Prospects for the Coming Accelerator and Reactor Neutrino Experiments

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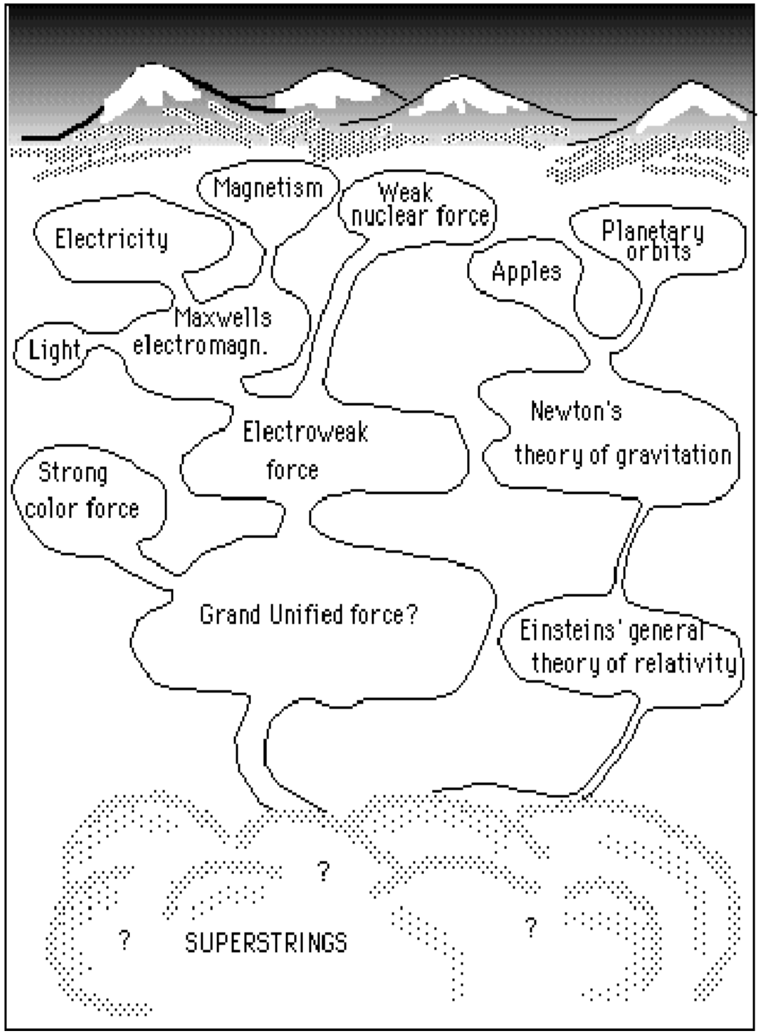
Physics Beyond the Standard Model

Theoretical arguments:

SM **does not exist without** cutoff
Higgs-doublett = only **simplest extension**
Gauge hierarchy problem
Why: **3 generations , fermion representations**
Many parameters (9+? Masses, 4+? Mixings)
Charge quantisation, unification: GUTs, ...,
Gravitation, ...

2 directions: Sym. breaking & Flavour

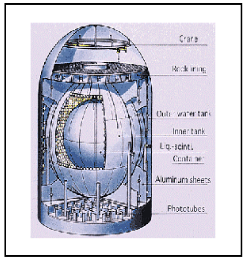


Experimental facts:

- **Dark Matter** & **Dark Energy** exist!
- **Neutrino masses** have been detected!
- **Baryon asymetry** of the universe ←→ $m_\nu > 0$

➔ **physics beyond the standard model**
➔ results ←→ **implications for theory**

Current Oscillation Results



KamLAND CHOOZ

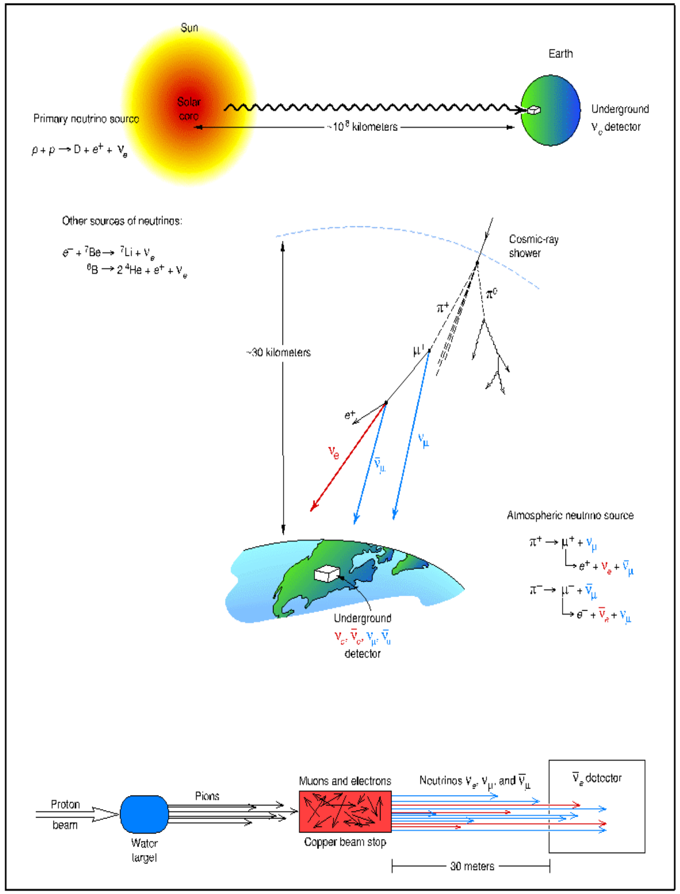
⇔

solar

atmospheric
+
K2K

neutrino oscillation signals

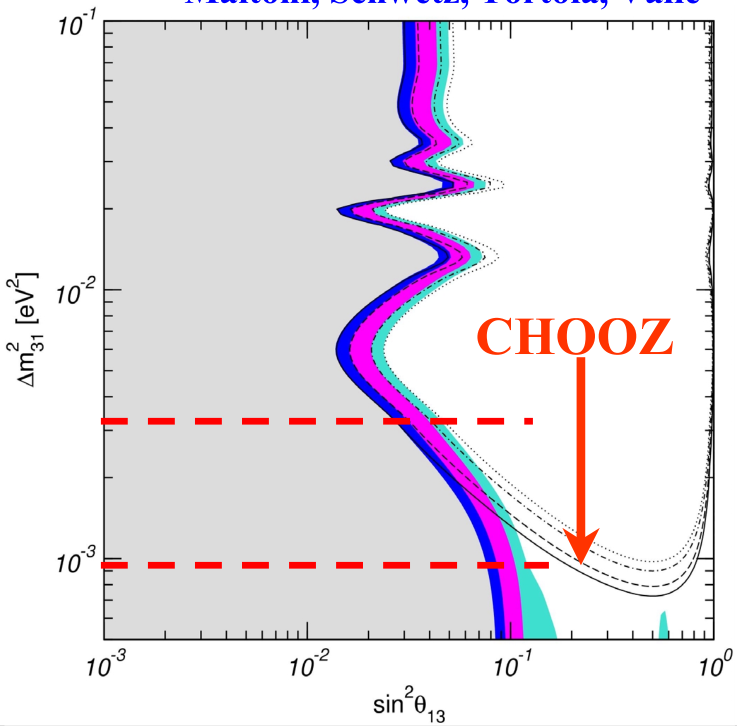
LSND?



$\Delta m^2_{12} = 8.2 \pm 0.3 * 10^{-5} eV^2$
$\tan^2\theta_{12} = 0.39 \pm 0.05$
$\Delta m^2_{13} = 2.2 \pm 0.6 * 10^{-3} eV^2$
$\tan^2\theta_{23} = 1.0 \pm 0.3$

$\sin^2\theta_{13} \leq 0.041$ @ 3σ

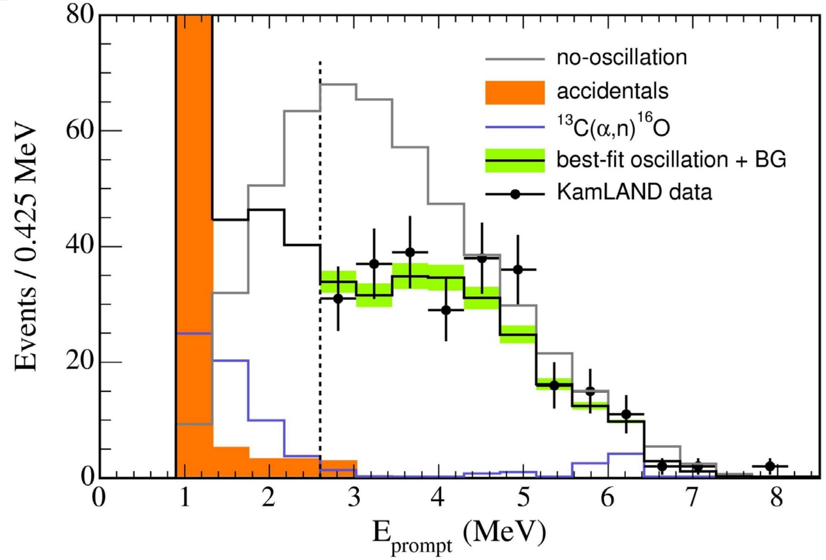
Maltoni, Schwetz, Tortola, Valle



➔ **approximately two 2x2 oscillations**

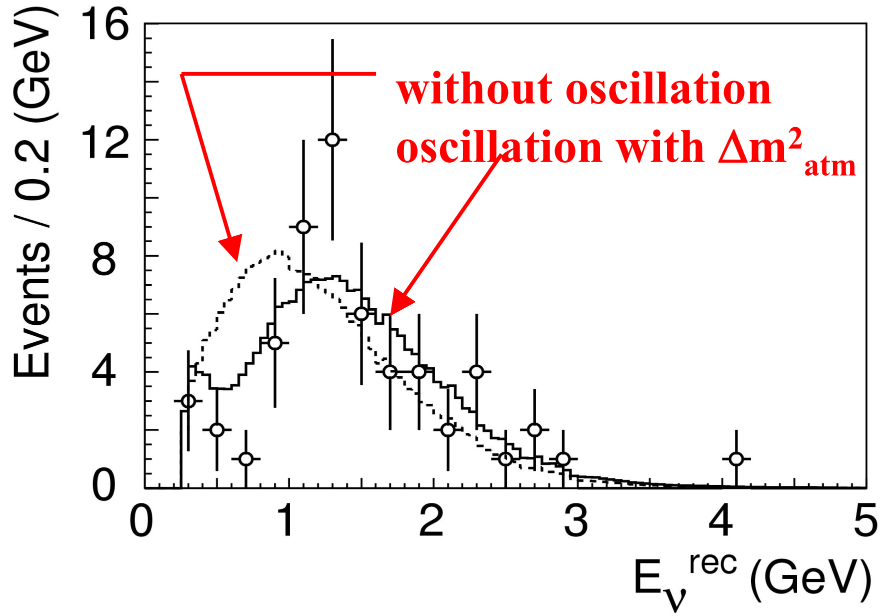
Accelerator & Reactor Experiments Now:

- **CHOOZ & Palo Verde**
  ⇔ θ_{13} limit



- **KamLAND**
  ⇔ solar oscillation

- **K2K**
  ⇔ atmospheric oscillation



The Future of Oscillation Physics

Δm^2 and θ_{ij} regions fixed:

➔ precision oscillation experiments

➔ controlled detectors & neutrino sources

➔ long baseline accelerator experiments with neutrino beams

➔ reactor experiments with identical near & far detector

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

x Majorana-CP-phases

➔ S_{13} ➔ δ

Aims:

➔ improved precision of the leading 2x2 oscillations

➔ detection of generic 3-neutrino effects

Three Flavour Oscillations

$$\left.\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\} \xrightarrow{oscillation} \left\{\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right.$$

$$\left.\begin{matrix}\overline{\nu}_e\\ \overline{\nu}_\mu\\ \overline{\nu}_\tau\end{matrix}\right\} \xrightarrow{oscillation} \left\{\begin{matrix}\overline{\nu}_e\\ \overline{\nu}_\mu\\ \overline{\nu}_\tau\end{matrix}\right.$$

2 flavour approximations:

$P_{ab} = \sin^2(2\theta)\ \sin^2(\Delta m^2 L/4E)$
$P_{aa} = 1 - P_{ab}$

➔ **precision not sufficient**

3 flavour-oscillations

$$J_{ij}^{e_l e_m} := U_{li} U_{lj}^* U_{mi}^* U_{mj} \qquad \Delta_{ij} := \frac{\Delta m_{ij}^2 L}{4E} = \frac{(m_i^2 - m_j^2) L}{4E}$$

$$P(\nu_{e_l} \to \nu_{e_m}) = \underbrace{\delta_{lm} - 4 \sum_{i>j} \mathrm{Re} J_{ij}^{e_l e_m} \sin^2 \Delta_{ij}}_{P_{CP}} \underbrace{-2 \sum_{i>j} \mathrm{Im} J_{ij}^{e_l e_m} \sin 2\Delta_{ij}}_{P_{\not{CP}}}$$

+ matter effects
➔ sgn(Δm^2)

- **2➔3 flavours ➔ more mixings & CP phase**
- **MSW matter effects**

Analytic Approximations

- $\Delta = \Delta m^2_{31} L/4E$
- qualitative understanding $\Rightarrow$ expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31}$; $V = \sqrt{2} G_F n_e$

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^2\theta_{13}\sin^2 2\theta_{23}\sin^2\Delta + 2\,\alpha\,\cos^2\theta_{13}\cos^2\theta_{12}\sin^2 2\theta_{23}\Delta\cos\Delta$$

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

➔ analytic discussion / full simulations

➔ degeneracies, correlations ➔ $(\sin^2 2\theta_{13})_{\mathrm{eff}}$

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

Degeneracies, Correlations, ...

Fixed L/E ➔ probabilities invarinat under transformations:

- $\theta_{23} \rightarrow \pi/2 - \theta_{23}$ **Fogli, Lisi**
$P(\nu_e \rightarrow \nu_\mu)$ not really invariant ➔ compensation by small parameter off-sets

- $\Delta m^2 \rightarrow -\Delta m^2$ **compensated by offset in δ** **Minakata, Nunokawa**

- $P(\nu_e \rightarrow \nu_\mu)$**=const. ➔** $\delta - \theta_{13}$ **manifolds** **Koike, Ota, Sato & Burguet-Castell et al.**

- **➔ 8-fold degeneracy** **Barger, Marfatia, Whisnant**

- $P(\nu_e \rightarrow \nu_\mu)$ **depends on** $\sin(A\Delta) = \sin(VL/2)$
$VL=2\pi$ ➔ magic baseline: $L_{magic} = 2\pi/V = 8100$ km **Huber, Winter**

- **parameter extraction suffers from correlations & degeneracies**
- **how to break degeneracies & correlations?**

Future Long Baseline Experiments

K2K	analysis	establish atmospheric oscillations with beam
MINOS OPERA , ICARUS	running construction	expected precision: 8% for Δm^2_{13} , 25% for $\sin^2\theta_{23}$, θ_{13} ?
T2K	approved	4% for Δm^2_{13} , 15% for $\sin^2\theta_{23}$, ➔ θ_{13}
NOνA	LOI	3% for Δm^2_{13} , 15% for $\sin^2\theta_{23}$ (combined with T2K) , ➔ θ_{13} , ➔ δ ? , ➔ sgn(Δm^2_{13})
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

New Reactor Experiments

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

identical detectors ➔ many errors cancel

- **The survival probability:**
  - expand in small quantities

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

  - last term negligible for $\frac{\Delta m^2_{31} L}{4E_\nu} \sim \pi/2$ and $\sin^2 2\theta_{13} \gtrsim 10^{-3}$
  - atmospheric frequency is dominant
  - most important:

- **No degeneracies!**
- **Practically no correlations!**
- **No matter effects!**

Simulation of Future Experiments

- select a setup (beam, detector, baseline, ...)
- take „most realistic“ parameters ←→ best guess!
- simulate all relevant aspects as good as possible

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)

- determine the potential: „true“ ←→ fitted parameters
- compare only realistic simulations (all relevant effects, errors & uncertainties)

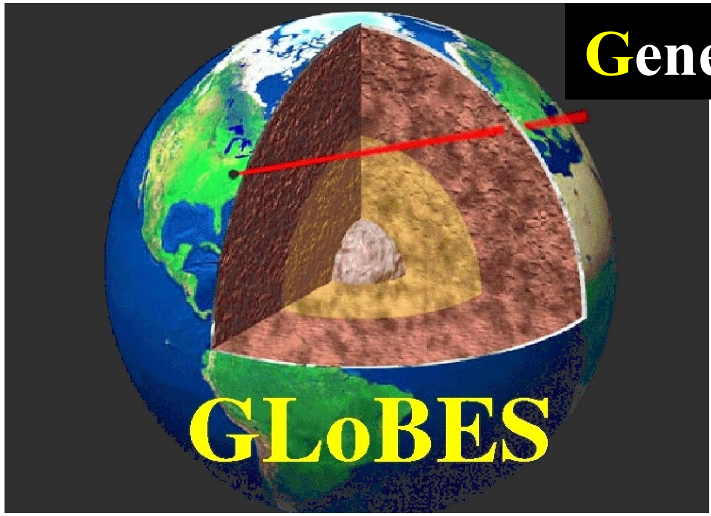
Apologies

Simulations of various options by various:

Barger, Geer, Raja, Whisnant, Marfatia
Cervera, Donini, Gavela, Gomez-Cadenaz, Hernandez, Mena, Rigolin, ...
Bueno, Campanelli, Rubbia
Minakata, Yasuda
...

Freund, Huber, ML, Winter
Huber, ML, Rolinec, Schwetz, Winter
...

A Powerful Simulation Tool



General Long Baseline Experiment Simulator

http://www.ph.tum.de/~globes

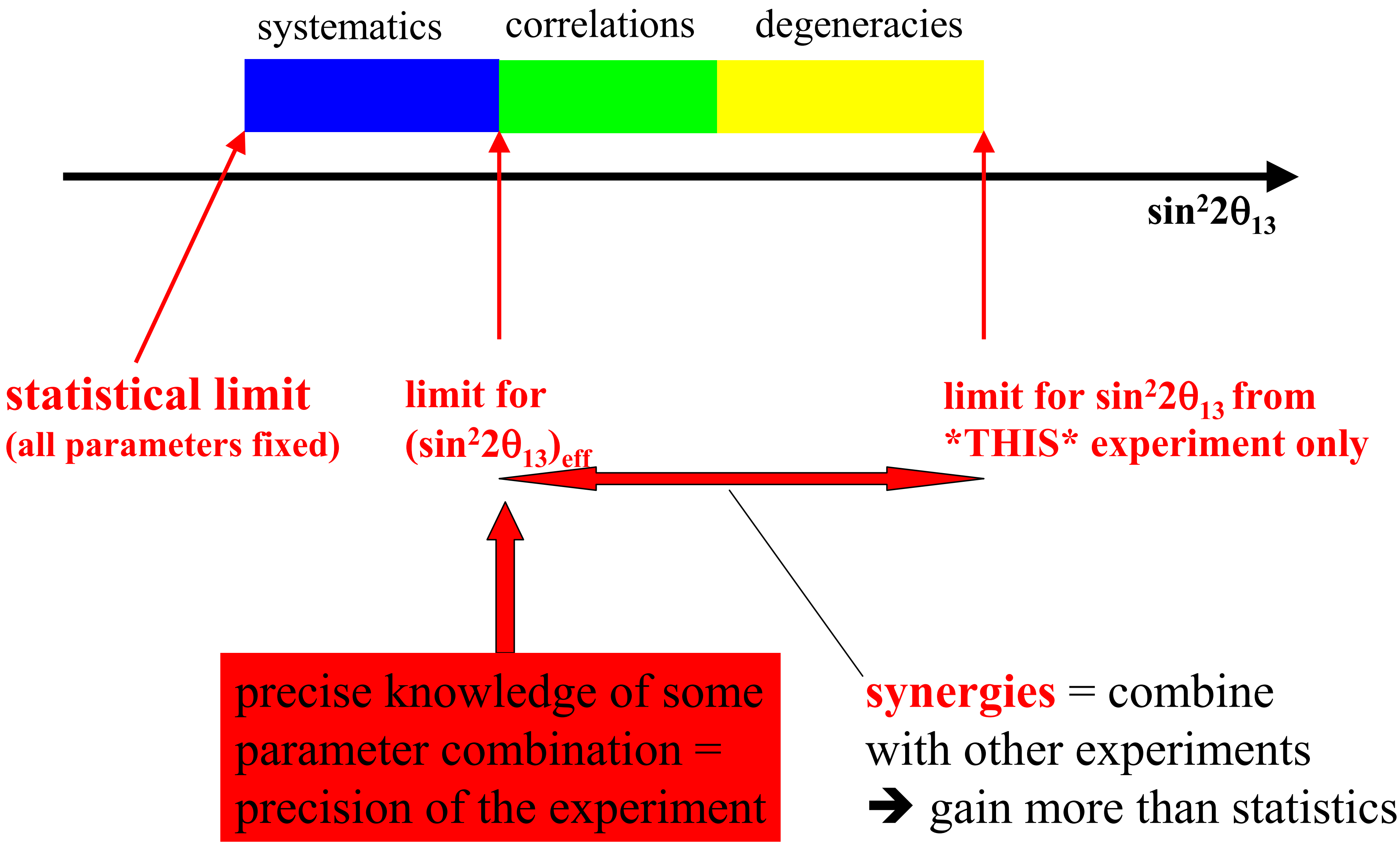
hep-ph/0407333

P. Huber, ML, W. Winter

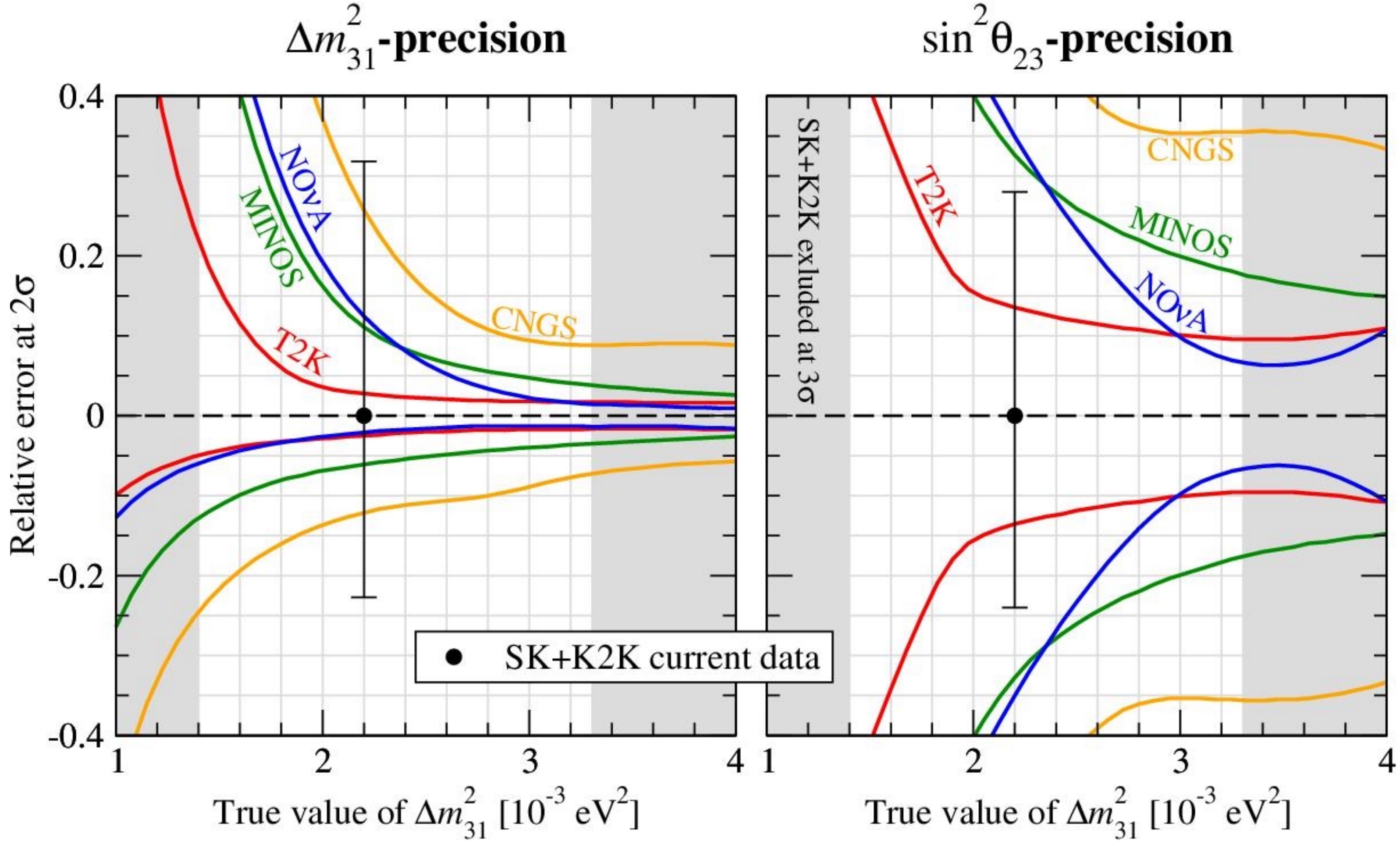
- **C-based simulation software (GPL – free, for Linux systems)**
- **extensive documentation & examples**
- **3 phase approach:**

• AEDL (**Abstract Experiment Definition Language**)
• simulation of an experiment ➔ 3-ν oscillations; scan „true values“
• analysis ➔ event distriutions, ..., sensitivities, ...

Sensitivity Plots

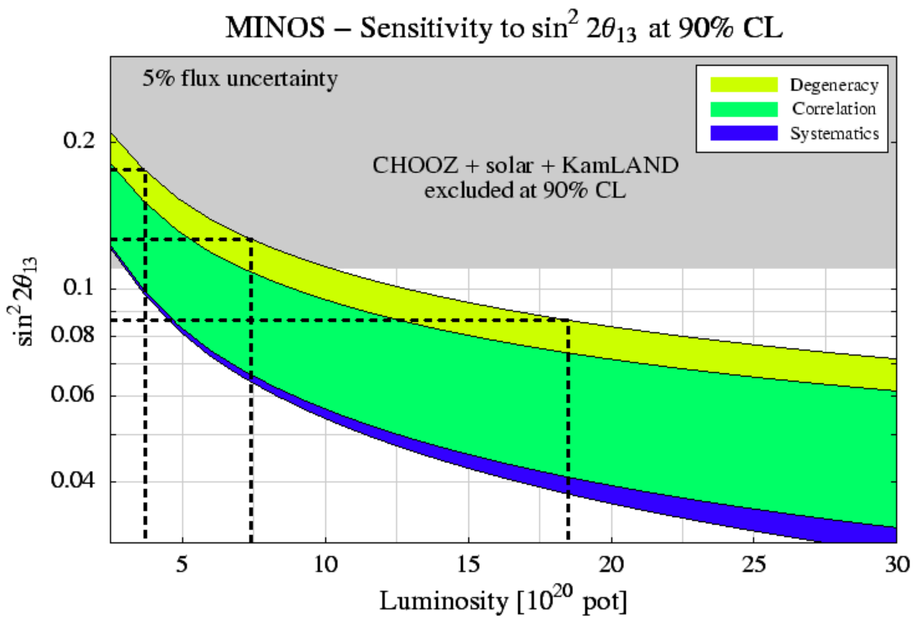


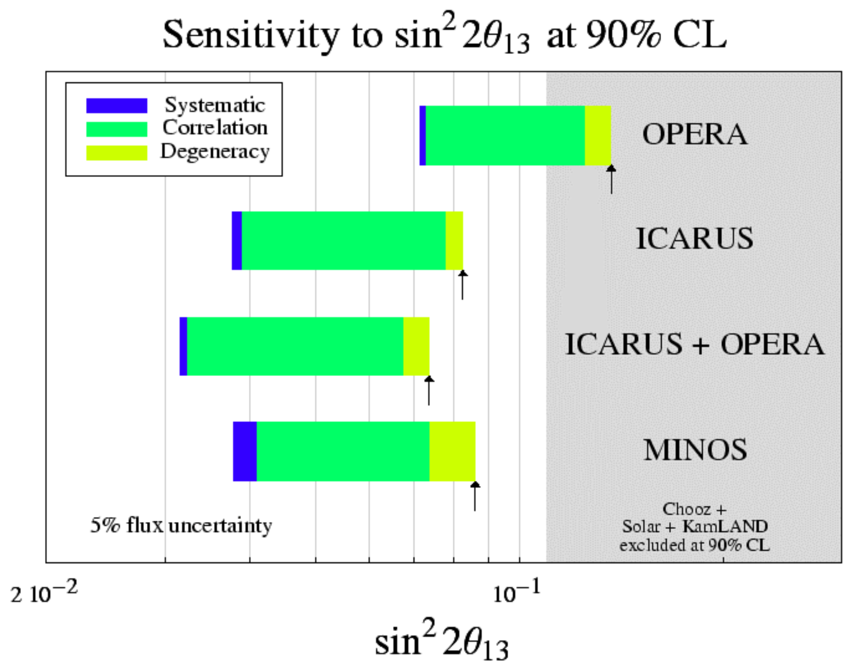
Improvement of Δm^2_{31} and $\sin^2\theta_{23}$



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

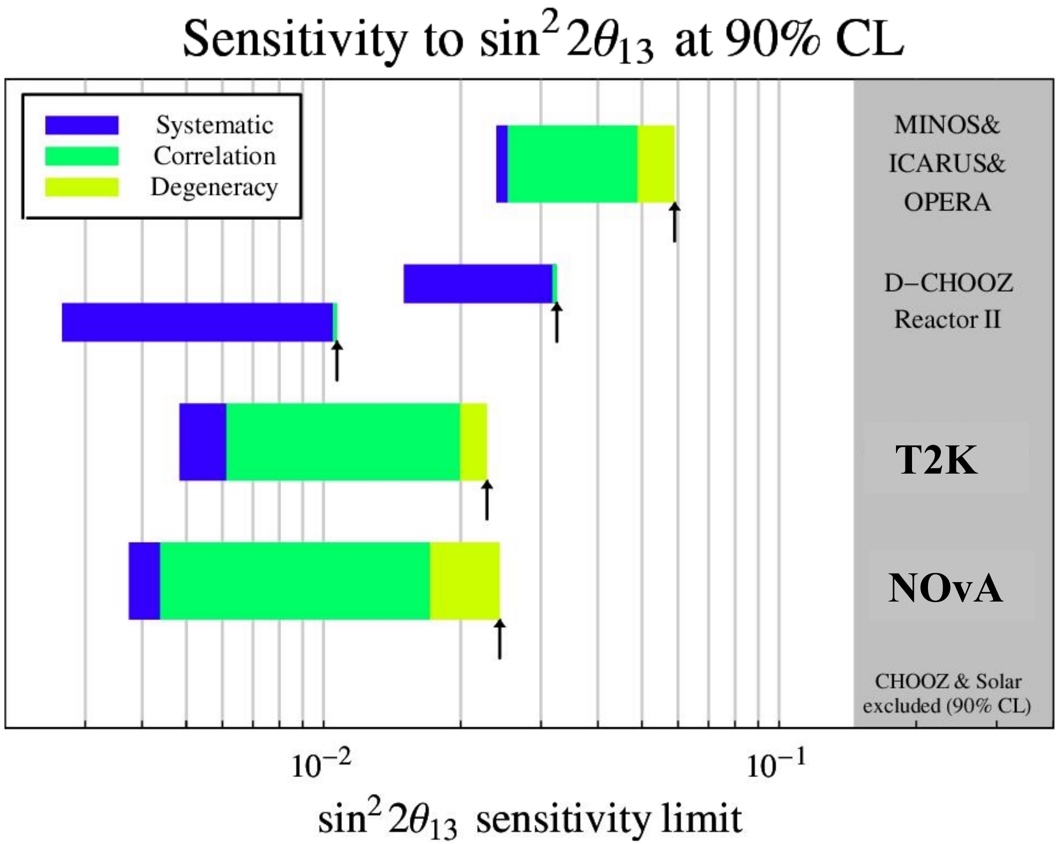
– 1,2,5 years

Compare: 5 years, 5% flux uncertainty

– CNGS: $4.5 \cdot 10^{19}$ pot/y

- **only modest improvements for θ_{13}**
- **other objectives...**

θ_{13} Sensitivity in the Next Generation



coming long baseline experiments

1 reactor +2 detectors

next generation long baseline experiments

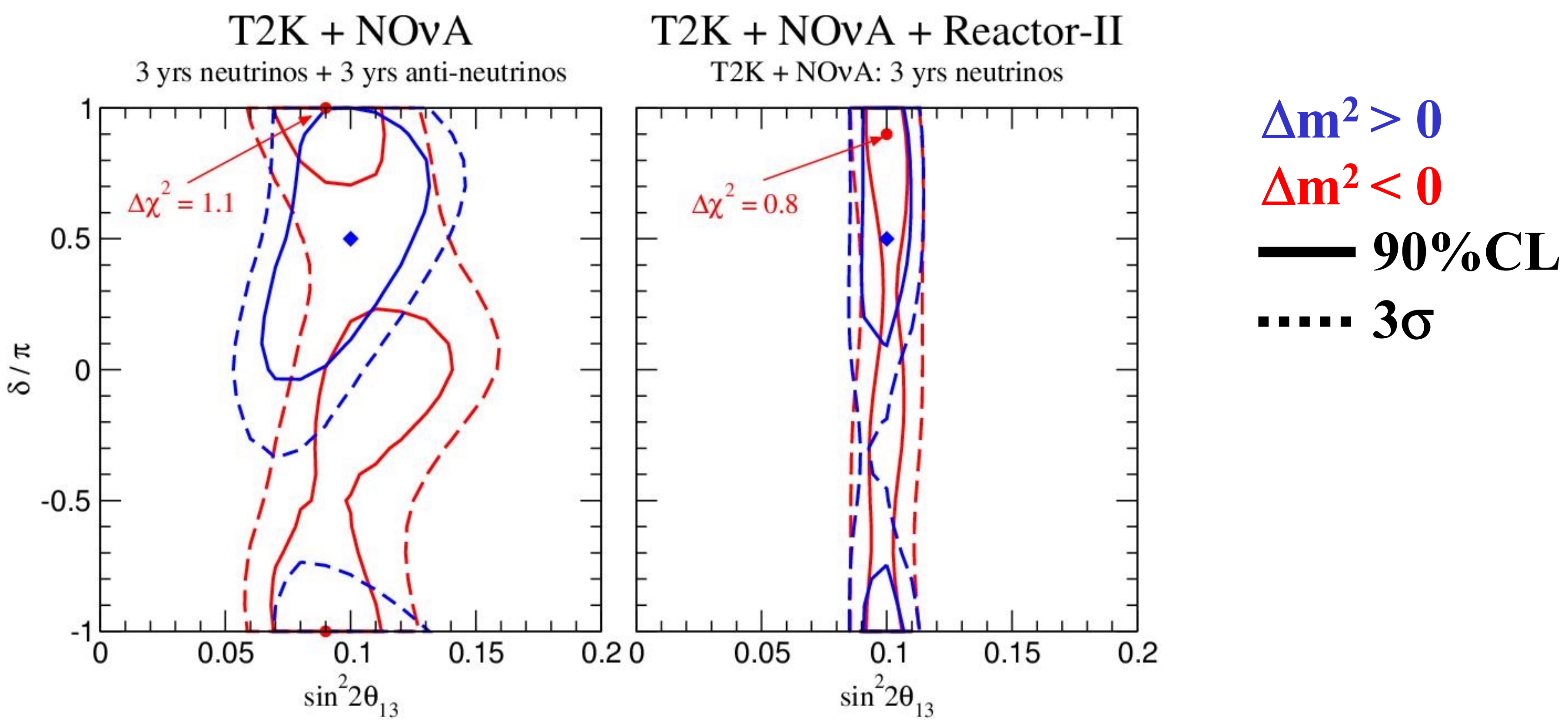
Compare:

- 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 ⇒ NOvA 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



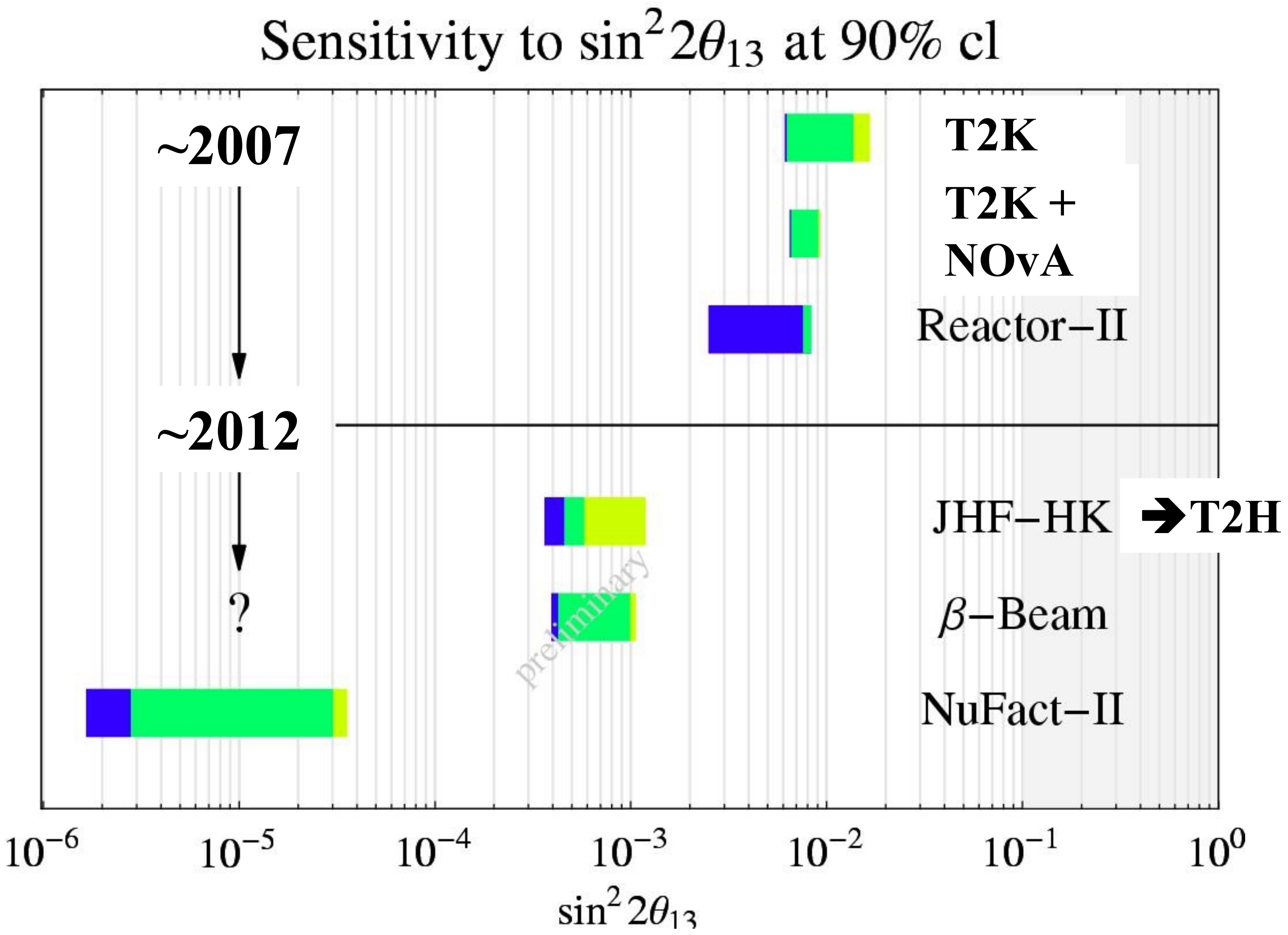
Huber, ML, Rolinec, Schwetz, Winter

Long Term Perspectives

- **superbeams: $E_\nu \approx$ GeV** ➔ large low Z sampling calorimeters ≈ 50 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

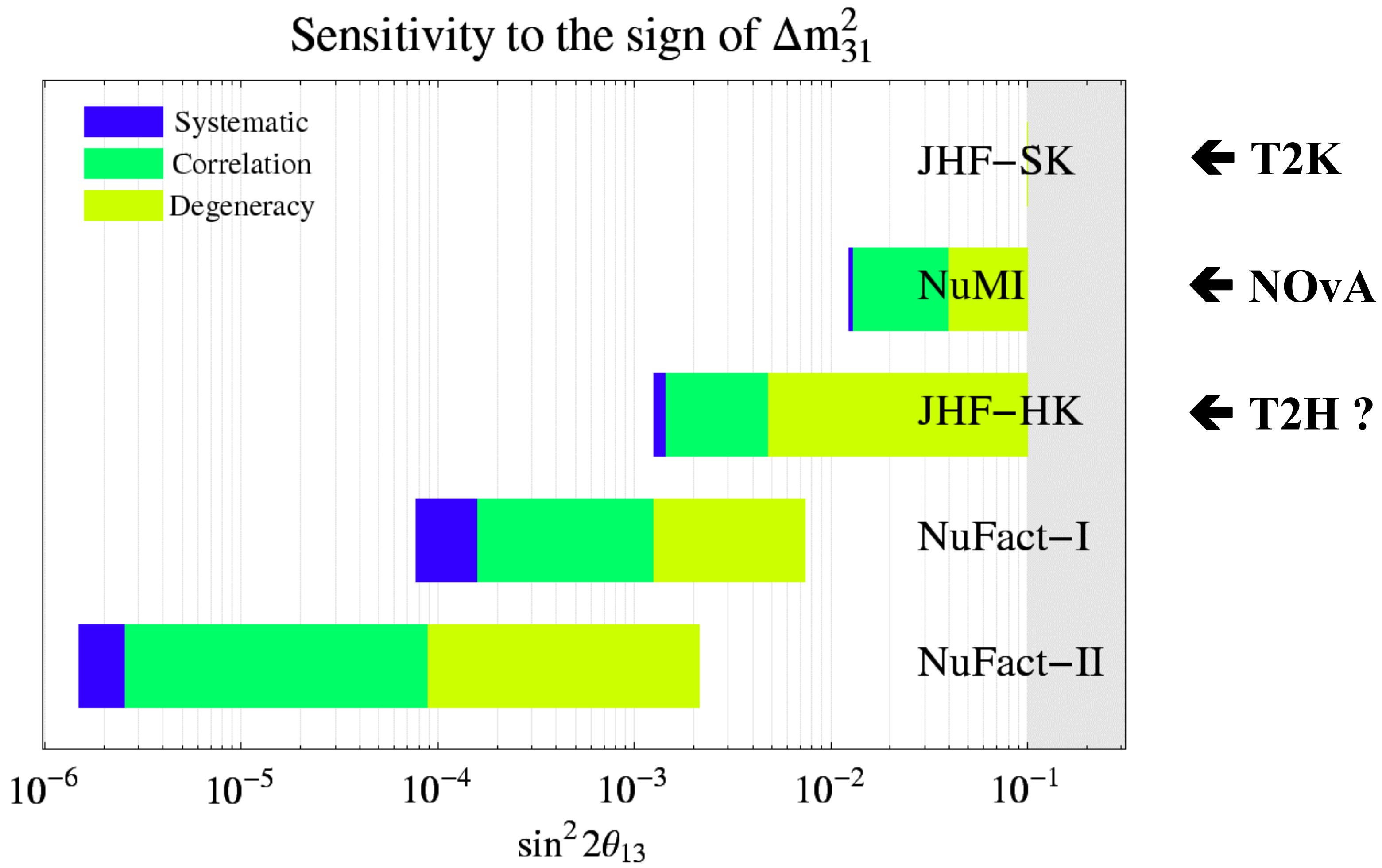
	P(MW)	μ's/year	$T_\nu+T_{\bar{\nu}}$ (y)	M(kt)
Neutrino factory I:	0.75	10^{20}	5	10
Neutrino factroy II:	4.00	$5.3*10^{20}$	8	50



- **very powerful**
- **many good ideas**
- **...challenges**

➔ **further R&D**

- **different sensitivity reductions by systematics**
- **correlations & degeneracies lead to severe sensitivity reductions**
- **break C&D by combining different experiments of comparable potential**



- $sign(\Delta m^2_{31})$ very hard to determine with superbeams
- degeneracies with δ_{CP} are the main problem

$\Rightarrow$ combine experiments!

How to Break Degeneracies & Correlations

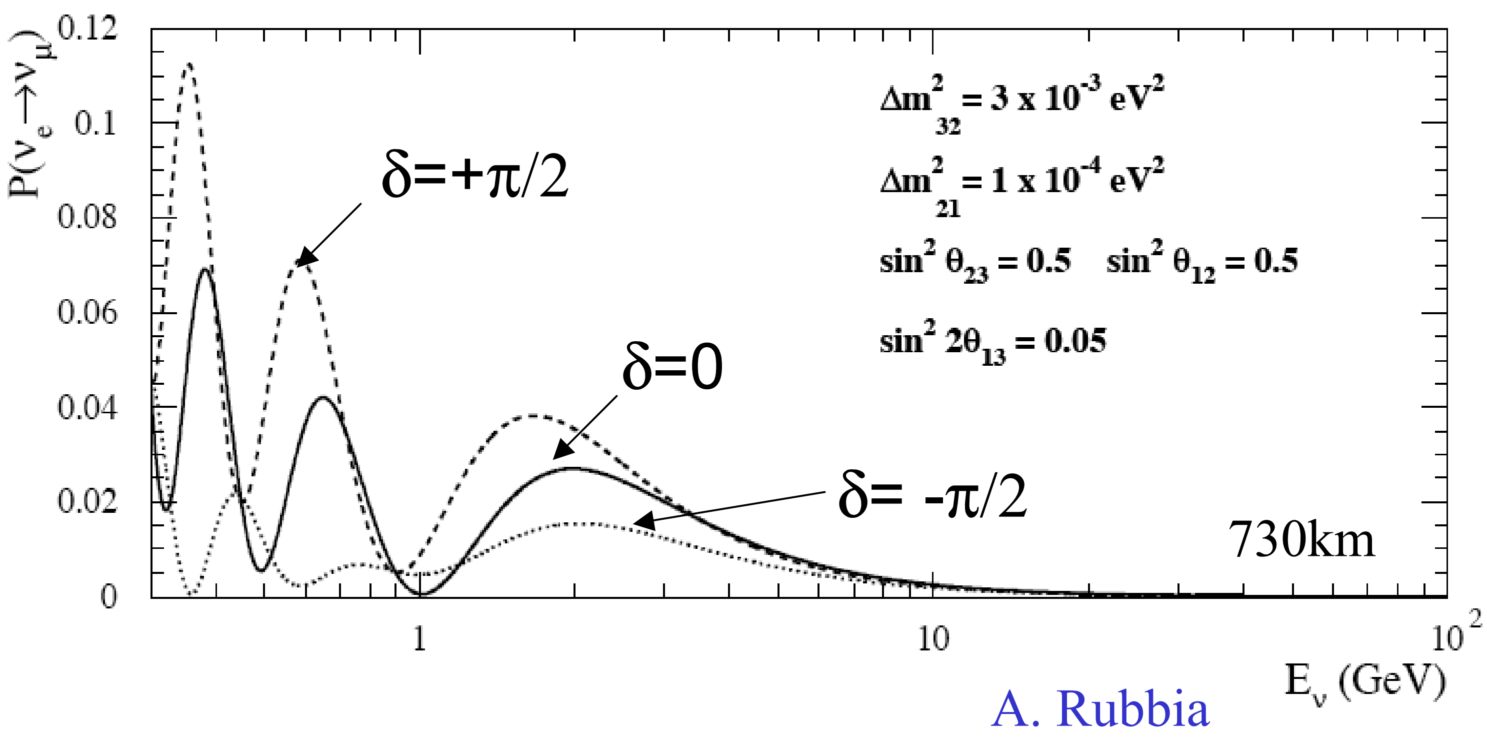
Rates only ➔ degeneracies ...broken by

- ➔ combination of different oscillation channels
- ➔ 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

Energy Resolution

Rate based degeneracies have different energy spectra



➔ use energy resolution to break degeneracies

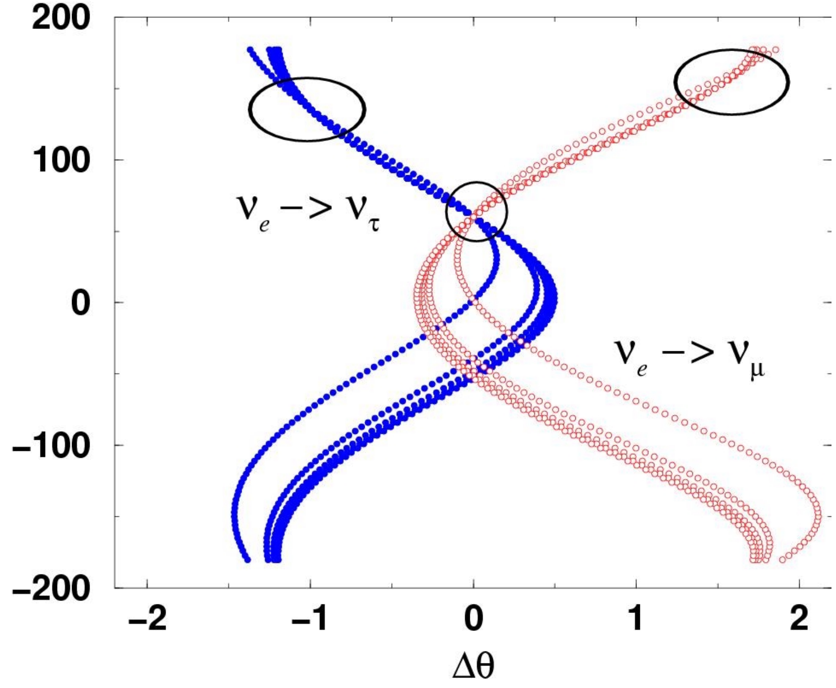
Silver Channels

Neutrino factory:

- **golden channel: wrong sign μ's**
- **silver channel : τ's**

➔different oscillation probabilities

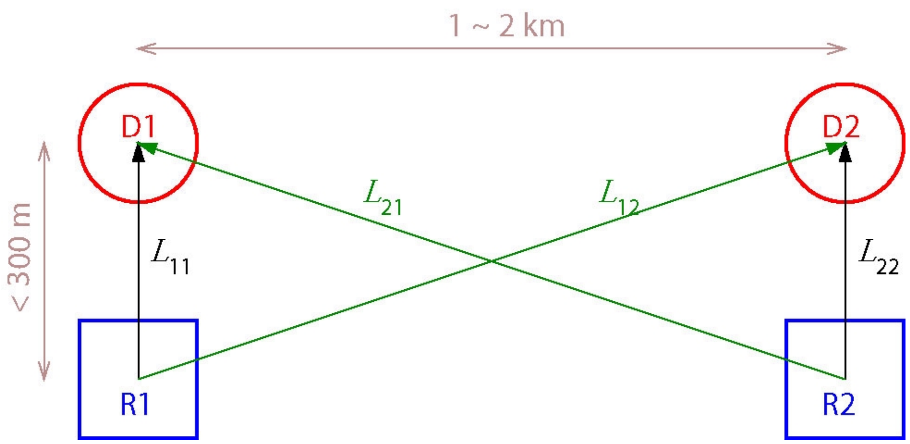
➔ break degeneracies!

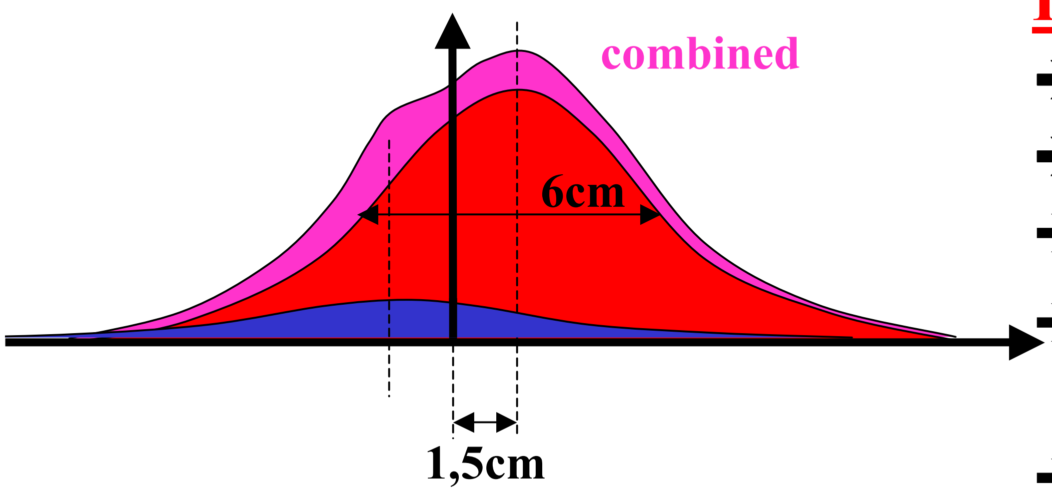


Donini, Meloni, Migliozzi
Autiero, et al.

New Ideas: R2D2 - Reactor Experiments

- **Symmetric reactors,detectors:**
  - **R1, R2, D1, D2 - may be different**
  - **L_{11}=L_{22} and L_{12}=L_{21}**
- **Separate events from R_1 and R_2**
  - **R1 and R2 on/off times**
  - **Neutron displacement**
- **Simplest case: 1d line-up**





High statistics:

→ **precise statistical separation**

→ **N11, N21, N12, N22**

→ **self-calibration: N11/N21=N22/N12**

→ $$\frac{N11 * N22}{N21 * N12} = \frac{r^4}{R^4}$$ ←→ oscillation

→ **stable against size, backgrounds, ...**

→ **factor 2 – 10 compared to R1D2**

Theoretical Implications of Precision

Precision allows to identify / exclude:

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

Provides also tests of:

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

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 CP-violation

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

<u>physics question: small θ_{13}</u>
→ numerical coincidence
→ systematic (symmetry,...)
- **how small?**
- **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

Mass Models & Renormalization

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

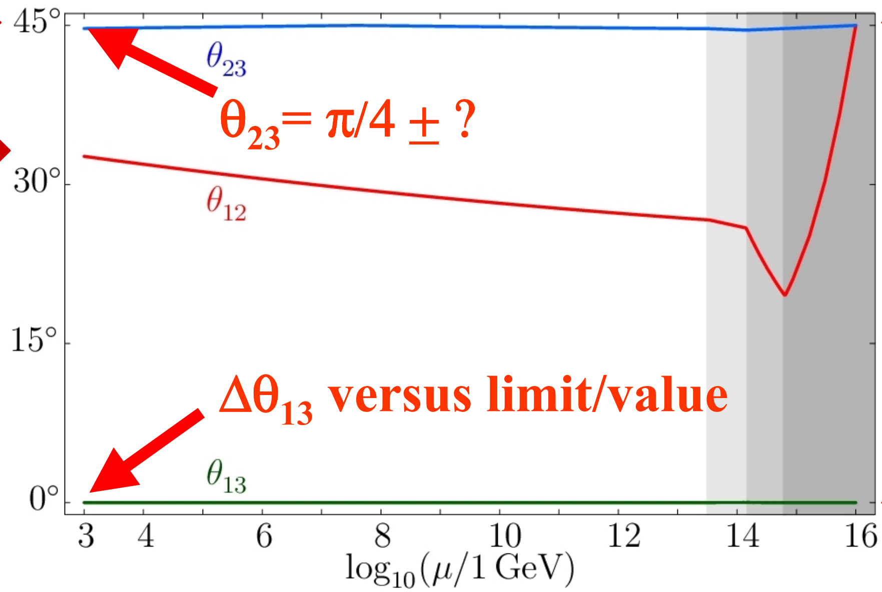
renormalization group running →

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

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

The Interplay of Various Topics

Standard Model extensions

flavour symmetries

m_{LL}	Scheme	$0\nu\beta\beta$-decay
$\frac{m}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$ + corr.	hierarchical, normal	small
$\frac{m}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$ + corr.	hierarchical, inverted	small
$m\begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{1}{2} & \frac{1}{2} \end{pmatrix}$ + corr.	hierarchical, inverted	large
$m\begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}$ + corr.	degenerate	small
$m\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$ + corr.	degenerate	large

leptogenesis mechanisms
supernovae
nucleosynthesis
structure formation
...

renormalization group

mass spectrum, mixings, CP-phases, LVF, 0ν2ββ–decay, ...

➔ν-parameters extremely valuable

➔ long term: most precise flavour info

Conclusions

➔ very precise neutrino oscillation parameters can be obtained
➔ long term: most precise flavour information
➔ $\sin^2 2\theta_{13}$, sign(Δm^2) and CP phase should be measured
➔ unique impact on our understanding of flavour
- model building (symmetries, GUTs, mixing angle relations,...)
- quantum corrections
- limits on 3ν unitarity, decay, decoherence

➔ tests also
- coherent forward scattering , matter profiles
- NSI
- MVN, extra dimensions, ...

➔ **very promising program!**