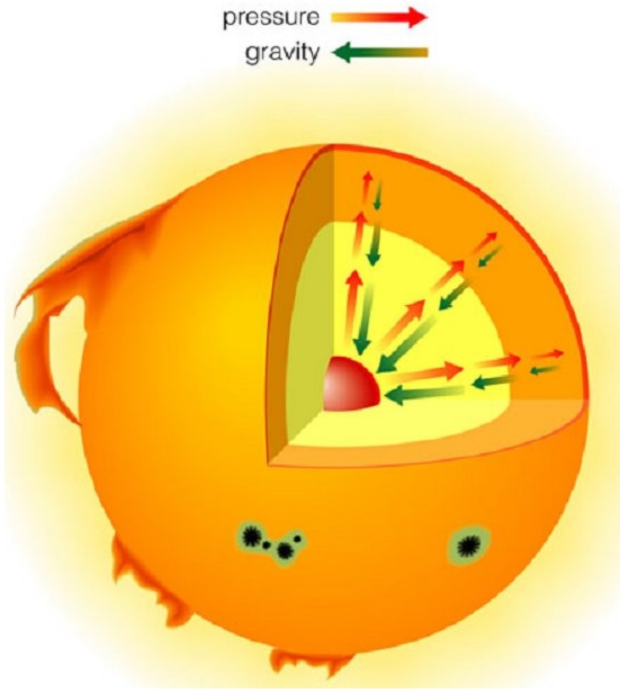
$^8B \mapsto {}^8Be^* +e^+ + \nu_e$

$^8Be^* \mapsto {}^4He + {}^4He$

$^7Be+ e^- \mapsto {}^7Li+\nu_e$

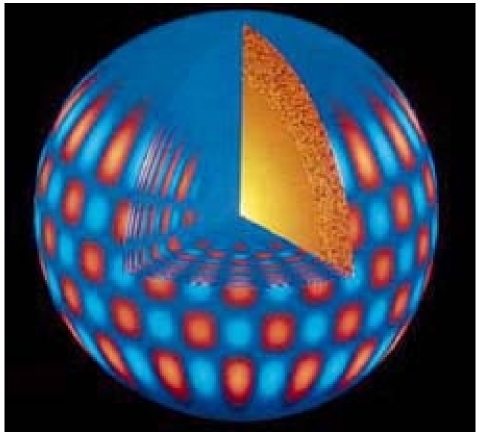
$^7Li + p \mapsto {}^4He + {}^4He$

$^3He+p \mapsto {}^4He+e^+ + \nu_e$

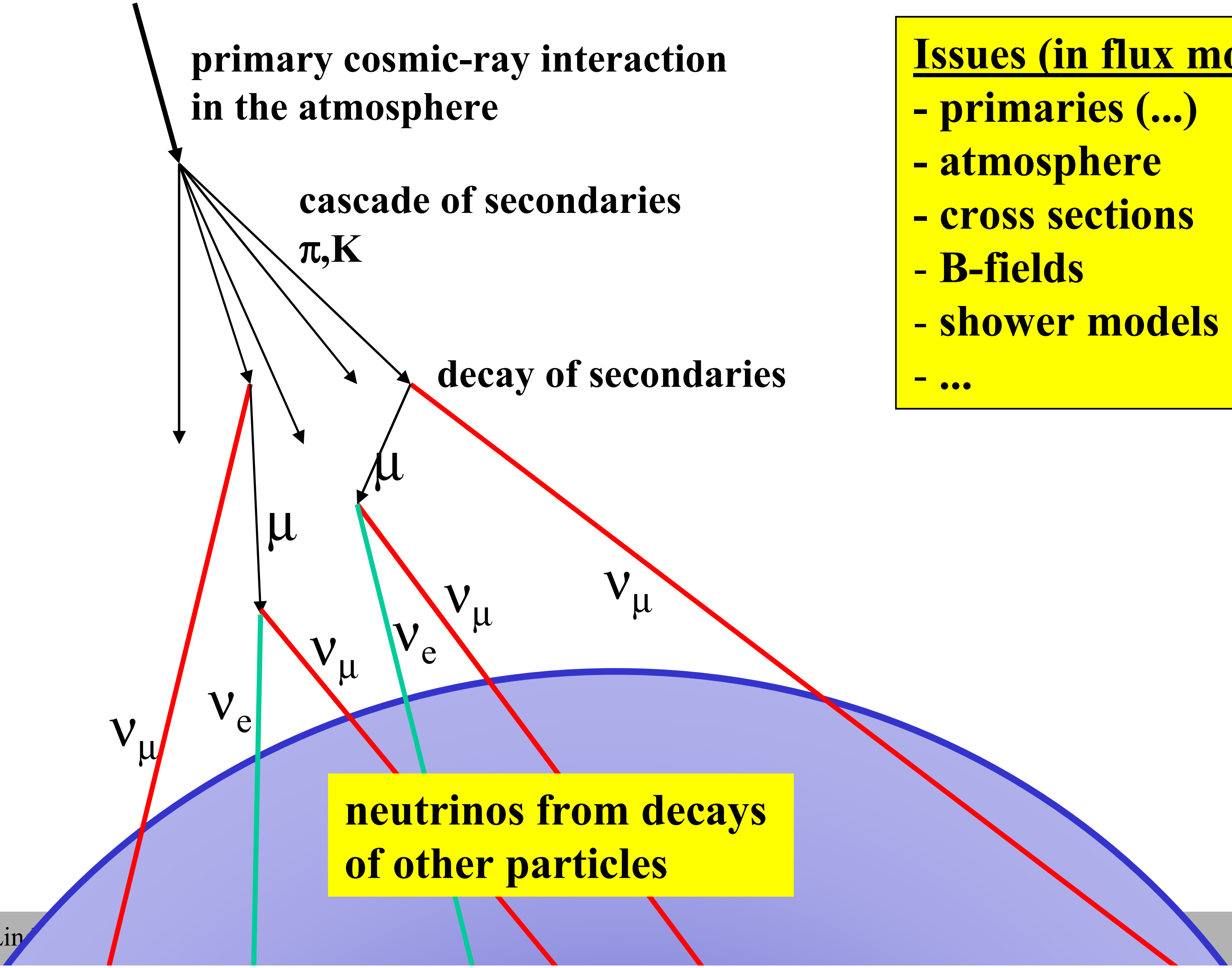


Topics:

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



Learning from Atmospheric Neutrinos



primary cosmic-ray interaction in the atmosphere

cascade of secondaries
π,K

decay of secondaries

neutrinos from decays of other particles

Issues (in flux models):

- **primaries (...)**
- **atmosphere**
- **cross sections**
- **B-fields**
- **shower models**
- **...**

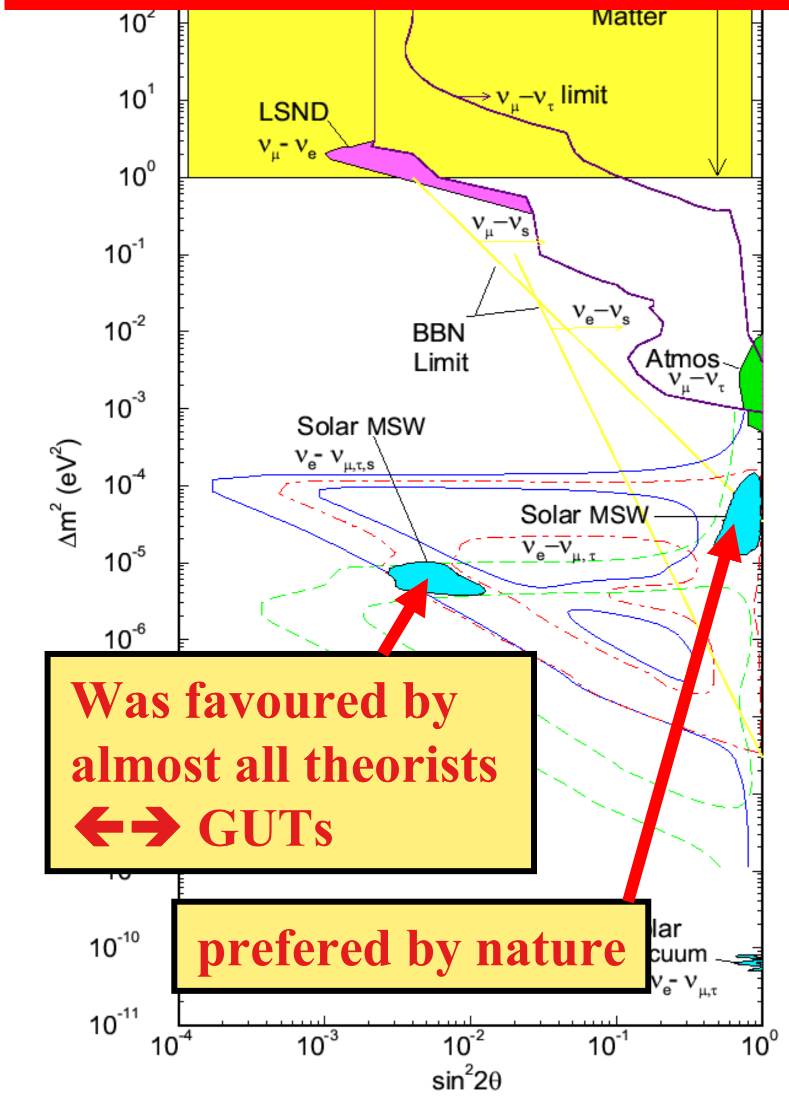
Learning about…

- Geo neutrinos → Earth
- Reactor neutrinos → nuclear physics
- Neutrino beams → accelerator physics
- Supernova neutrinos → element formation, …
- UHE neutrinos → sources
- …
- Flavour:

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

Learning about Flavour

History: Elimination of SMA



Was favoured by almost all theorists ↔ GUTs

prefered by nature

Next: Smallness of θ_{13}

- models for masses & mixings
- input: known masses & mixings
  - ➔ distribution of θ_{13} „predictions“
  - ➔ θ_{13} often close to experimental bounds

What if $\sin^2 2\theta_{13} < 0.01$?

question: why is θ_{13} so small ?

→ numerical coincidence

→ symmetry

↔ precision!

Renormalization Group Running

low energies:
- **small masses**
- **large mixings**

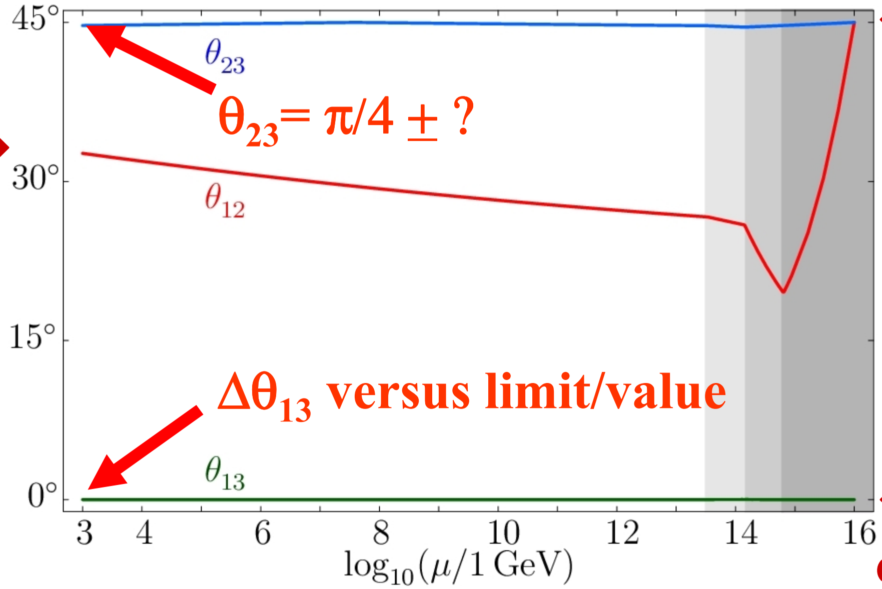
renormalization group running

high energies:
- **mass models**
- **flavour-symmetries**
- **GUT-models, ...**

atmospheric →

solar →

reactor →



$\theta_{23} = \pi/4 \pm ?$

$\Delta\theta_{13}$ versus limit/value

← bi-maximal

← Small or even zero

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

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, ...

→ various synergies with LHC and LFV see talk by J. Valle

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

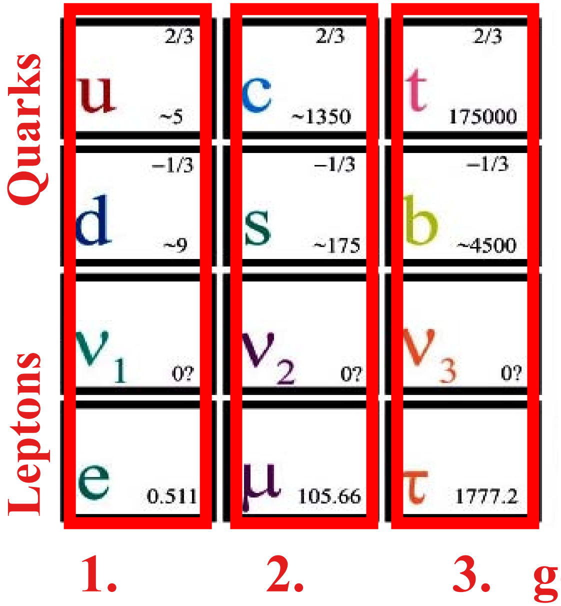
Requirements:

gauge unification

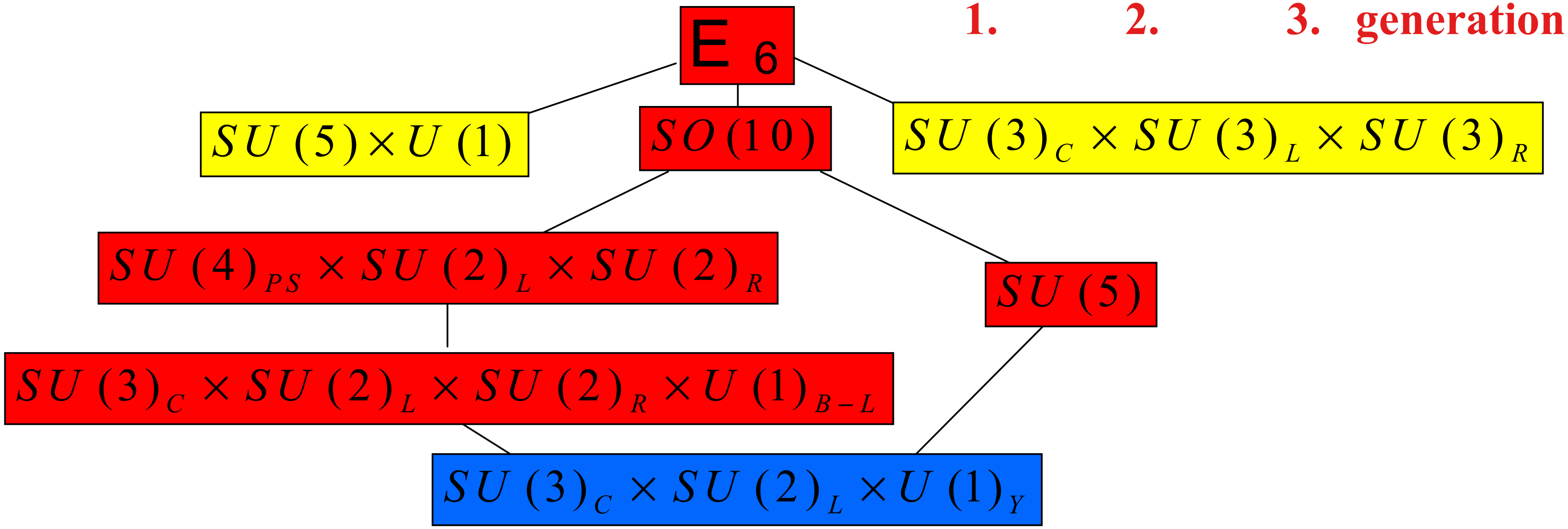
particle multiplets ⇔ ν_R

proton decay

…



		1.	2.	3. generation
Quarks		u 2/3 ~5	c 2/3 ~1350	t 2/3 175000
		d −1/3 ~9	s −1/3 ~175	b −1/3 ~4500
Leptons		ν_1 0?	ν_2 0?	ν_3 0?
		e 0.511	μ 105.66	τ 1777.2



E_6

$SU(5) \times U(1)$

$SO(10)$

$SU(3)_C \times SU(3)_L \times SU(3)_R$

$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$

$SU(5)$

$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$SU(3)_C \times SU(2)_L \times U(1)_Y$

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

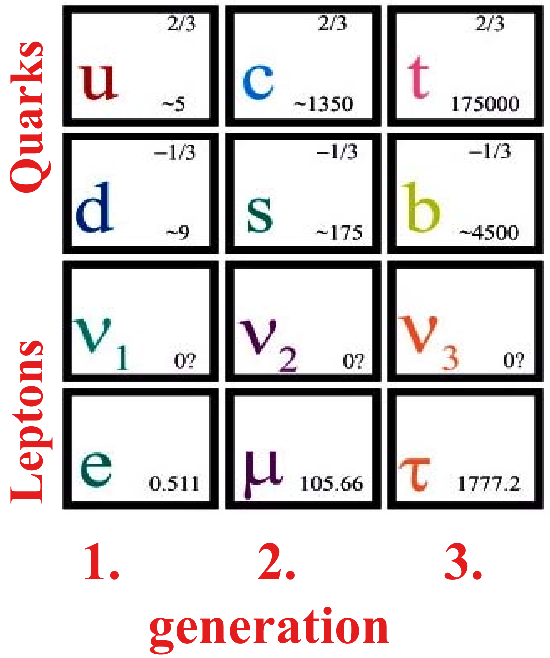
➔ …

Flavour Unification

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

➔ flavour symmetries

➔ not texture zeros



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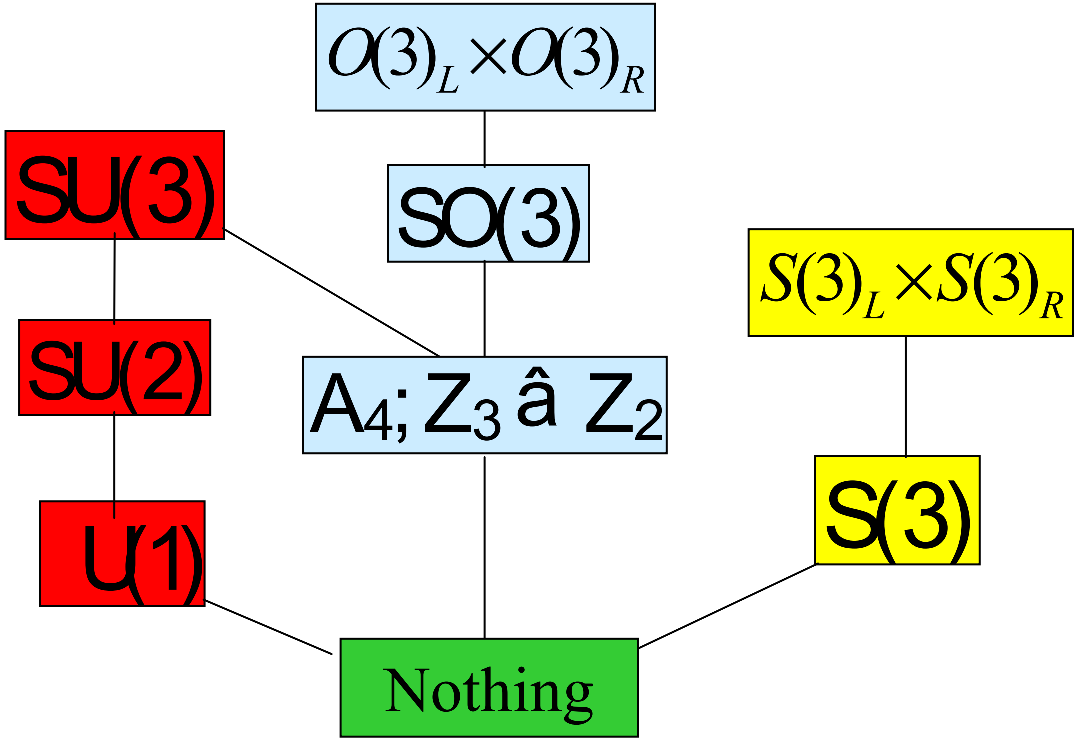
generation

Examples:



$O(3)_L \times O(3)_R$

SO(3)

SU(3)

SU(2)

U(1)

A_4; Z_3 â Z_2

$S(3)_L \times S(3)_R$

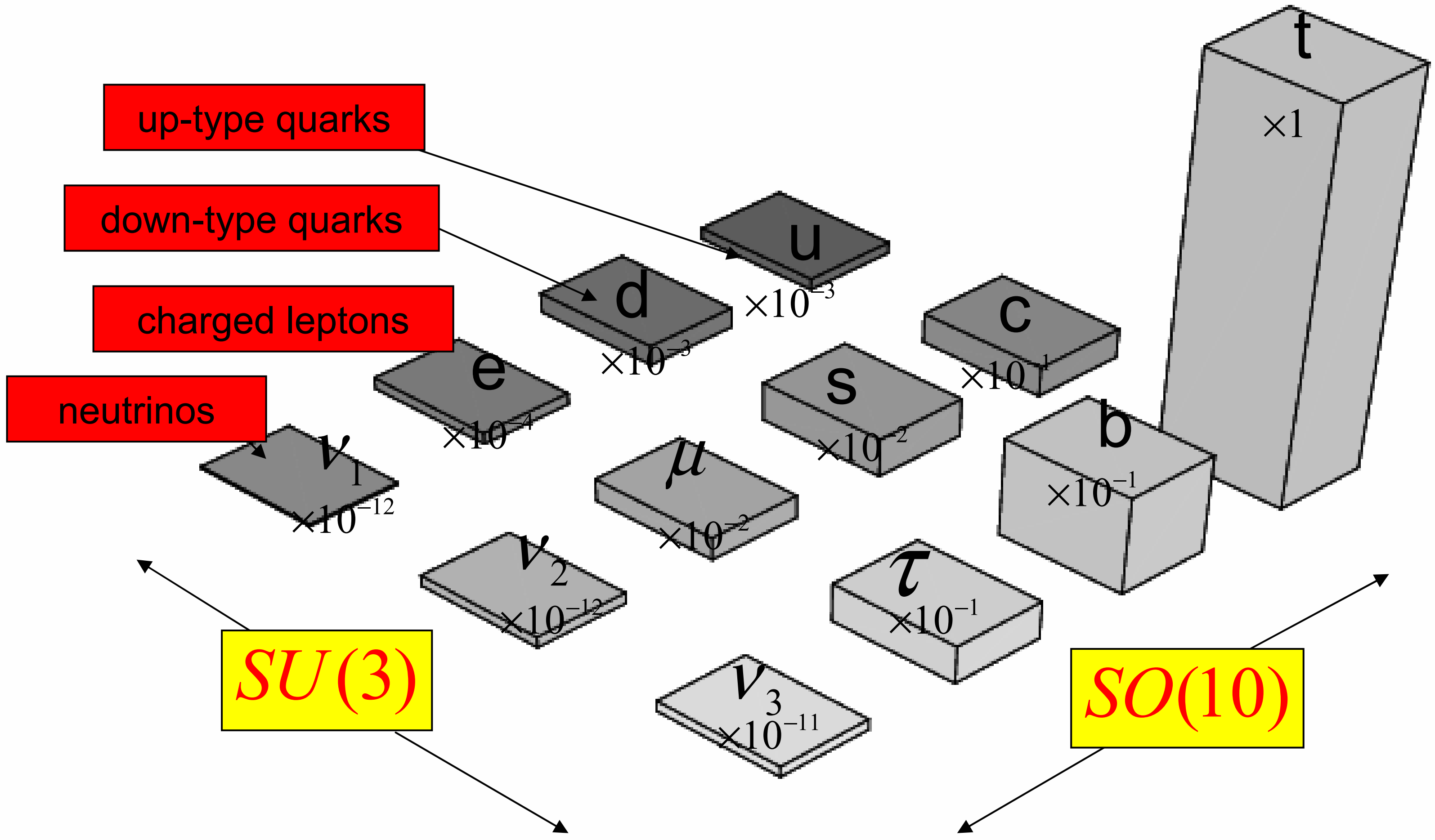
S(3)

Nothing

➔ See talk by E. Ma

GUT *and* Flavour Unification

Example: SO(10) x SU(3)



GUT $\otimes$ Flavour Unification

➔ GUT group $\otimes$ continuous, gauged flavour group

- for example SO(10) $\otimes$ $SU(3)_{\text{flavour}}$
- Generations are 3_F
- SSB of $SU(3)_{\text{flavour}}$ 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

Conclusions

- The potential of future experiments is very promising:
  - precision oscillation parameters
  - potential for the discovery of various new effects
  - allows to study several other subjects

- Synergies of oscillation experiments:
  - running strategies (e.g. next gen. reactor + beams)
  - parameter sensitivity (e.g. next gen. …)
  - absolute mass measurements, $0\nu2\beta$ decay
  - interplay with LFV
  - related to LHC physics
  - connected to astrophysics and cosmology