Neutrino Physics: Goals and Perspectives

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WHEPP9

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High Energy Physics Phenomenology
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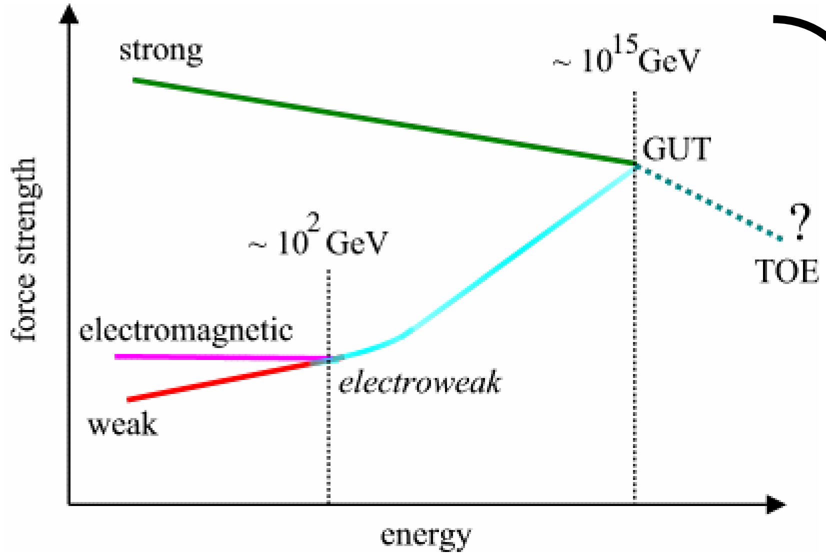
Motivation: Physics Beyond the SM

gauge bosons



experimental facts:

Dark Matter
Dark Energy
neutrino masses
baryon asymetry: $m_\nu > 0$

SUSY ~TeV

Higgs

gauge hierarchy problem
$\delta m_H^2 \sim \Lambda^2$

astrophysics & cosmology

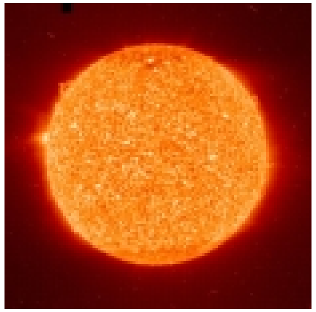
quarks leptons

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

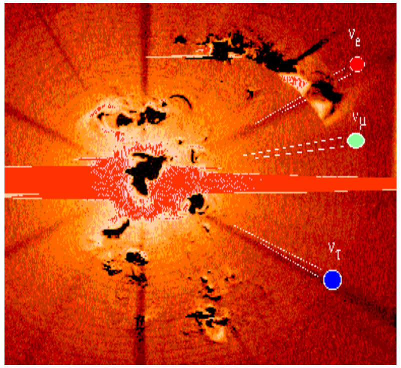
$\sim\Lambda_{GUT}$ +seesaw

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

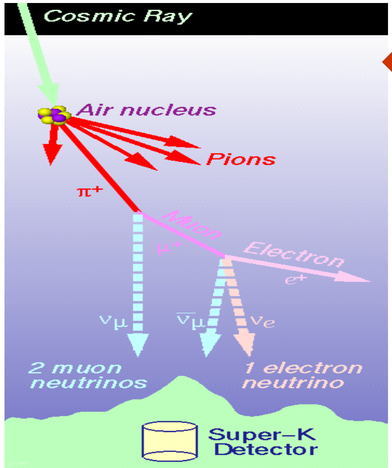
New Physics: Neutrino Sources



← **Sun**

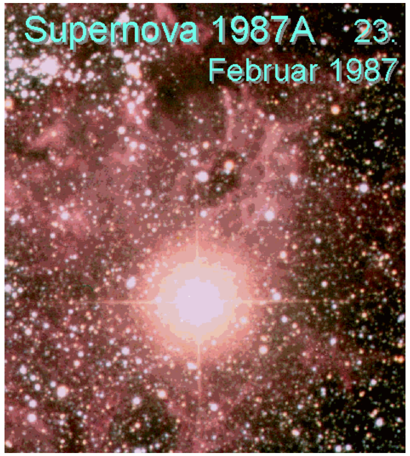


← **Cosmology**



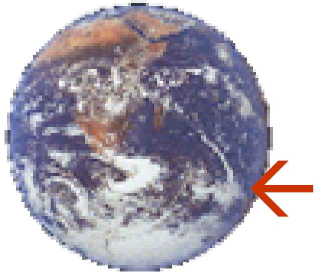
← **Atmosphere**

Astronomy: →
Supernovae
GRBs
UHE ν's



Reactors →

Accelerators →



← **Earth**

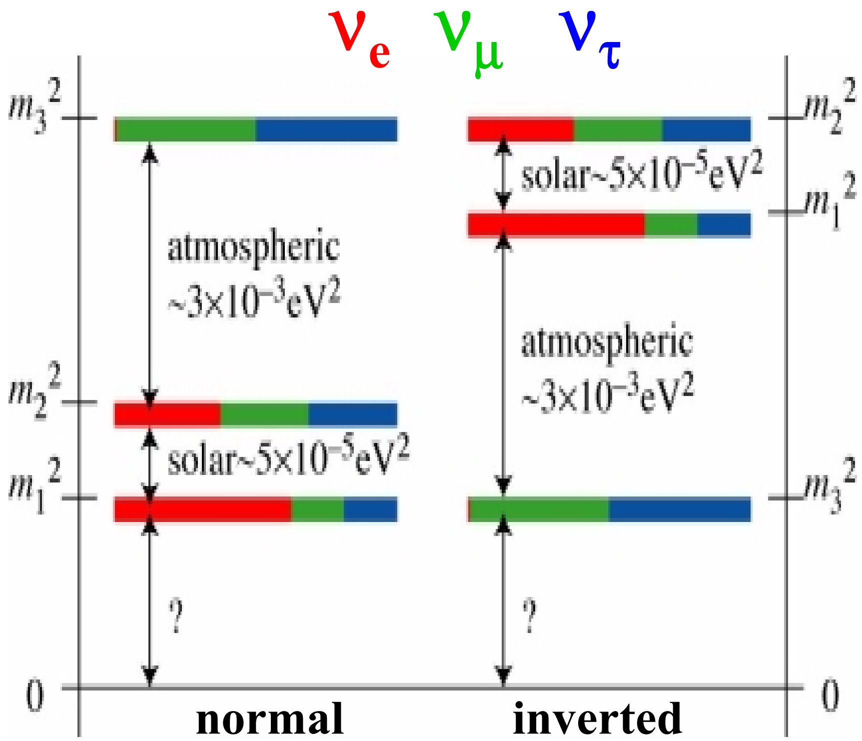
Parameters for 3 Light Neutrinos

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 or Majorana
- ➔ absolute mass scale: m_1
- ➔ mass ordering: sgn(Δm^2_{31})
- ➔ how small is θ_{13}, θ_{23} maximal?
- ➔ leptonic CP violation
- ➔ LSND ←➔ sterile neutrino(s)
- ➔ L/E pattern of oscillations



normal **inverted**

hierarchical or degenerate

Four Methods of Mass Determination

- **kinematical**
- **lepton number violation**
  ↔ Majorana nature
- **oscillations**
- **astrophysics & cosmology**

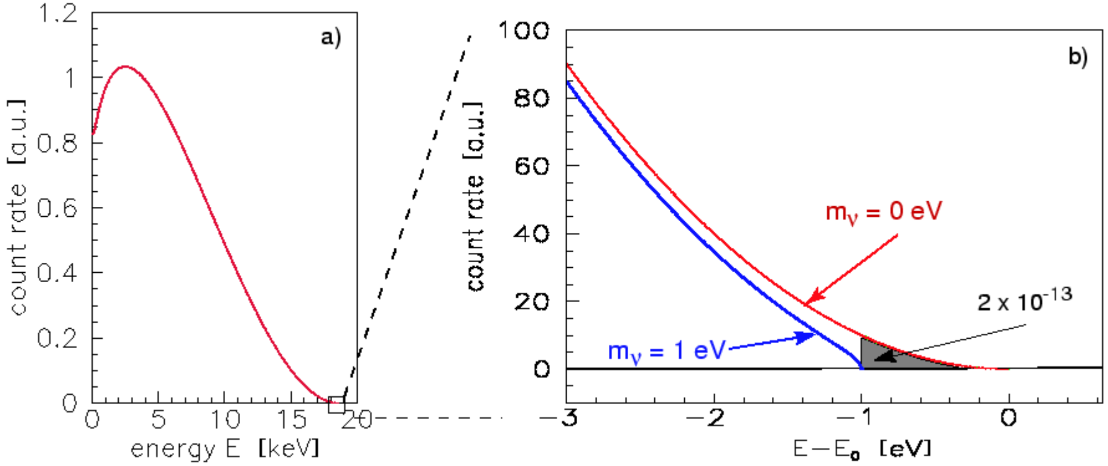
Kinematical Mass Determination

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:

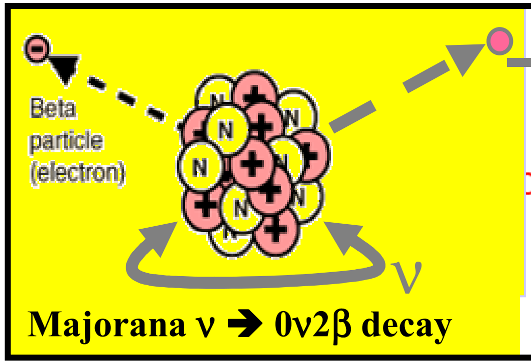
"Elektron-Neutrino": $m < 2.2$ eV (Mainz, Troitsk)
"Muon-Neutrino": $m < 170$ keV
"Tau-Neutrino": $m < 15.5$ MeV

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

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

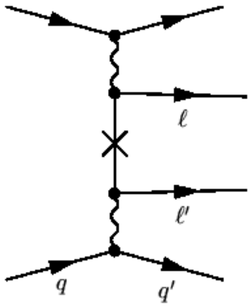
Future: **KATRIN → 0.25 eV** **→ ?** **←→ c.f. comological bounds**

Neutrino-less Double β-Decay



Majorana ν ➔ 0ν2β decay

$\propto$

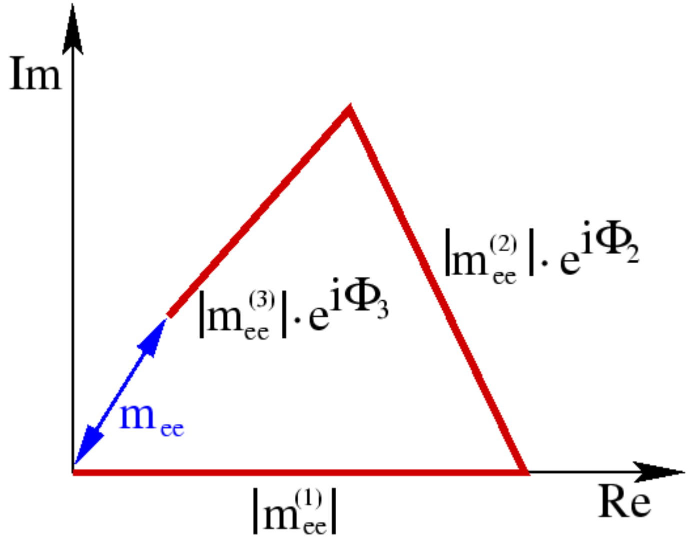


$$\propto |\langle m_{ee} \rangle| \;=\; |\sum m_i U_{ei}^2| \quad \leq 0.35 \text{ eV ?}$$

Heidelberg-Moscow experiment

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

$$\begin{aligned} |m_{ee}^{(1)}| &= |U_{e1}|^2 m_1 \\ |m_{ee}^{(2)}| &= |U_{e2}|^2 \sqrt{m_1^2 + \Delta m_{21}^2} \\ |m_{ee}^{(3)}| &= |U_{e3}|^2 \sqrt{m_1^2 + \Delta m_{31}^2} \end{aligned}$$



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

$m_1 \rightarrow$ small $\Rightarrow$ m_{ee} =const. ~ $(\Delta m_{ij}^2)^{1/2}$ $\Leftrightarrow$ sign(Δm^2_{31})
m_1 large $\Rightarrow$ $m_{ee} \sim m_1$

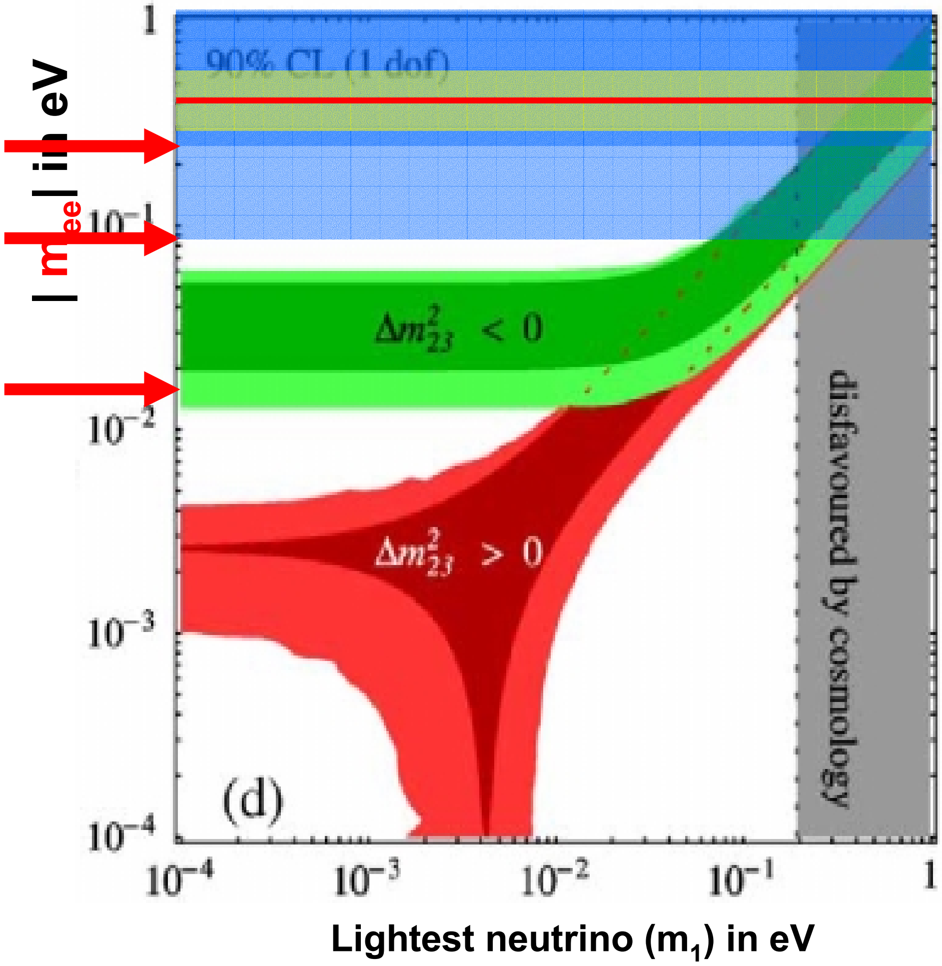
cosmological bound on m_1
HM-claim ➔ ‚tension'

new experiments:
CUORICINO, GERDA➔
CUORE, Majorana, …
aim: $(\Delta m_{31}^2)^{1/2} \simeq 0.05$eV

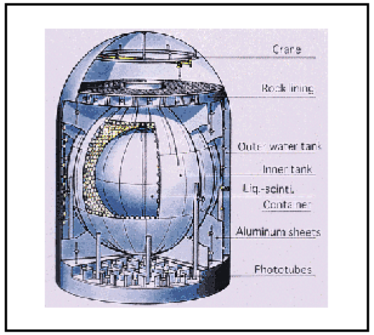
Cosmology: syst. errors ➔ X10?
0ν2β – nuclear matrix elements?
theory: LR, RPV-SUSY, ...

➔ lepton number violation

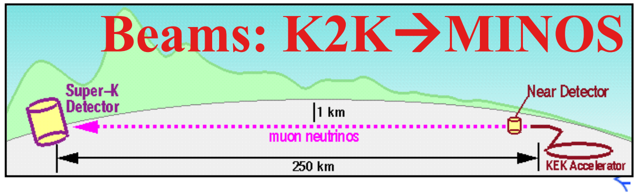
Feruglio Strumia Vissani

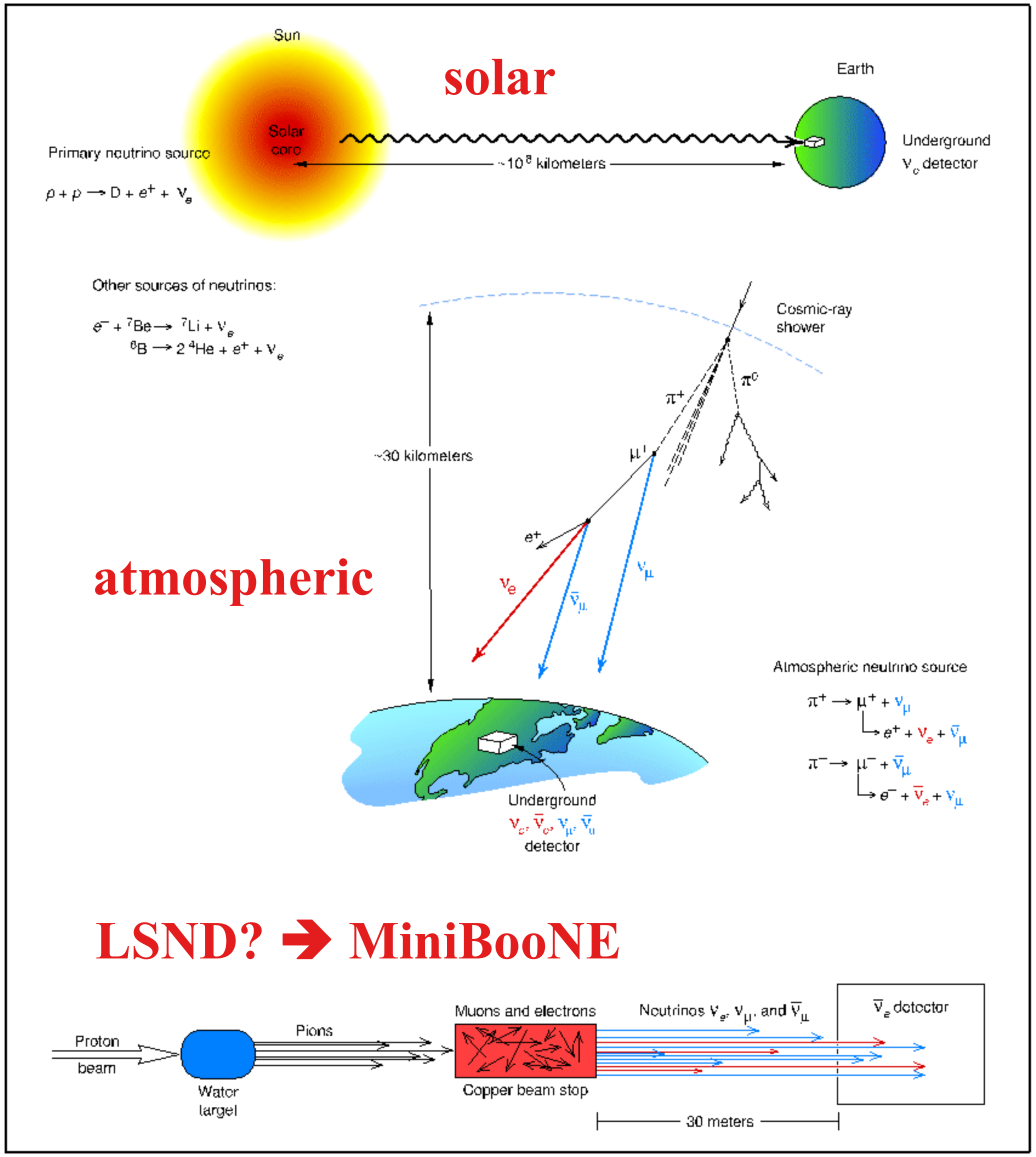


Neutrino Oscillation Signals



Reactors: KAMLAND


Beams: K2K→MINOS


solar

atmospheric

LSND? → MiniBooNE

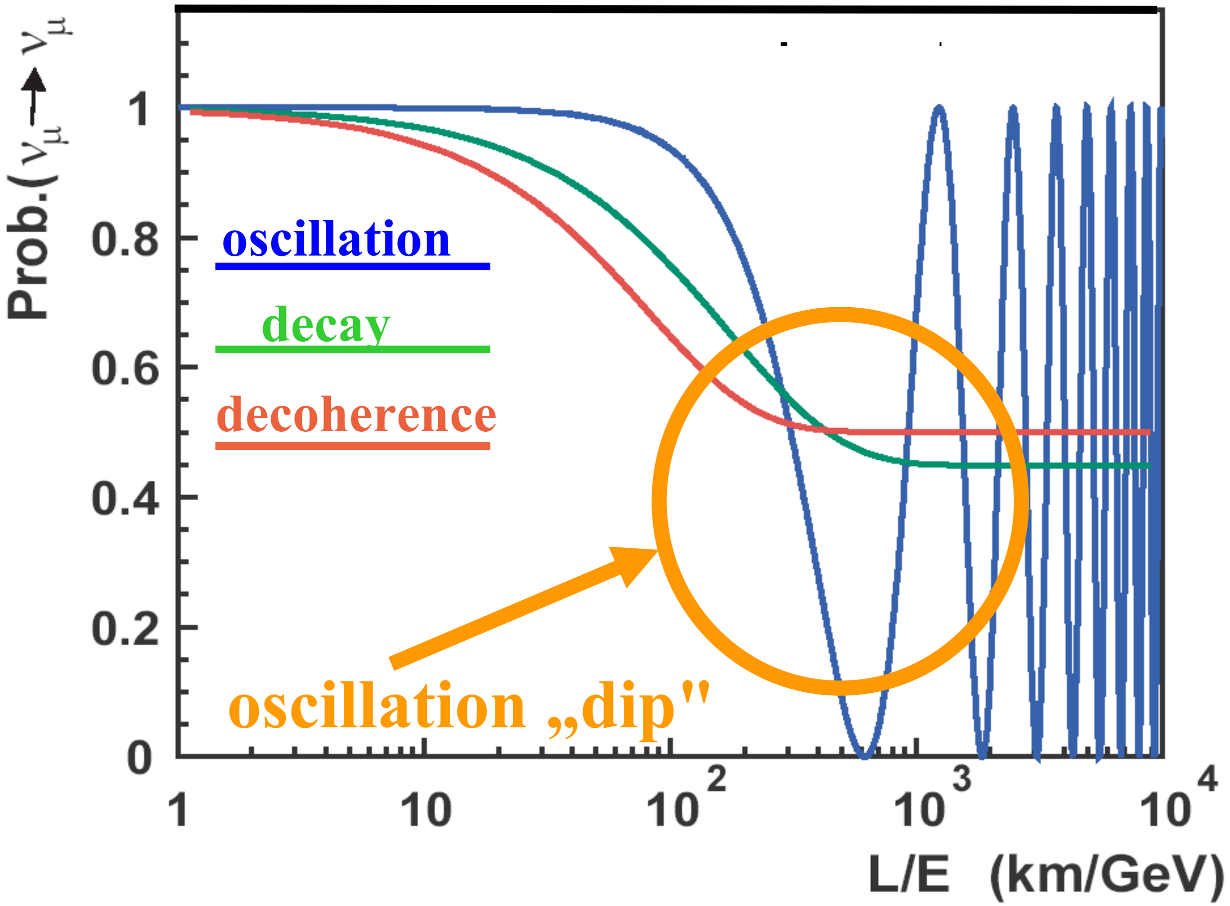
$$\Delta m^2_{21} = (8.2 \pm 0.3) * 10^{-5}\,eV^2$$
$$\tan^2\theta_{12} = 0.39 \pm 0.05$$
$$\Delta m^2_{31} = (2.2 \pm 0.6) * 10^{-3}\,eV^2$$
$$\tan^2\theta_{23} = 1.0 \pm 0.3$$
$$\sin^2 2\theta_{13} < 0.16$$

L/E Dependence: Atmospheric Oscillations

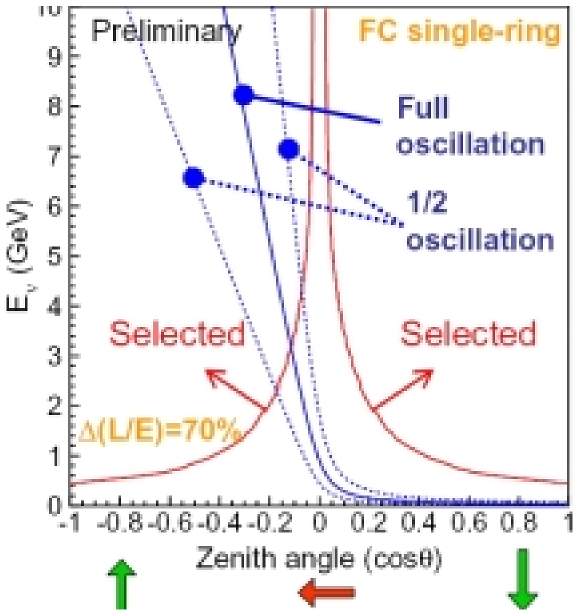
Neutrino oscillation : $P_{\mu\mu} = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

Neutrino decay : $P_{\mu\mu} = (\cos^2\theta + \sin^2\theta \text{ x } \exp(-\frac{m}{2\tau}\frac{L}{E}))^2$

Neutrino decoherence : $P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta \text{ x } (1 - \exp(-\gamma_0 \frac{L}{E}))$



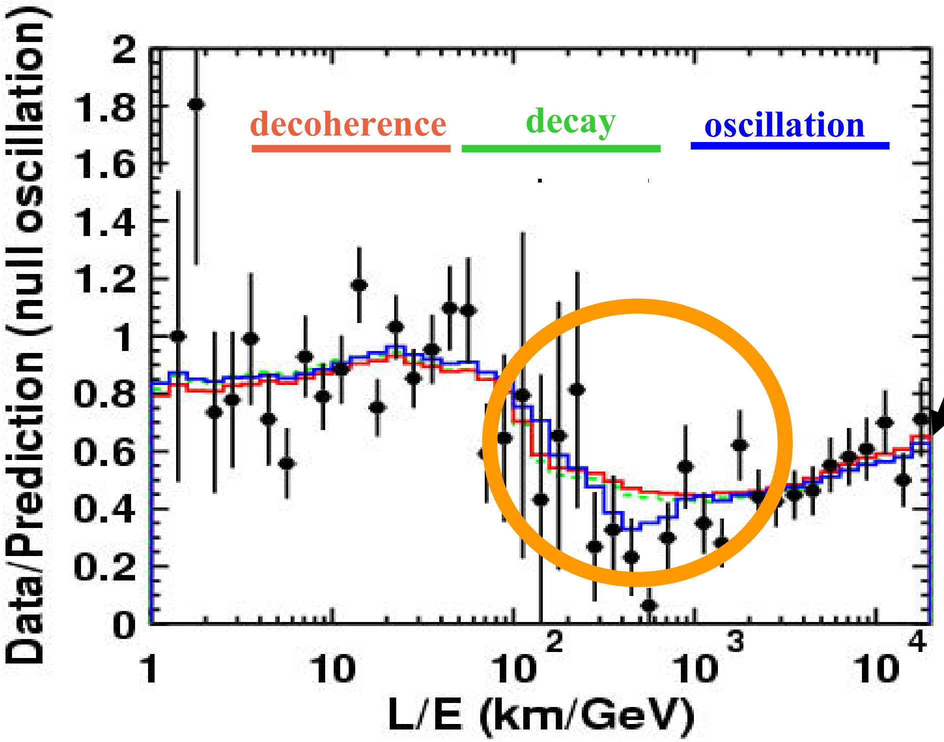
L/E dependence smeared out!



Bad L/E resolution for:

- horizontal events (dL/dcosθ is big!)
- events with small energy

←cuts in the E-cosθ plane



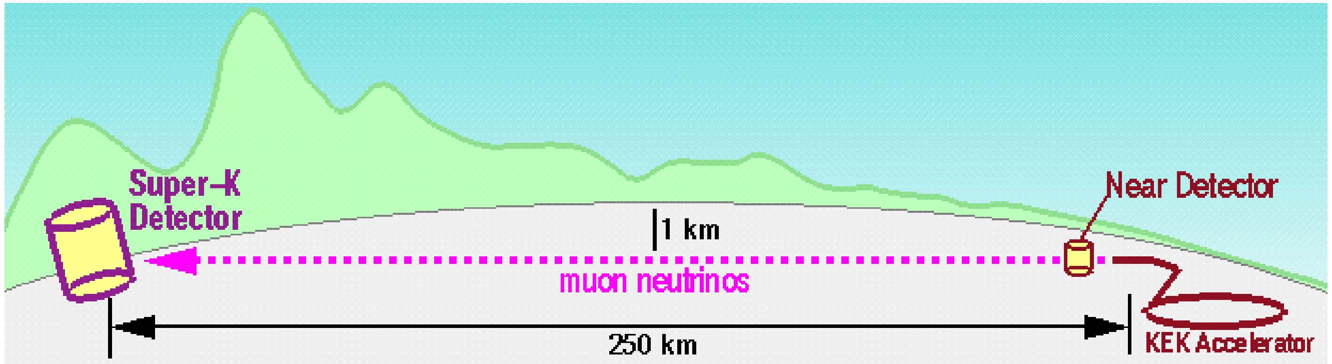
SK II data

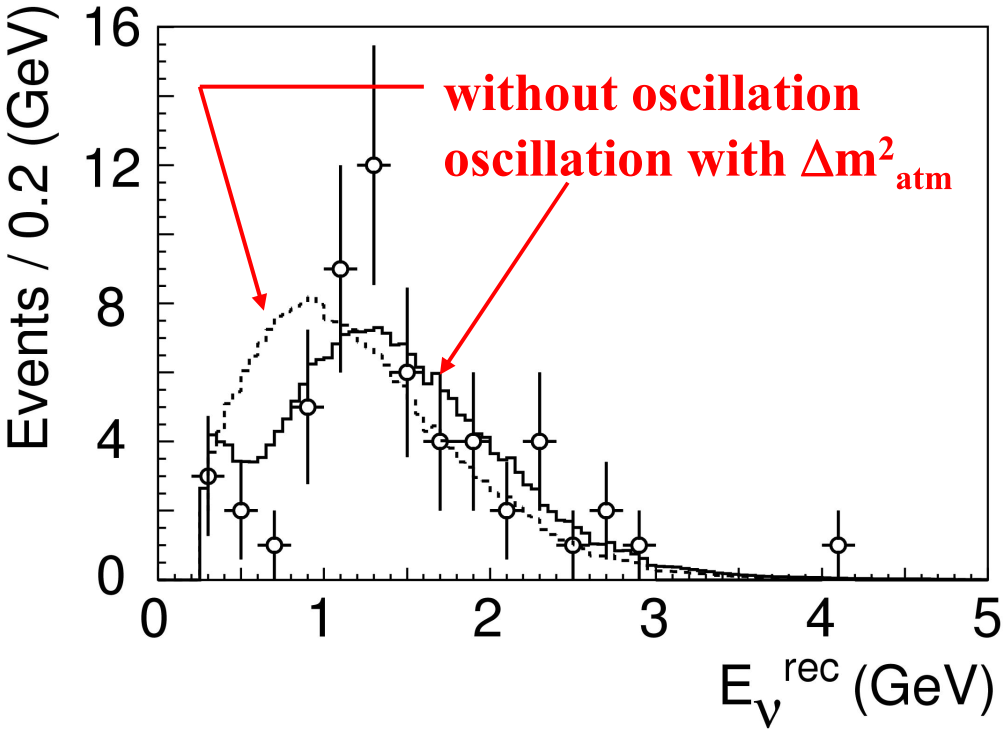
Result:

- 3,4σ for decay
- 3,8σ for de-coherence
- Δm^2=2.4 10^{-3}eV^2

←→long baseline exp.

K2K confirms atmospheric Δm^2

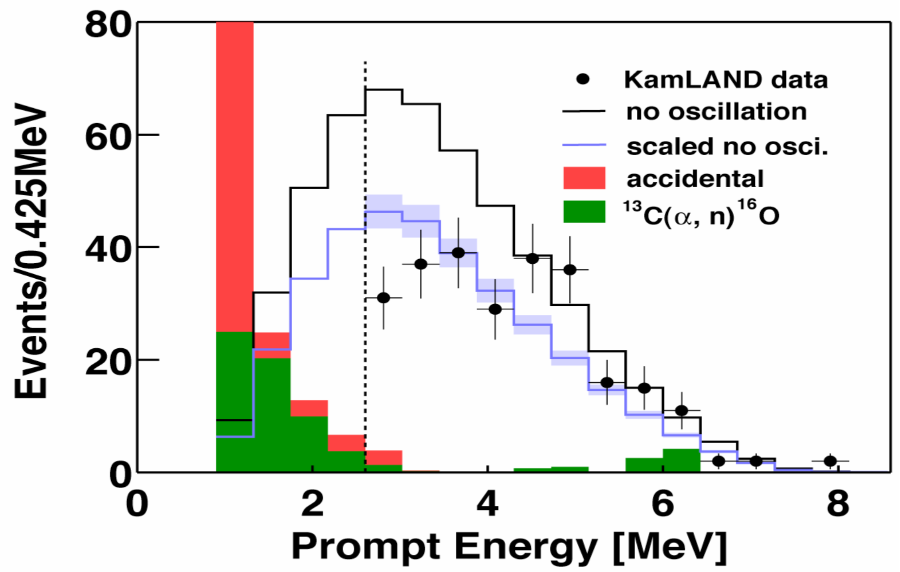




without oscillation

oscillation with Δm^2_{atm}

Testing Solar L/E with KamLAND

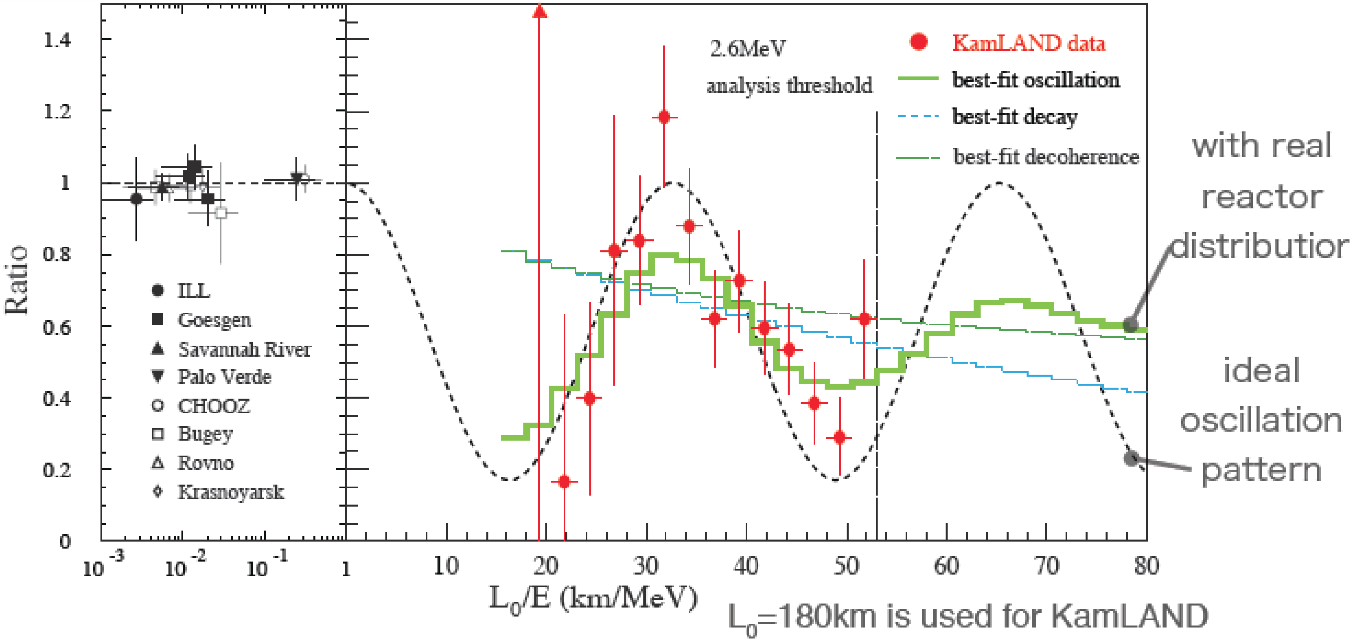


rate plus shape ➔
oscillations at 99.999995% CL

Best fit: $\Delta m^2=7.9^{+0.6}_{-0.5}\times10^{-5}eV^2$
$\tan^2\theta=0.46$

improved tests of L/E:

- Super Kamiokande
- KamLAND
- MINOS
- …



The Future of Neutrino Oscillations

Δm^2 and θ_{ij} regions ➔ **improved oscillation experiments**
➔ **controlled sources & detectors**

➔ long baseline experiments with neutrino beams
➔ reactor experiments with identical near & far detector

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

x Majorana-
CP-phases

➔ S_{13} ➔ δ

matter effects

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

➔ precision neutrino physics

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**

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

The magic Baseline

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

- All terms besides the first vanish for $\sin(\hat{A}\Delta) = 0$
- Condition for uncorrelated sensitivity to θ_{13} $\boxed{\hat{A}\Delta = \pi}$

$\Rightarrow$ inserting $\hat{A} = A/\Delta m^2_{31}$, $A = 2VE$, $\Delta = \Delta m^2_{31} L/4E$ one finds

$$\boxed{L_{magic} = \frac{2\pi}{\sqrt{2}G_F n_e} = 7630 \text{ km} \cdot \frac{\rho}{4.3 g/cm^3}}$$

Huber, Winter

- Note that this is not the MSW resonance condition

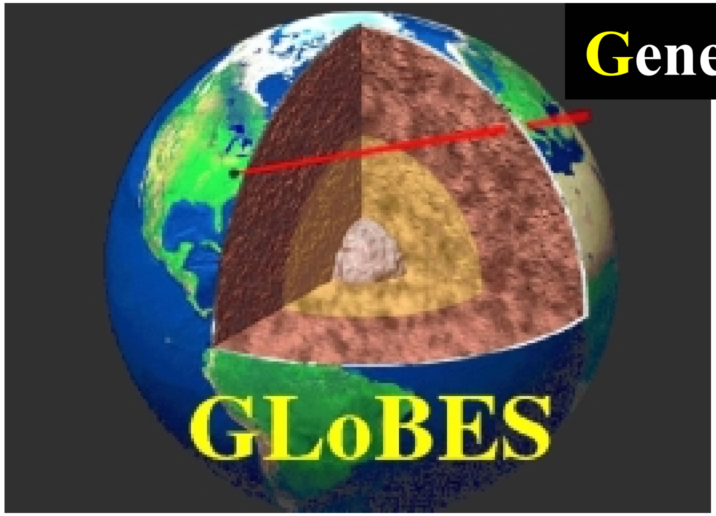
Simulation of Future Experiments

- 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		- 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		
- symmetric $\nu/\overline{\nu}$ operation		- correlations		- backgrounds
				- x-sections (at low E)

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

A Powerful Simulation Tool



General Long Baseline Experiment Simulator

Comp. Phys. Comm. 167 (2005) 195, hep-ph/0407333

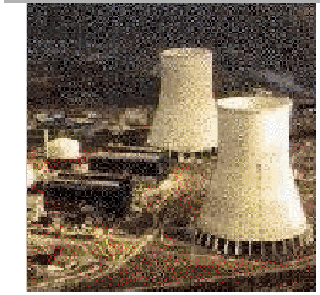
`http://www.ph.tum.de/~globes`

P. Huber, ML, W. Winter
M. Freund, M. Rolinec

- **C-based simulation software (GPL = free)**
- **extensive documentation & examples**
- **3 phase approach:**

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

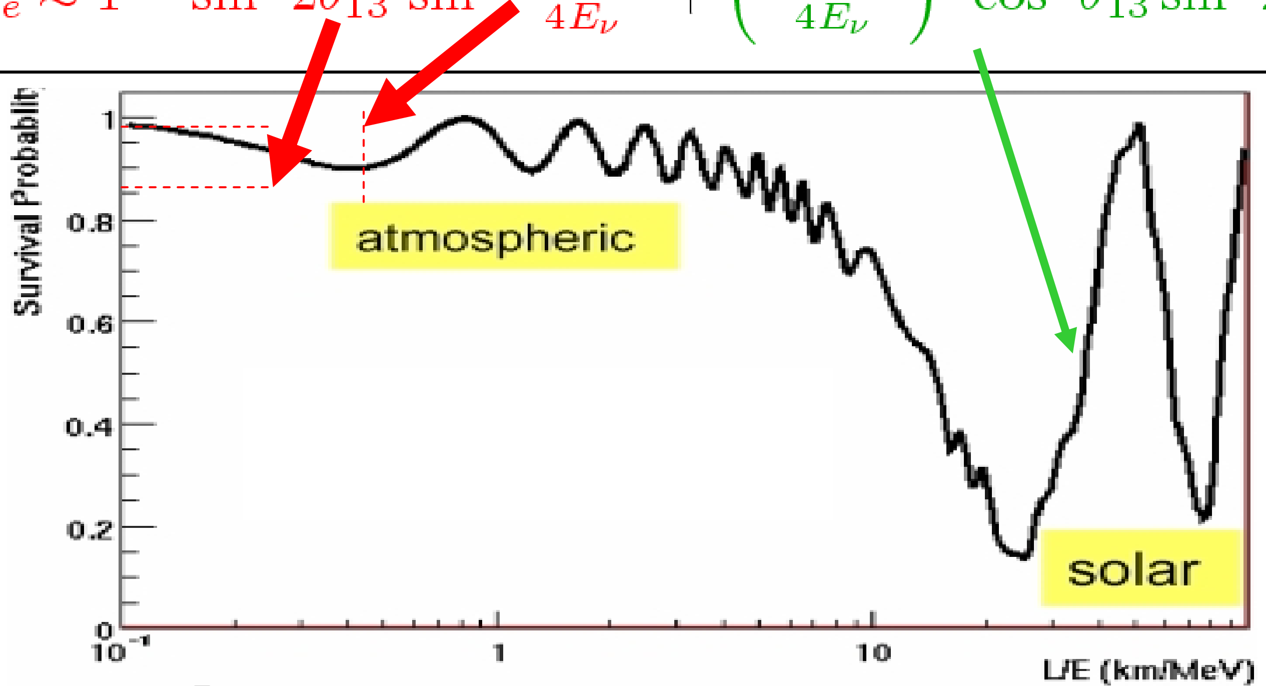
New Reactor Experiments



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

identical detectors ➔ many errors cancel

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

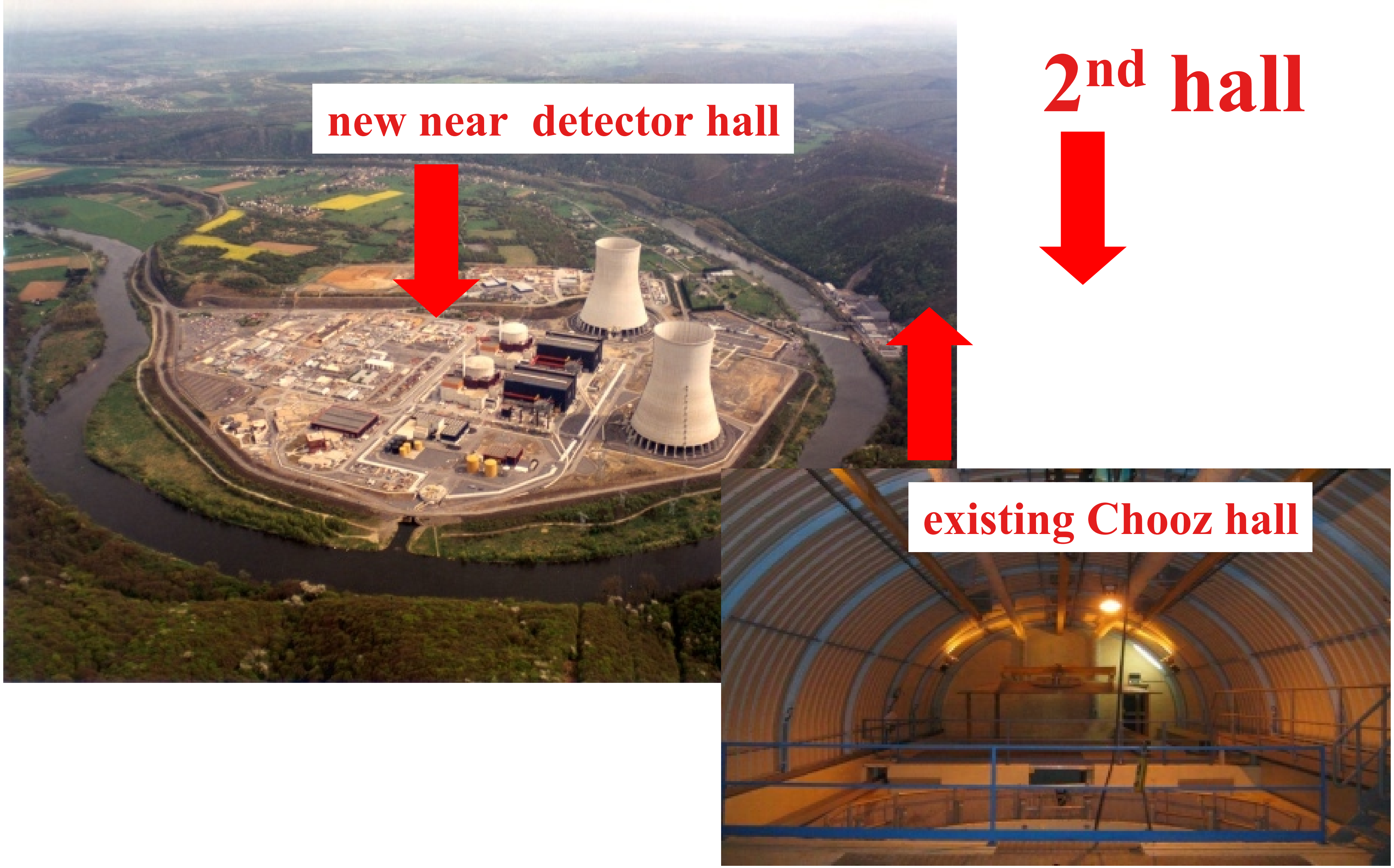


E=4MeV ➔ 2km 4km 40km 80km

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

no degeneracies
no correlations
no matter effects

Most Advanced Project: Double Chooz

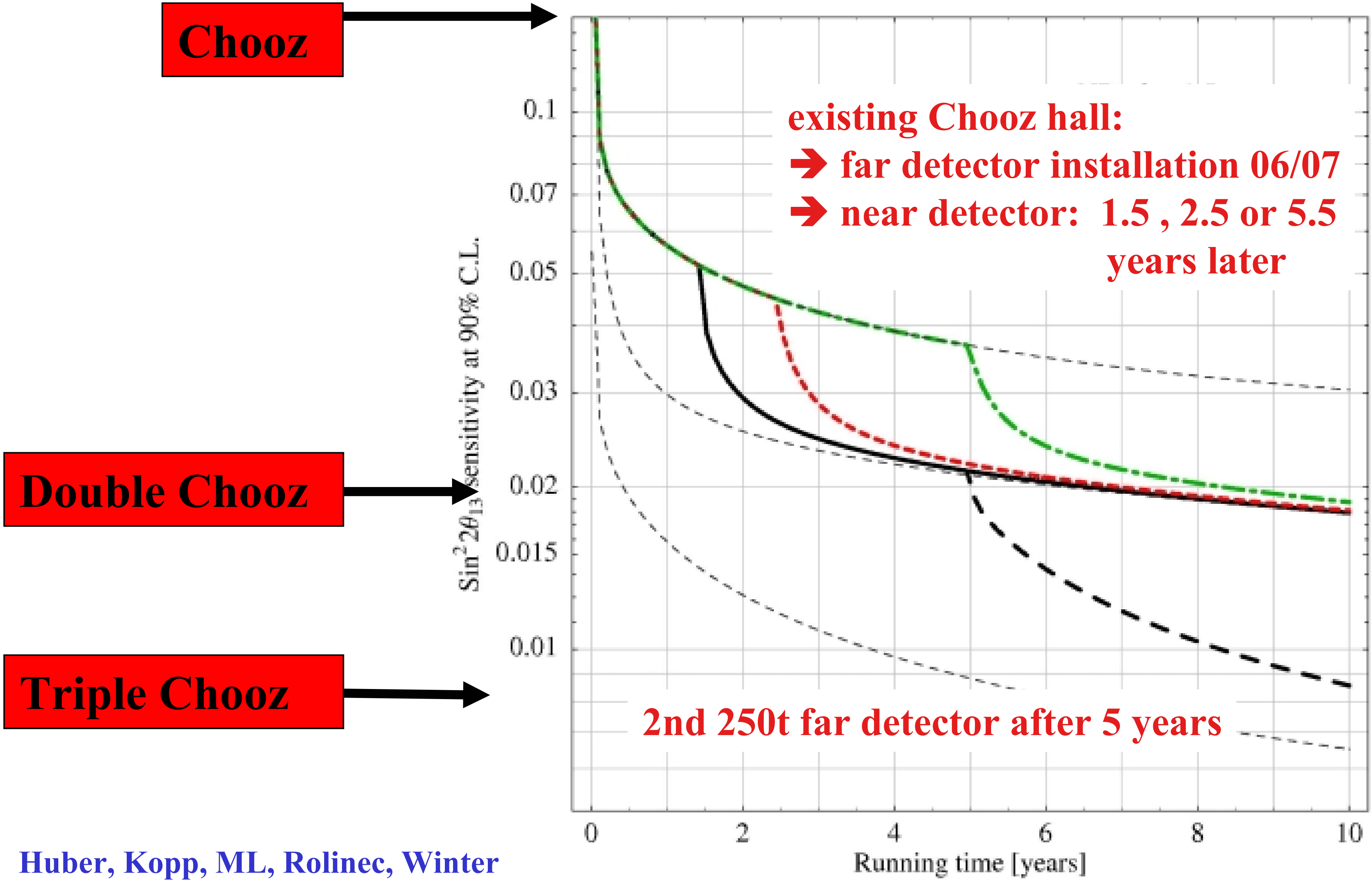


2nd hall

new near detector hall

existing Chooz hall

Double Chooz and Triple Chooz



existing Chooz hall:

- ➔ far detector installation 06/07
- ➔ near detector: 1.5 , 2.5 or 5.5 years later

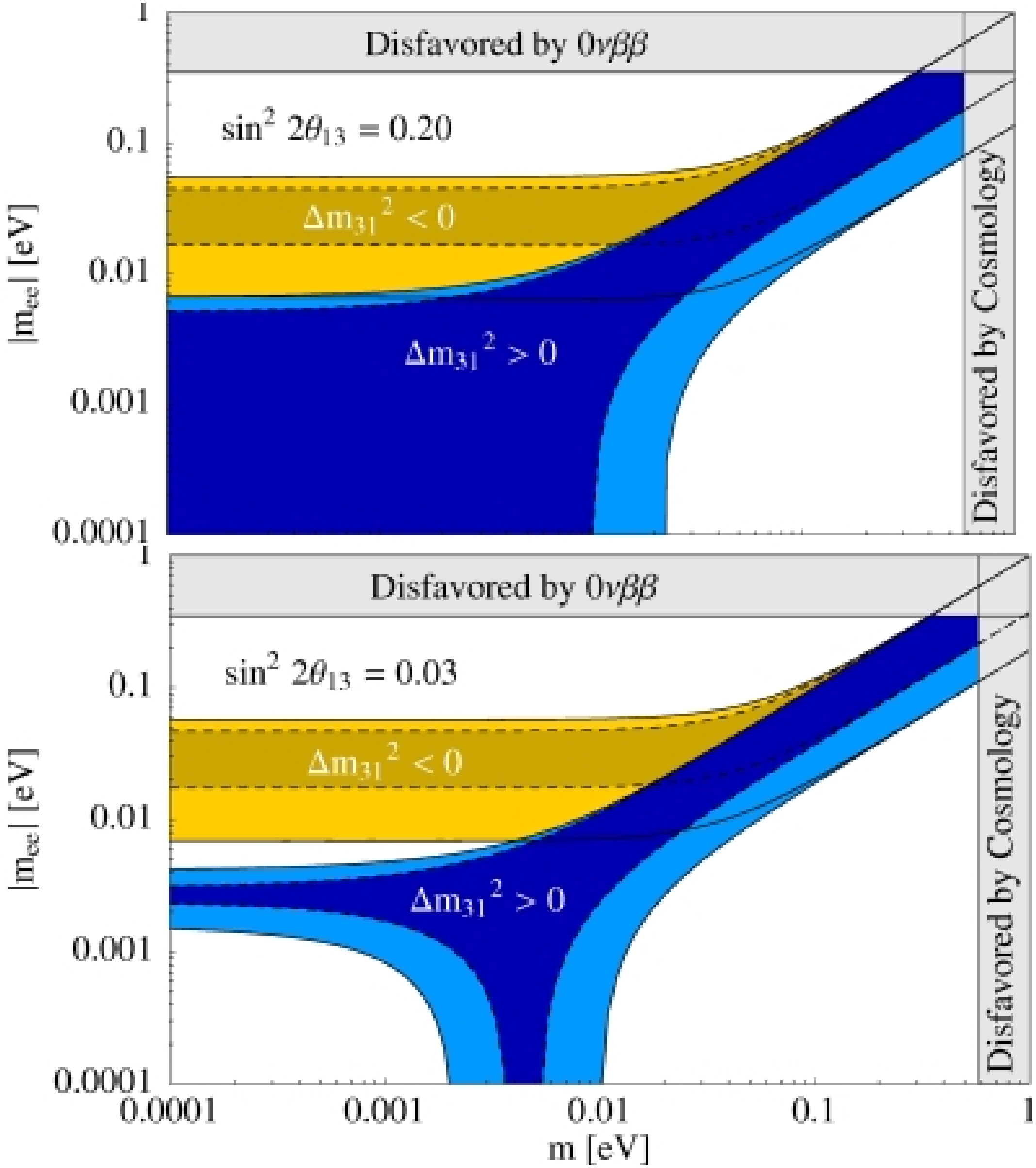
2nd 250t far detector after 5 years

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

ML,Merle, Rodejohann

New Neutrino Beams

- **conventional beams, superbeams**
  ➔ MINOS, CNGS: (OPERA CARUS, T2K, NOνA, T2H,…
- **β-beams**
  ➔ pure ν_e and $\bar{\nu}_e$ beams from radioactive decays; $\gamma \simeq 100\ldots1000$
- **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**

Detectors in a Nutshell

Most important features:

- which leptons can be detected: e, μ, τ
- can particles and anti-particles be distinguished ⇔ magnetic fields
- detector threshold and beam energy ⇒ defines energy window
- ...

Main players:

- water Cherenkov detectors a la SuperK
  sees $e^{\pm}$, $\mu^{\pm}$, i.e. no charge id
  very good for QE scattering at lower energies
- low Z calorimeter as proposed for NuMI
  sees $e^{\pm}$, $\mu^{\pm}$, i.e. no charge id
  best for medium energies were QE/DIS both contribute
- magnetized iron detectors
  sees μ^{+}, μ^{-}, no e and τ

Other players:

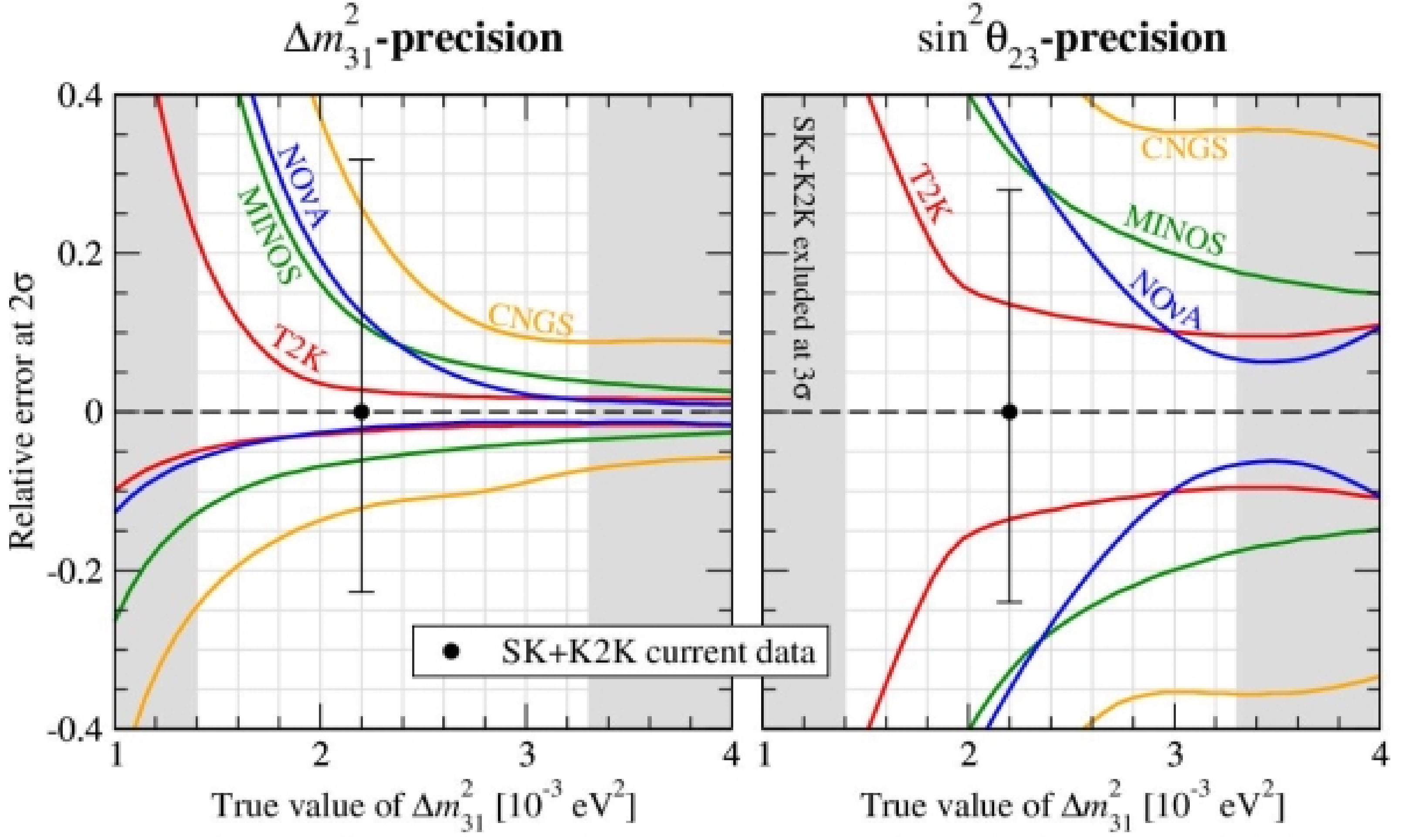
- liquid Argon a la ICARUS ⇒ τ
- emulsion detectors a la OPERA ⇒ sees all channels

Future Long Baseline Projects

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	pre-approved	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	...	

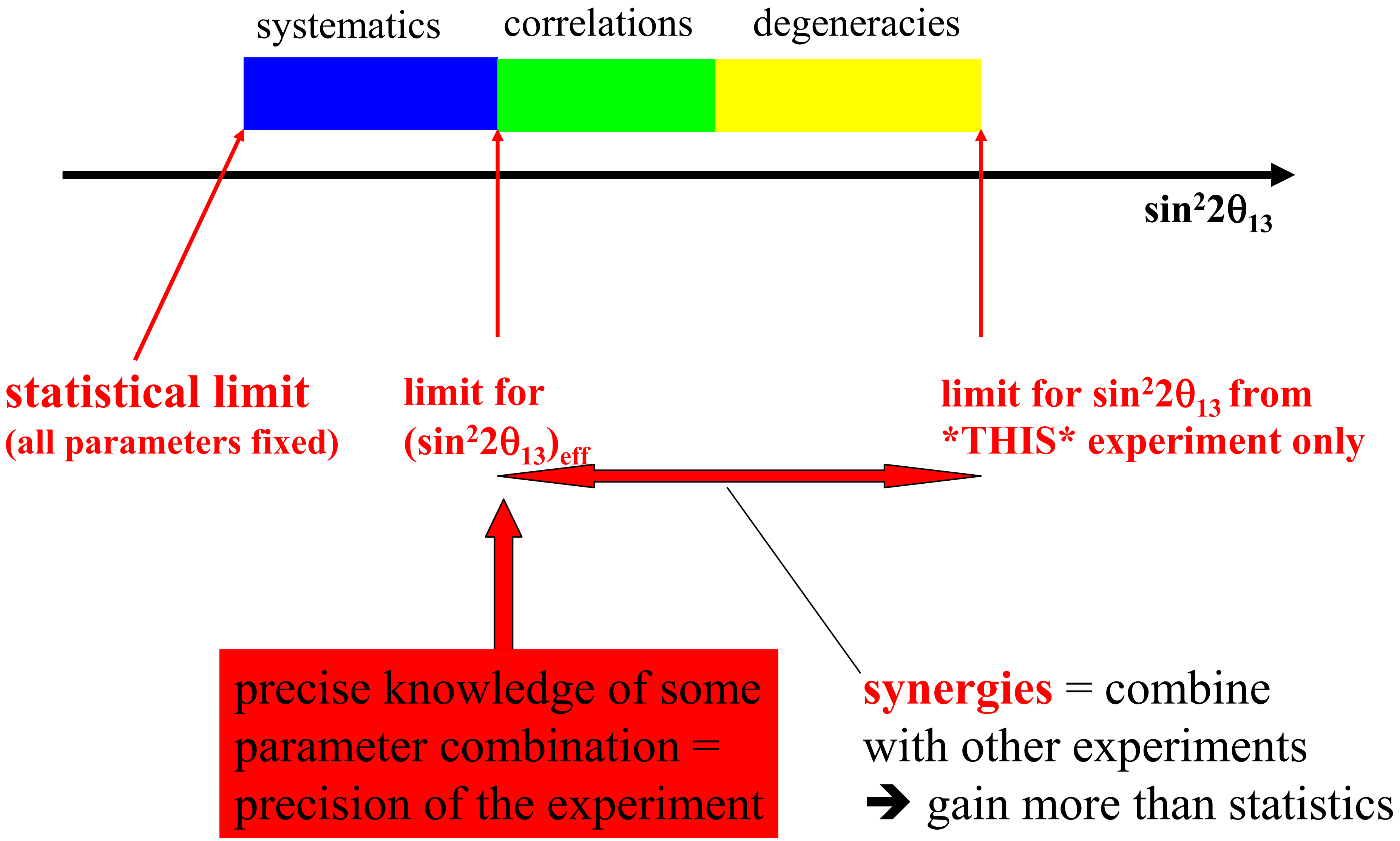
- every stage is a necessary prerequisite for the next
- continuous line of improvements for beams, detectors, physics

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



Huber, ML, Rolinec, Schwetz, Winter

Sensitivity Plots



systematics

correlations

degeneracies

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

statistical limit

(all parameters fixed)

limit for

$(\sin^2 2\theta_{13})_{eff}$

limit for $\sin^2 2\theta_{13}$ from

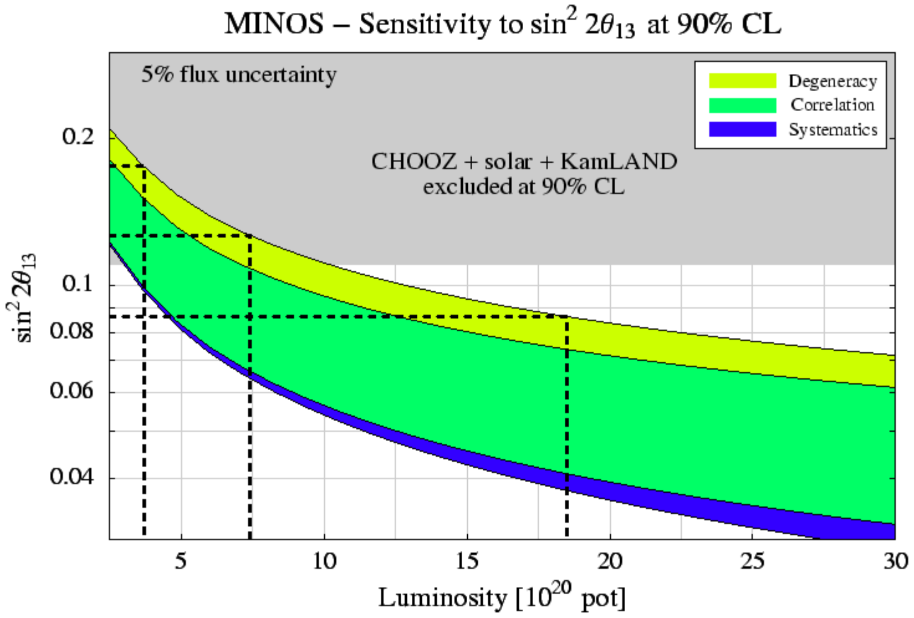
***THIS* experiment only**

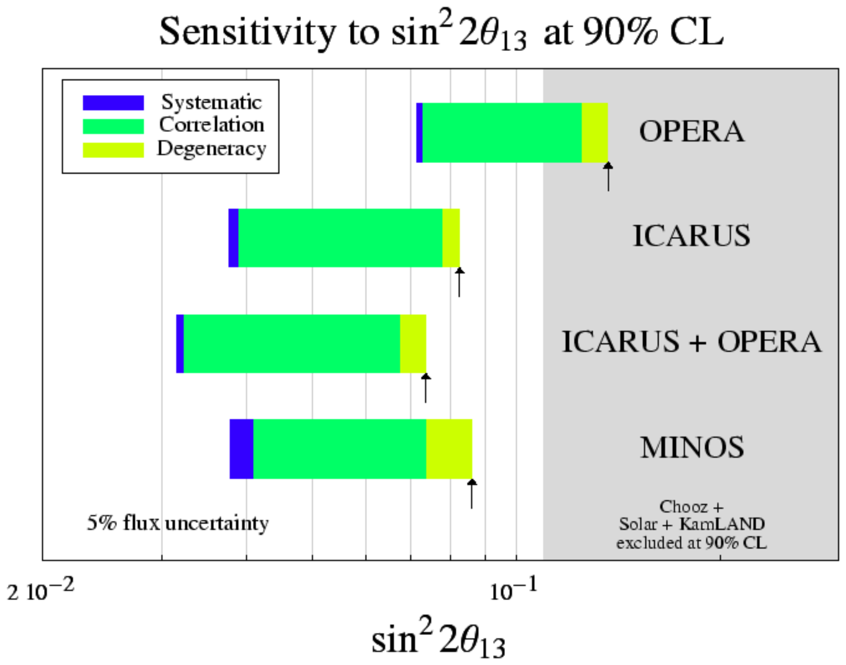
precise knowledge of some parameter combination = precision of the experiment

synergies = combine with other experiments

➔ gain more than statistics

θ_{13} in the Current LBL Generation





MINOS sensitivity as a funtion of time:

– MINOS: $3.7 \cdot 10^{20}$ pot/y

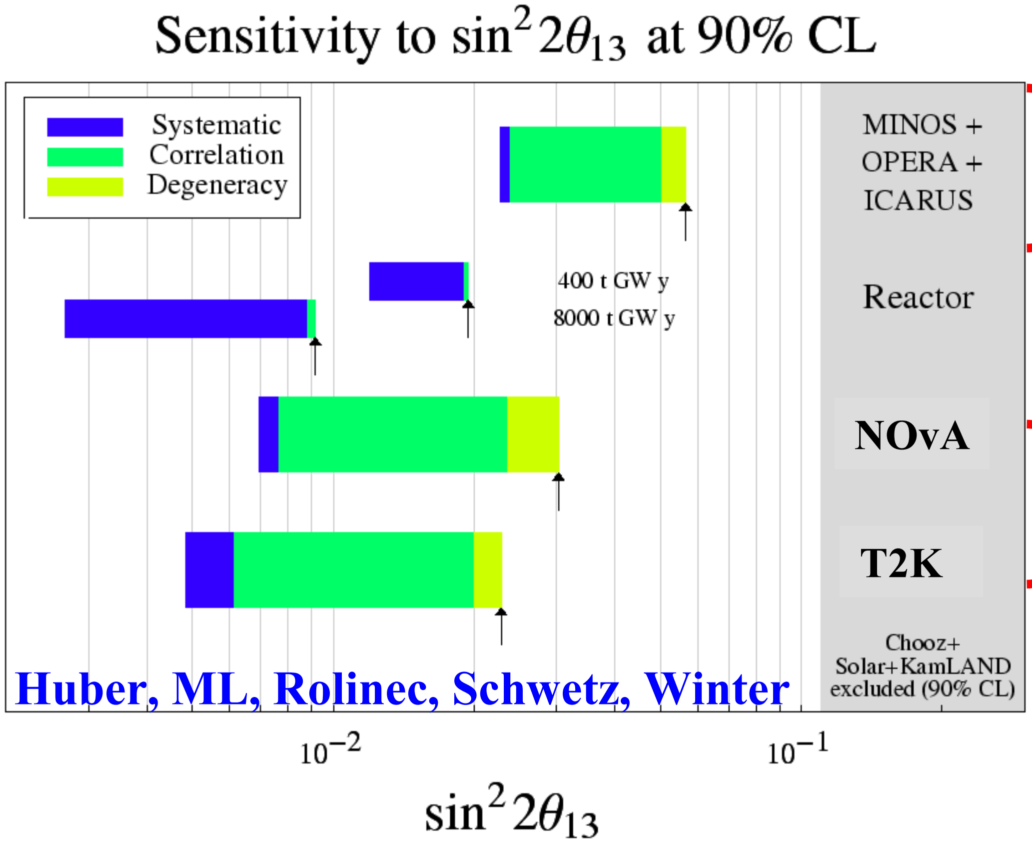
– 1,2,5 years

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



Huber, ML, Rolinec, Schwetz, Winter

coming long baseline experiments

Double Chooz
Reactor II (…Tripple Chooz)

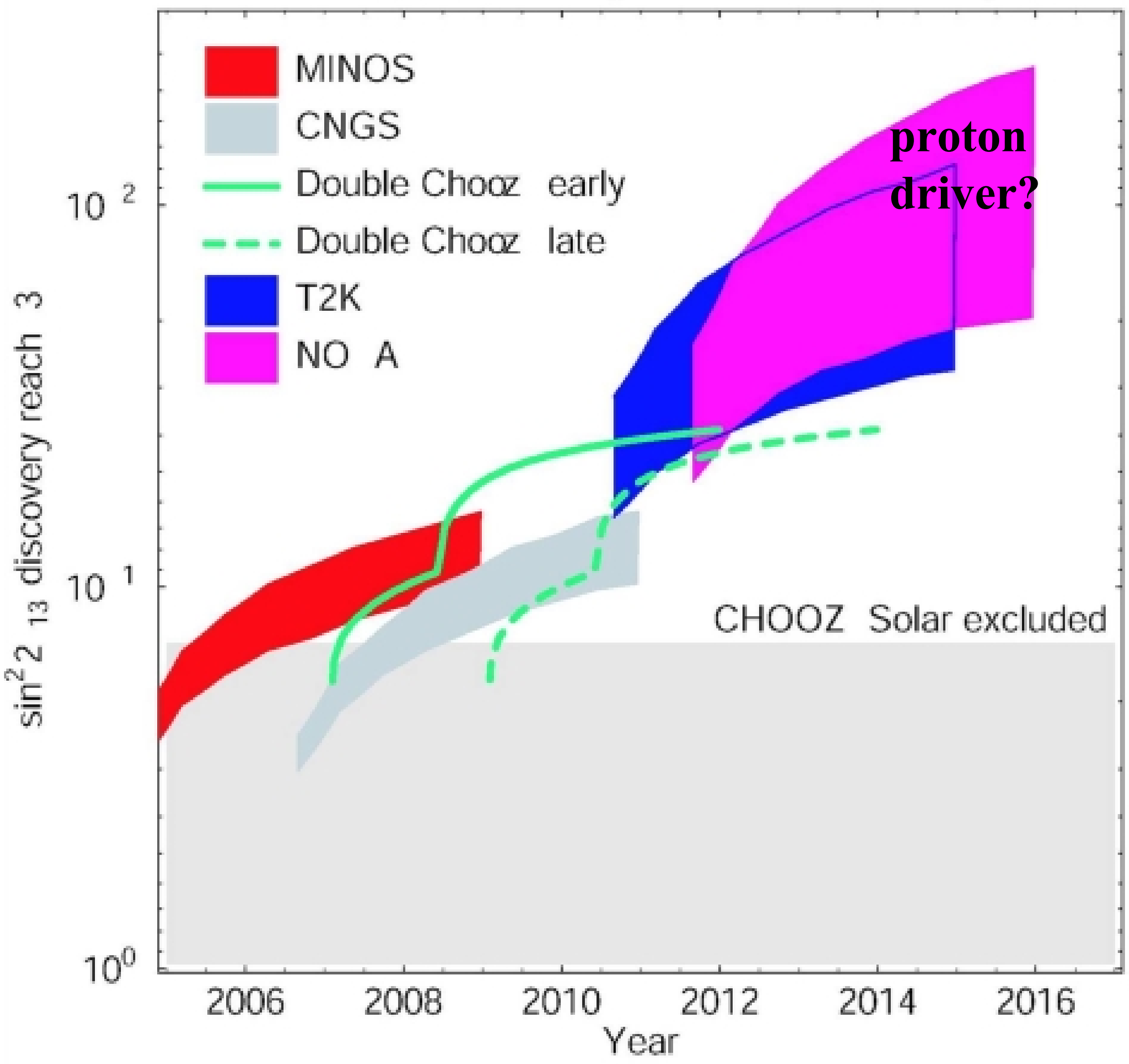
next generation long baseline experiments

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

θ_{13} Sensitivity Versus Time

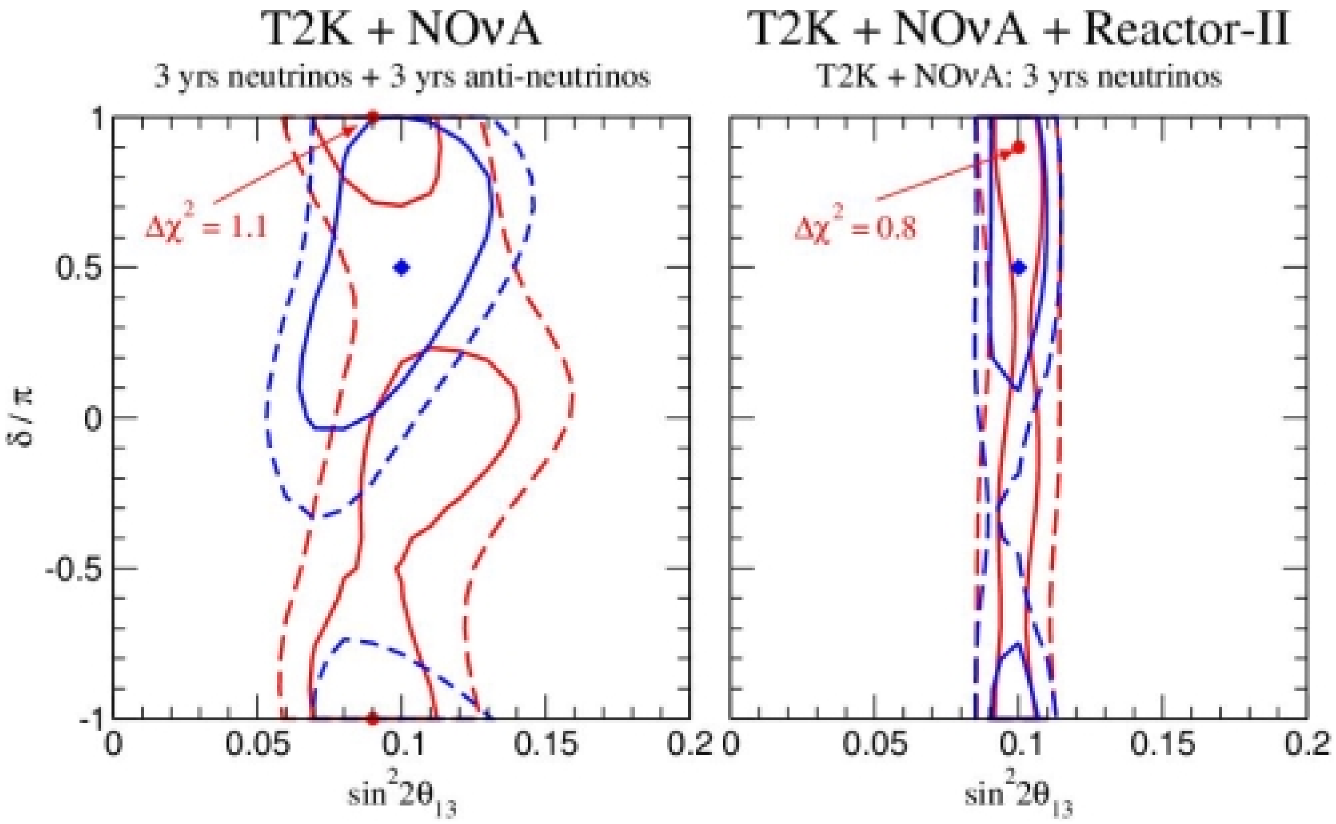


proton driver?

β-beams
neutrino factory

Leptonic CP-Violation

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



$\Delta m^2 > 0$

$\Delta m^2 < 0$

— 90%CL

····· 3σ

➔ bounds or measurements of leptonic CP-violation

➔ leptonic CP-violation in M_R ←➔ baryon asymetry via leptogenesis

How to Break Degeneracies & Correlations

Rates only ←→ degeneracies
can be resolved by:

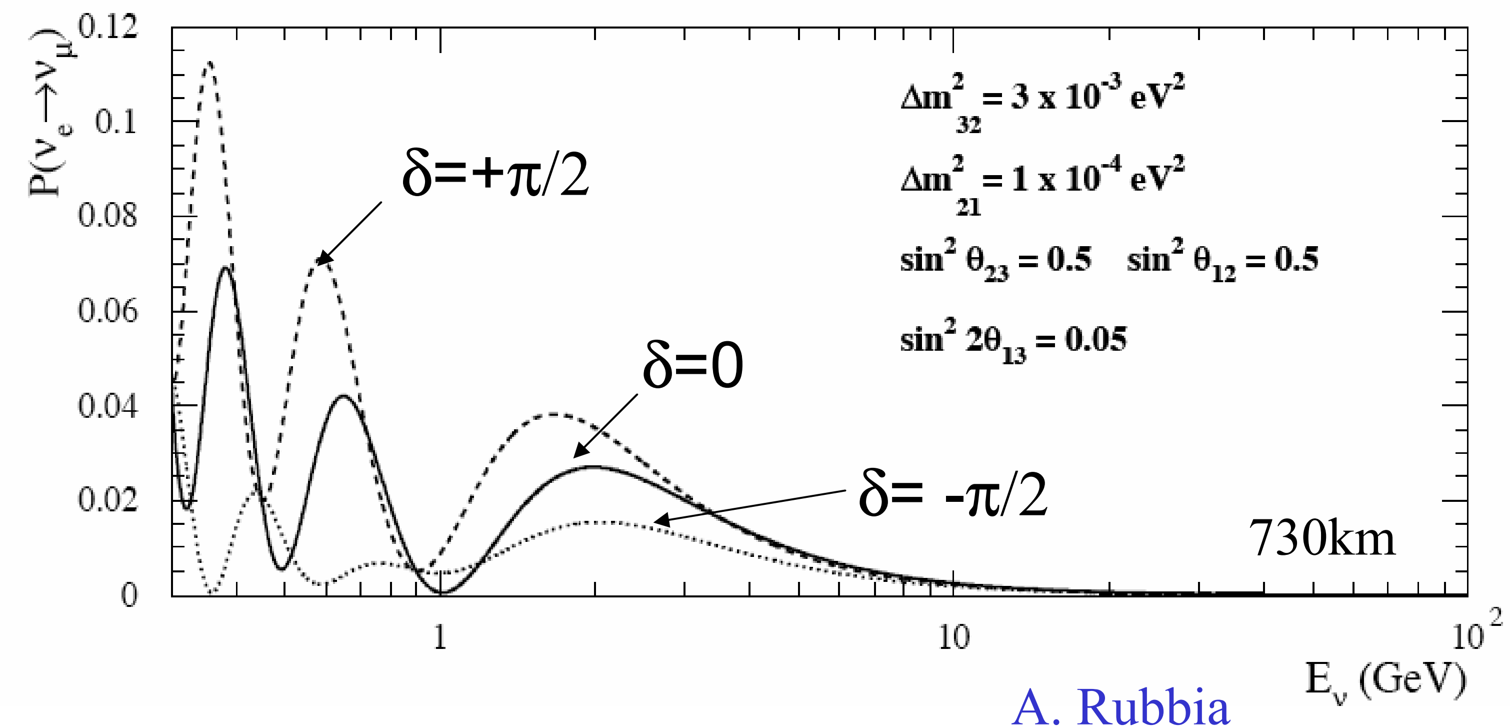
→ combination of different oscillation channels
→ use different baselines
→ combine different energies
→ use energy spectrum
→ go to „magic baseline“

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



A. Rubbia

➔ use energy resolution to break degeneracies

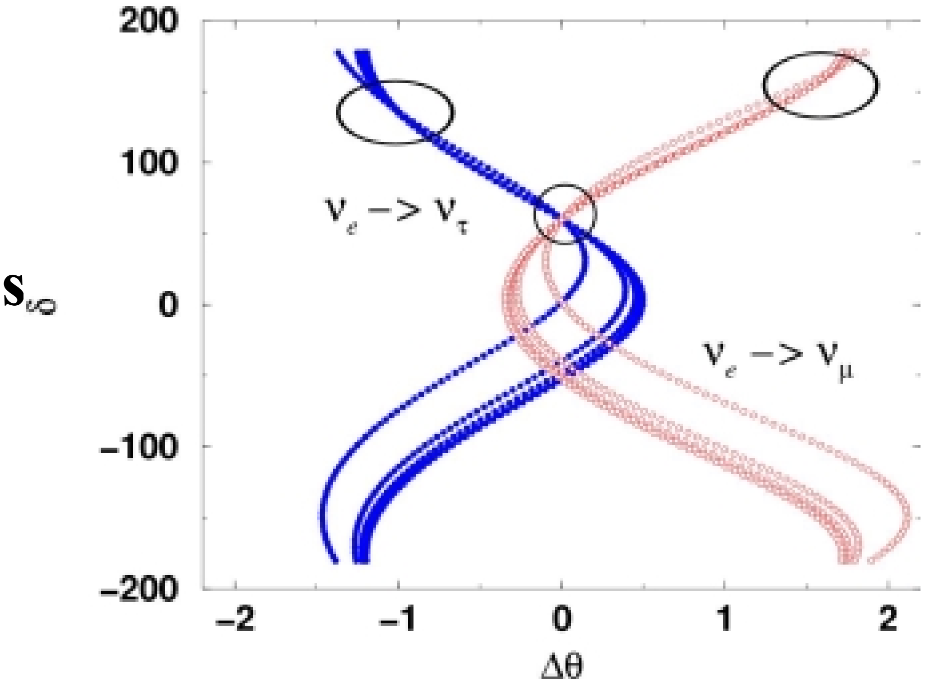
Silver Channels

Neutrino factory:

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

➔**different oscillation probabilities**

➔ **break degeneracies!**



Donini, Meloni, Migliozzi
Autiero, et al.

What is precison neutrino physics good for?

→ unique flavour information
→ tests models / ideas about flavour
→ history: elimination of SMA

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

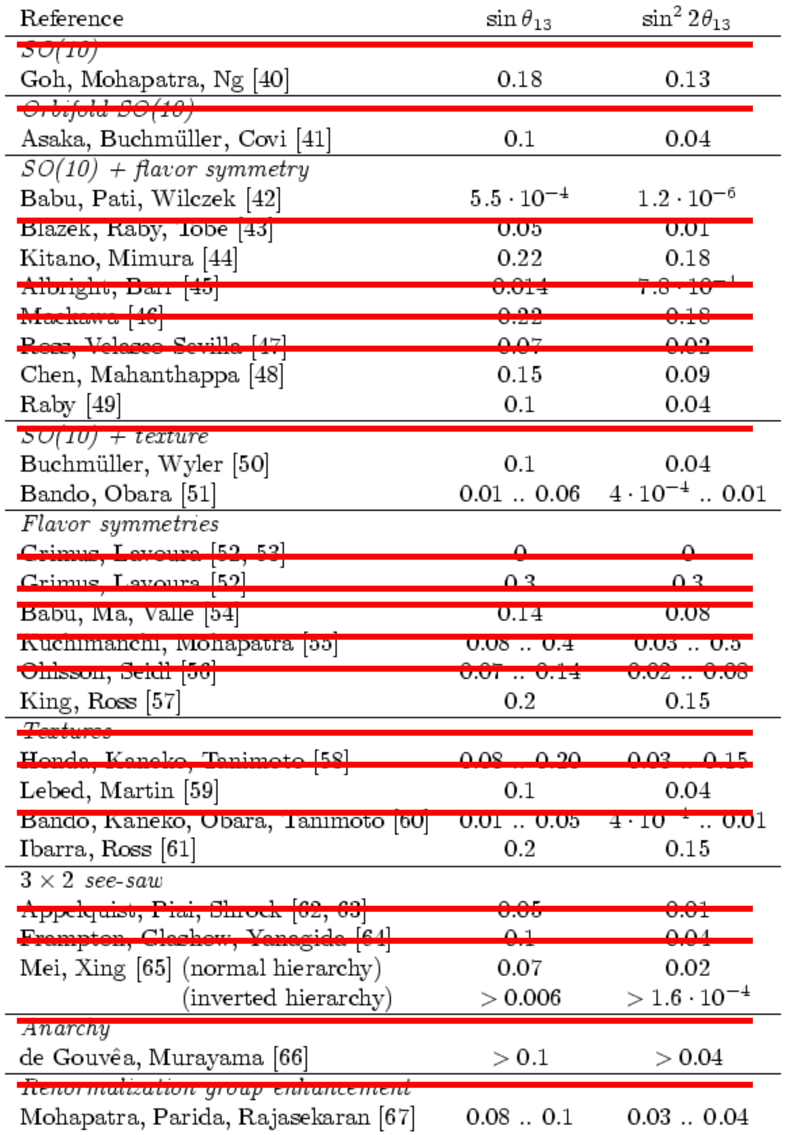
for example: $\sin^2 2\theta_{13} < 0.01$ ➔

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

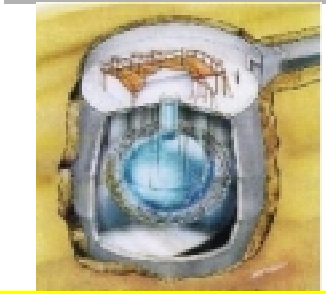
Precision allows to identify / exclude:

- 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, ...

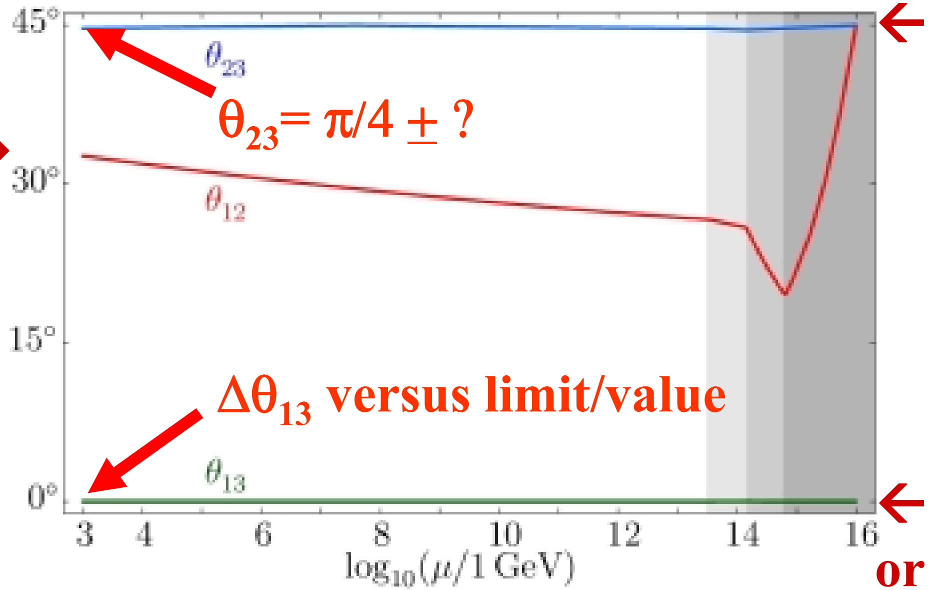
Renormalization Group Running



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

renormalization group running

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



atmospheric →

solar →

reactor →

← **bi-maximal**

← **Small or even zero**

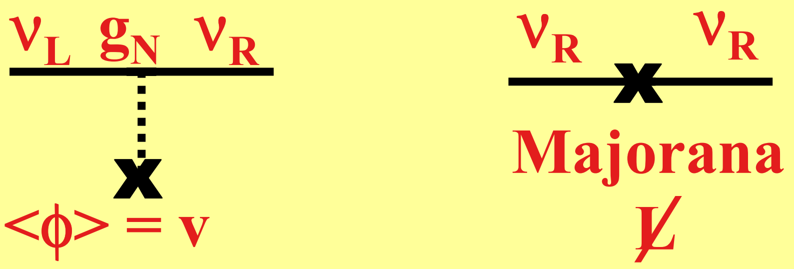
$\theta_{23} = \pi/4 \pm ?$

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

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

Neutrino Mass Terms

1) Postulate right handed neutrino fields ➔ SM+



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

Natural value of mass operators: scale of symmetry

m_D ~ electro-weak scale

M_R ~ embedding into GUT ⇔ L violation scale

See-saw mechanism (type I)

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

Numerical hints:

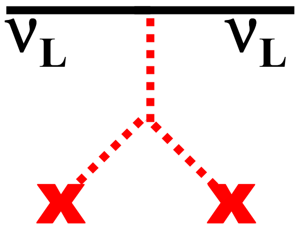
For $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim$ leptons ➔ $M_R \sim 10^{11} - 10^{16}$GeV

➔ν's are Majorana particles , m_ν probes ~ GUT scale physics!

➔smallness of m_ν ⇔ high scale of L, symmetries of m_D ,M_R

More Neutrino Mass Operators

2) new Higgs triplets Δ:

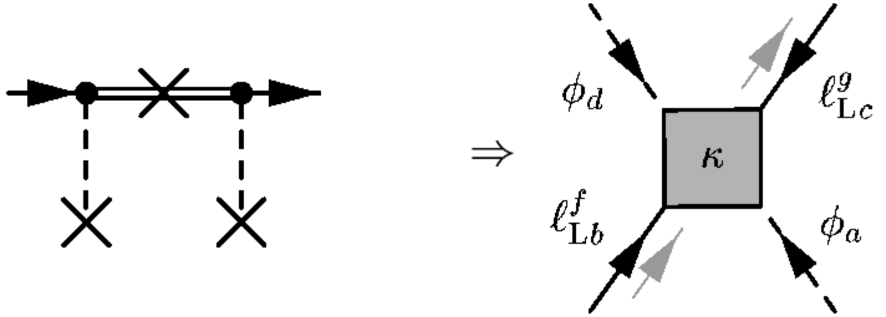


➔left-handed Majorana mass term $M_L L \overline{L^c}$

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, …



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

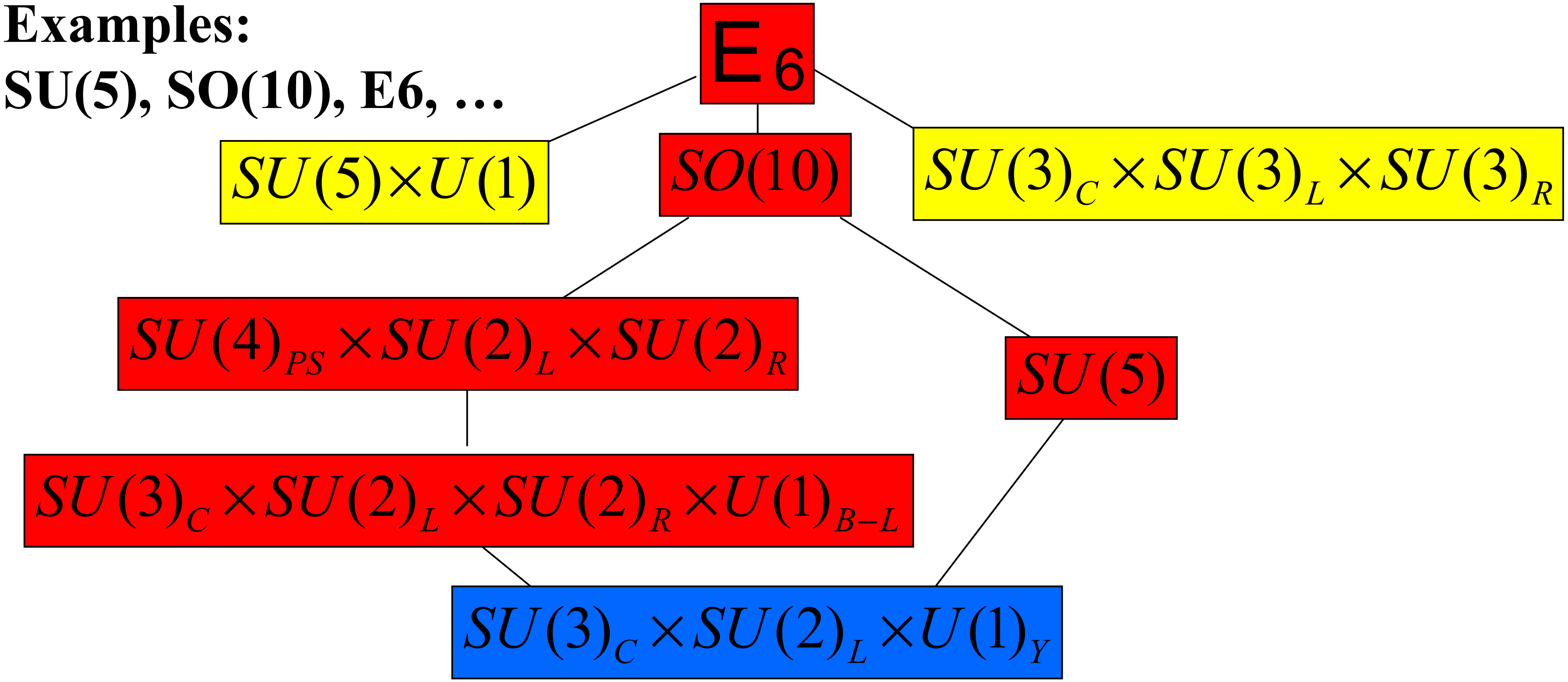
➔ $M_L \overline{L} L^c$

5) More speculative things …

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

Examples:
SU(5), SO(10), E6, …



E 6

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

$SO(10)$

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

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

$SU(5)$

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

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

Requirements: gauge unification, particle multiplets (e.g. 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 why many `predicted’
small mixing angles (SMA) – ruled out by data

Mechanisms to post-dict large mixings:

➔ sequential dominance
➔…
➔ 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 ~ $m_2 \cdot m_3$**
- ➔ **$m_2 << m_3$ i.e. a natural hierrachy**
- ➔ **tan $\theta_{23} \simeq a/c$ i.e. naturally large mixing**

Sequential Dominance

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

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

sequenatial dominance: $z >> y >> x$

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

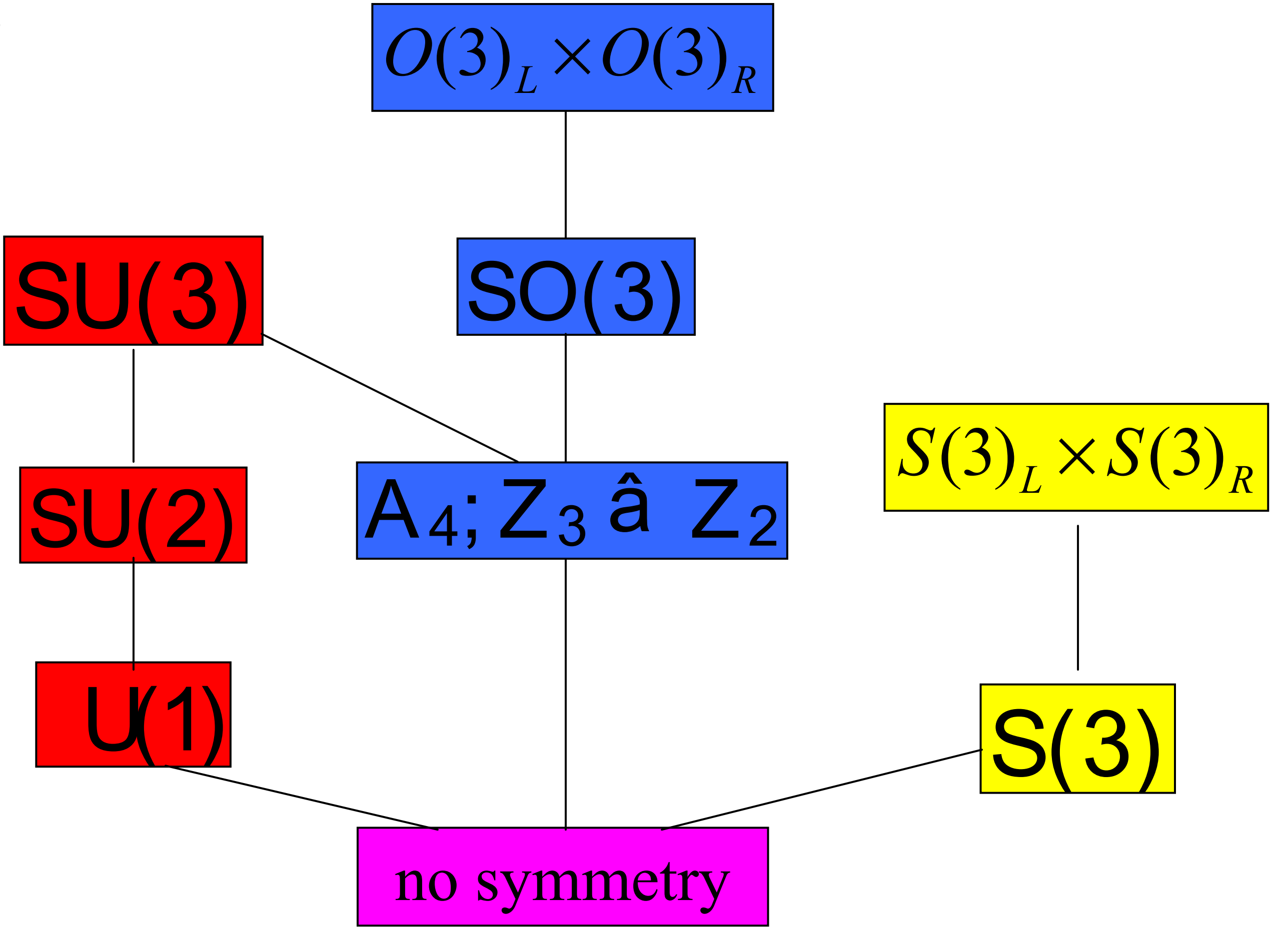
Flavour Unification

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

➔ flavour symmetries

➔ not texture zeros!

Examples for flavour symmetries and their relation:



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

SU(3)

SO(3)

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

SU(2)

$A_4; Z_3$ â Z_2

U(1)

S(3)

no symmetry

GUT $\otimes$ Flavour Unification

- So far no understanding of flavour, 3 generations
- Regularities in quark and lepton parameters
- Hints for 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
- **Hope: Distinguish models by future precision**
- **Question: Is it possible to systematically unlock the Yukawa structures in a GUT $\otimes$ flavour model**

Dirac Screening

ML, Schmidt Smirnov

Question: Do neutrino masses in GUT ⊗ flavour scenarios always depend on the same Yukawa couplings? ➔ no

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

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

fit fermions into GUT representations

➔ relation between Yukawa couplings, e.g. E6

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

Consequences of Screening

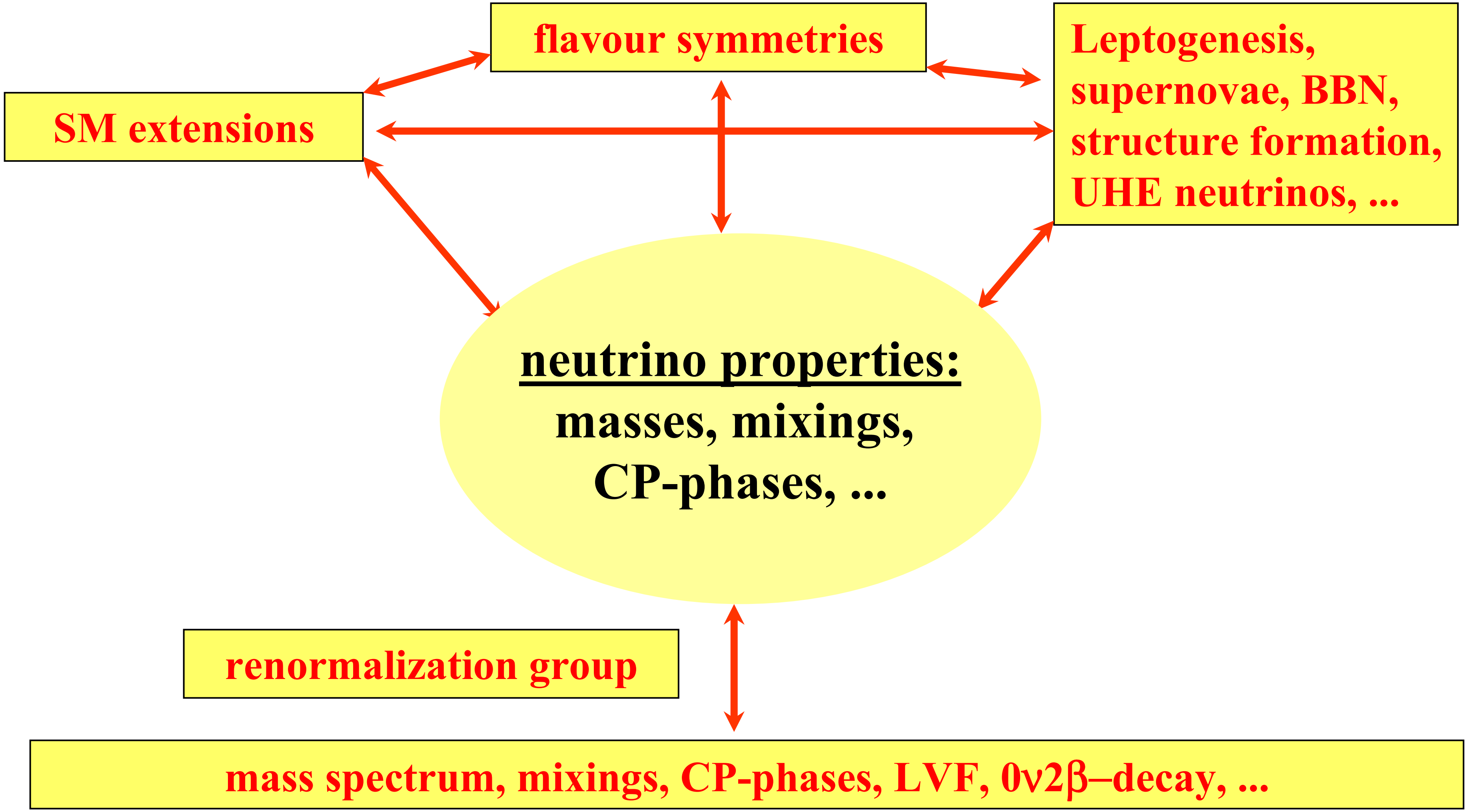
➔ complete screening of
Dirac structure

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

Consequences:

- Neutrino masses 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 is easily possible
- With or without degenerate neutrino masses
- Double see-saw predics for M_R from first see-saw
  to be lower than GUT scale by a factor $<s>/M_S \simeq 10^{-3}$
  ⇔ better fit to masses

The Interplay of Topics



flavour symmetries

SM extensions

Leptogenesis,
supernovae, BBN,
structure formation,
UHE neutrinos, ...

<u>neutrino properties:</u>
masses, mixings,
CP-phases, ...

renormalization group

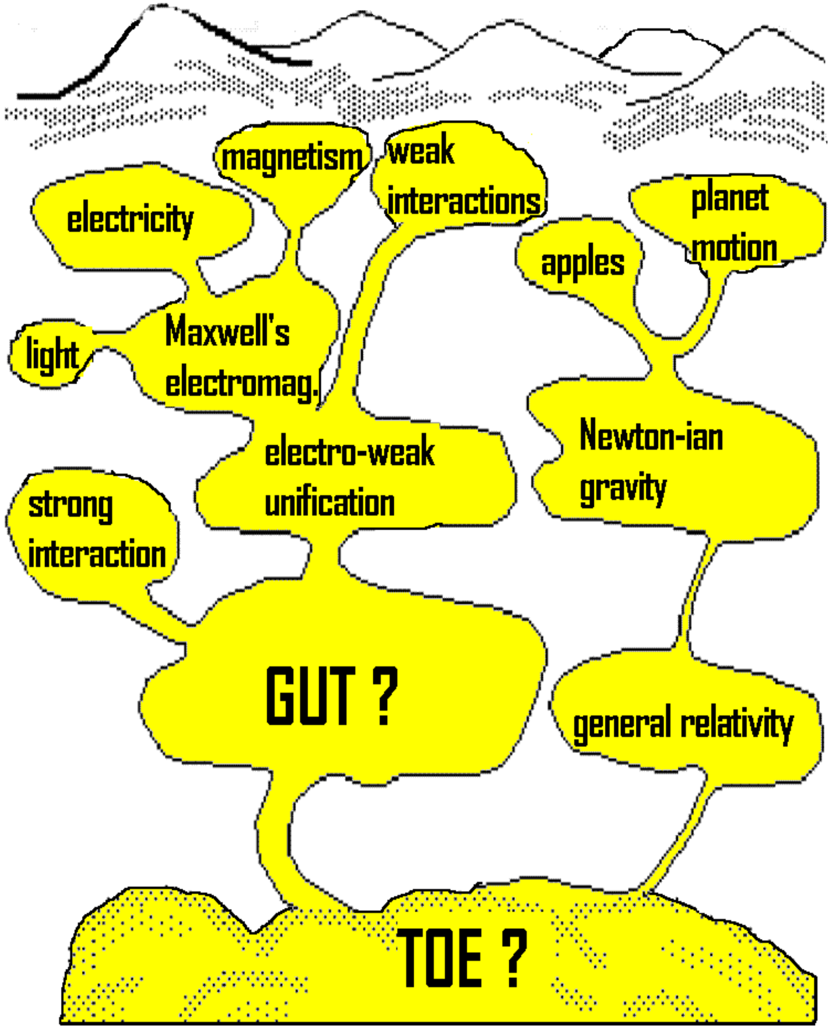
mass spectrum, mixings, CP-phases, LVF, $0\nu2\beta$–decay, ...

→ν-parameters extremely valuable

→ long term: most precise flavour info

Conclusions

neutrino properties & particle physics



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neutrinos as probes