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Double Chooz and its Physics Potential

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for the Double Chooz Collaboration

Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics
31st INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
Erice-Sicily: 16 - 24 September 2009

Neutrino hierarchy problem

- M. LINDNER, Heidelberg,

Reasons

Beyond t

SM does not

Higgs-double

Gauge hierar

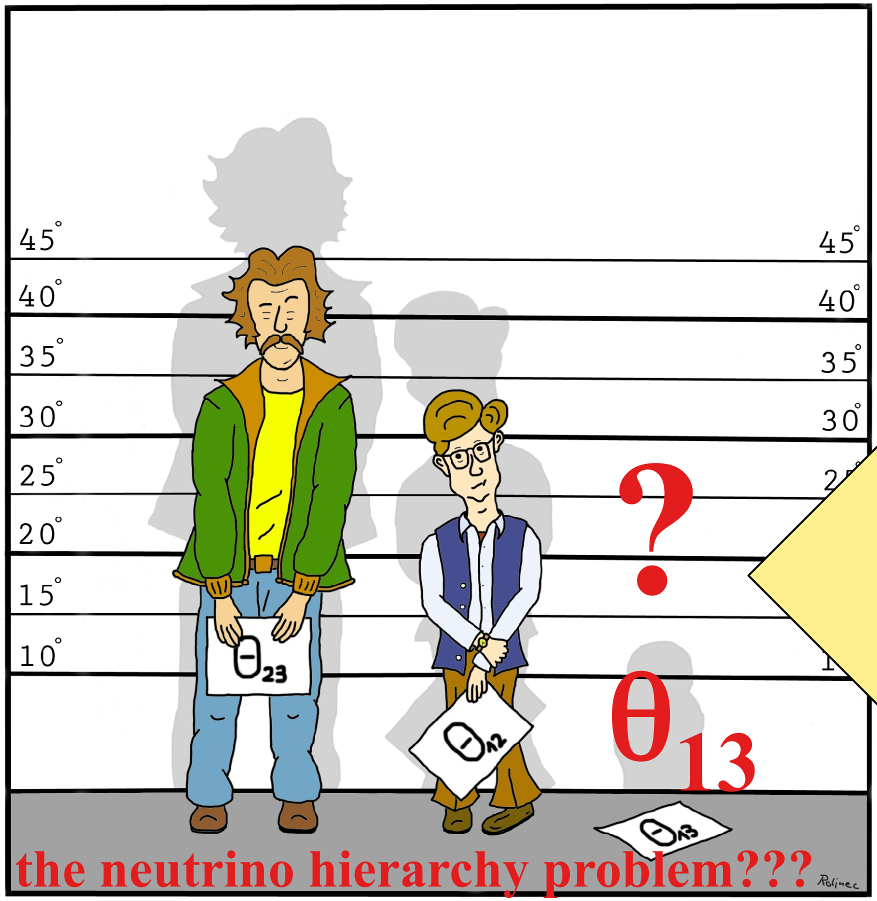
Gauge coupli

Strong CP pr

Why: 3 gener

Many param

Charge quan



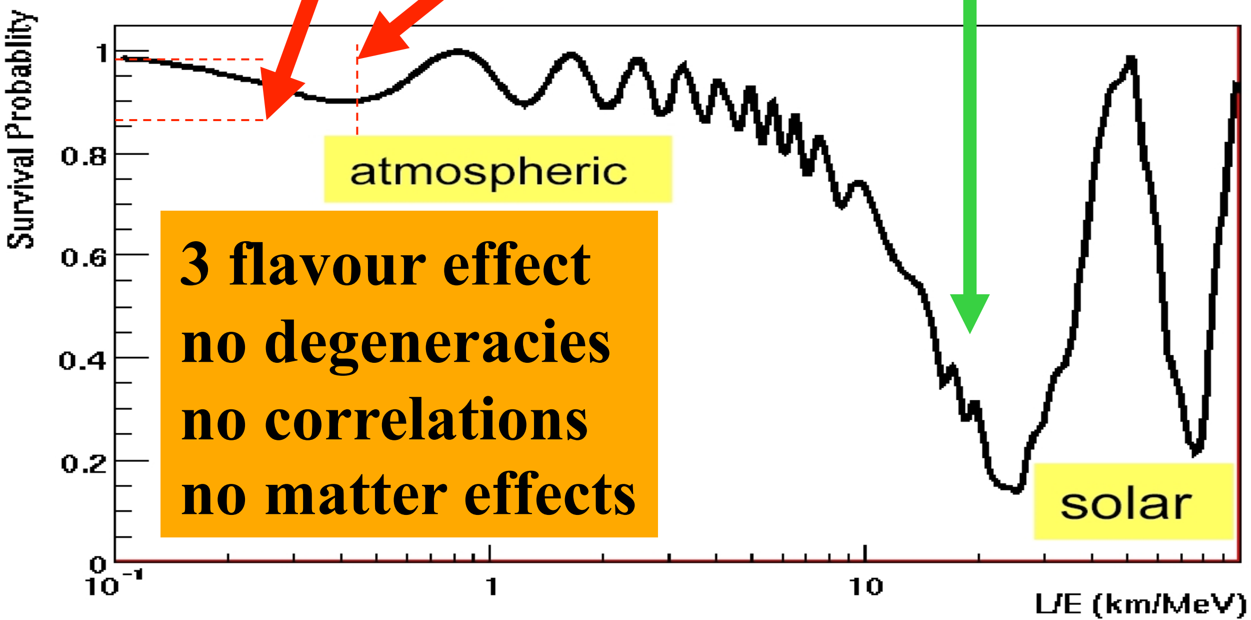
The Double Chooz experiment and its physics implications

But what is the neutrino hierarchy problem???

Future Precision with Reactor Experiments

identical detectors → many errors cancel

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



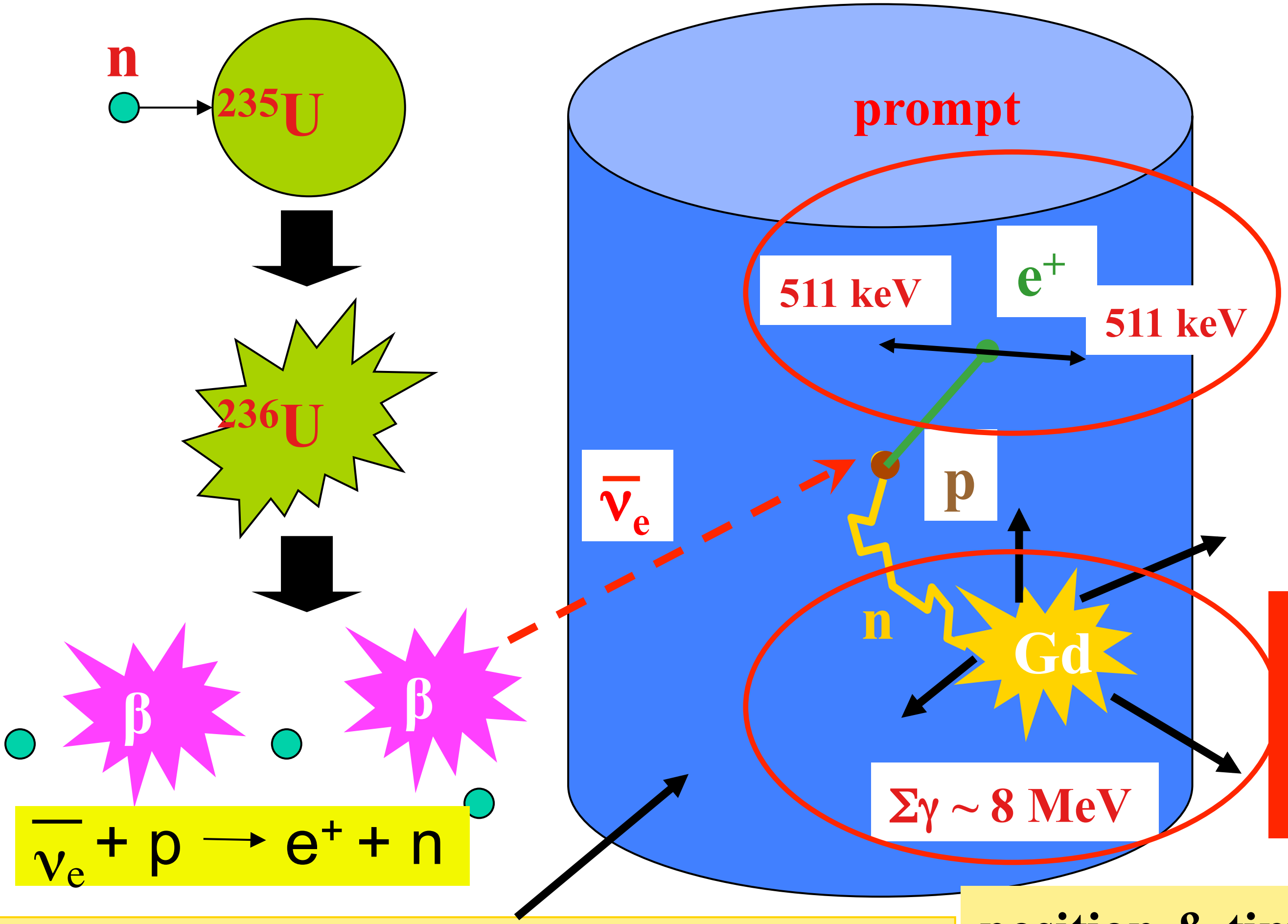
3 flavour effect
no degeneracies
no correlations
no matter effects

E=4MeV → 2km 4km 40km 80km

- → Double Chooz
- → Daya Bay
- → Reno

clean & precise
θ_{13} measurments
↔ beams

Anti-Neutrino Production and Detection



$\bar{\nu}_e + p \rightarrow e^+ + n$

prompt e^+ signal

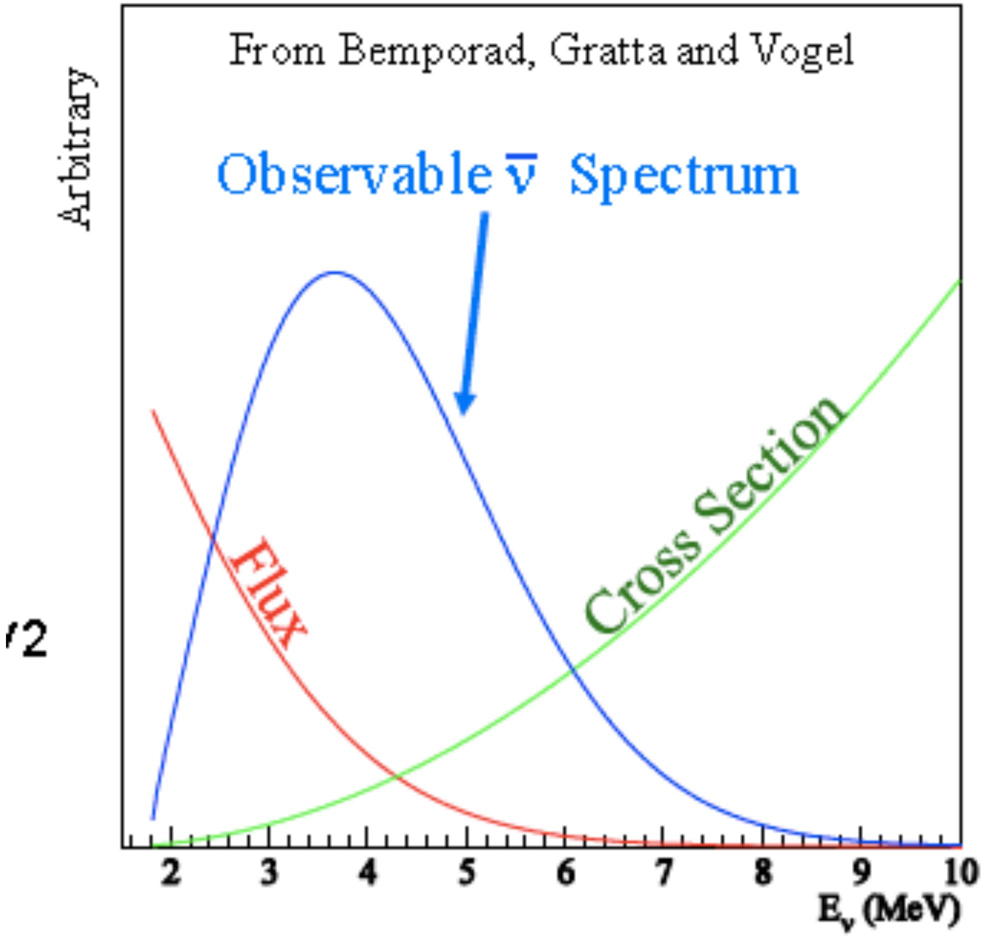
neutron capture
➔ Gd doping
➔ delayed γ (30 μs)

Target: Gd loaded liquid scintillator
transparency, stability, density, matching

position & time correlation
and delayed energy information
➔ enormous background reduction!

Reactor Anti-Neutrinos

x-section ⊠ flux➔ event rates



Oscillations:
- affect total rate
- spectral shape

The Chooz experiment:
- one detector
- theoretical ν flux
- normalized by $P_{thermal}$
- scintillator unstable

Problems:
- precision of $P_{thermal}$
- ν spectrum (high E)
- short lifetime

➔limiting factors

The Double Chooz Collaboration

France: APC Paris, CEA/Dapnia Saclay, Subatech Nantes, Strasburg

Germany: Aachen, MPIK Heidelberg, TU München, EKU Tübingen, Hamburg

Spain: CIEMAT Madrid

UK: Sussex

Japan: HIT, Kobe, Niigata, TGU, TIT, TMU, Tohoku

Russia: RAS, RRC Kurchatov Institute

USA: Alabama, ANL, Chicago, Columbia, Drexel, Illinois, Kansas, LLNL, LSU, Notre Dame, Sandia, Tennessee, UCD

Brazil: CBPF, UNICAMP

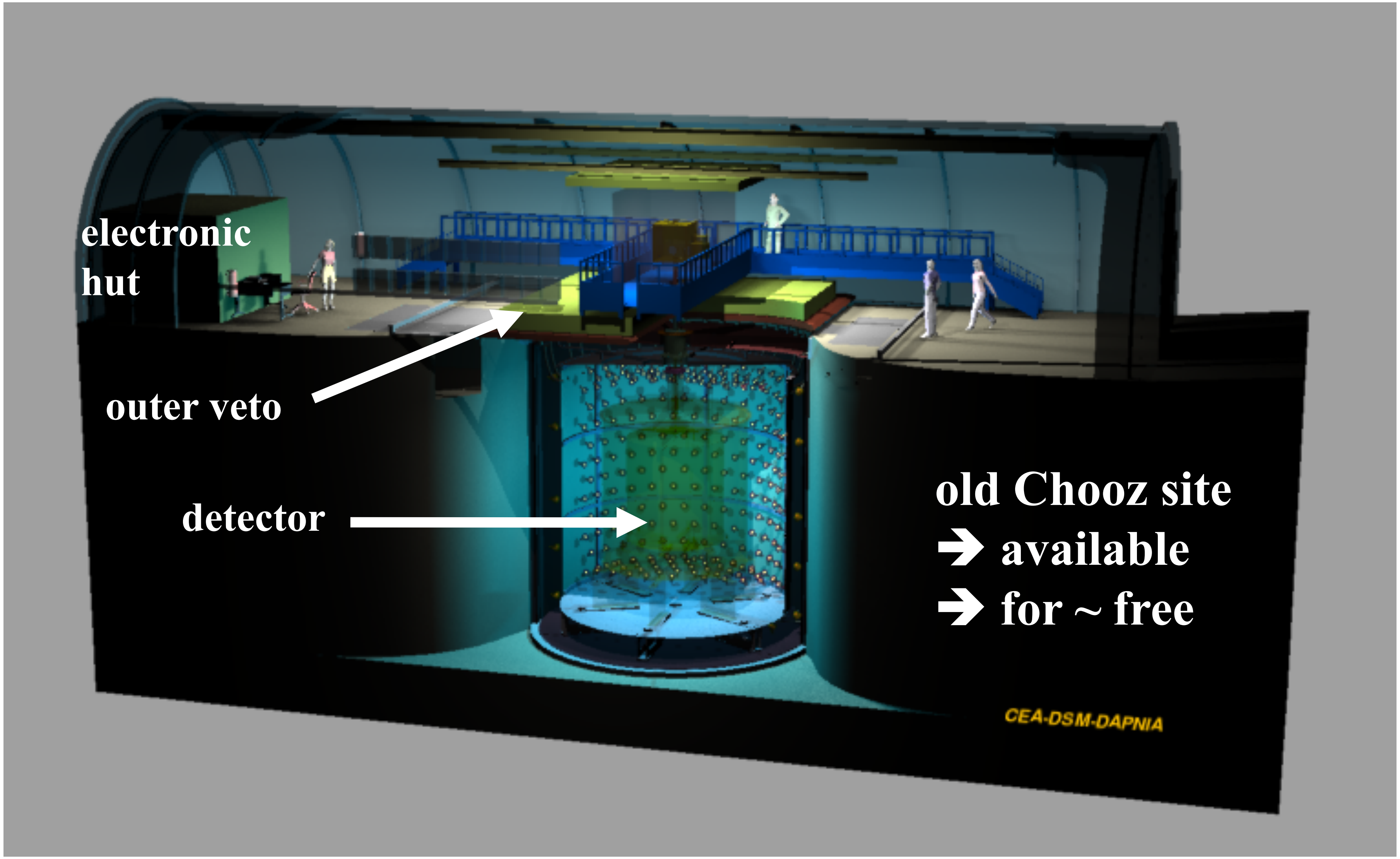
The Chooz Site

Near lab:
410m, 115 mwe
~500 ν's/day

Far lab:
1050m, 300mwe
~70 ν's/day

Chooz reactors:
- 8.5GW$_{th}$
- pure $\bar{\nu}_e$ source
- 10^{20} ν/(sGW)
- E_{ϖ} ~MeV
- E_{min} ~1.8 MeV

Far Detector Hall Layout



electronic hut

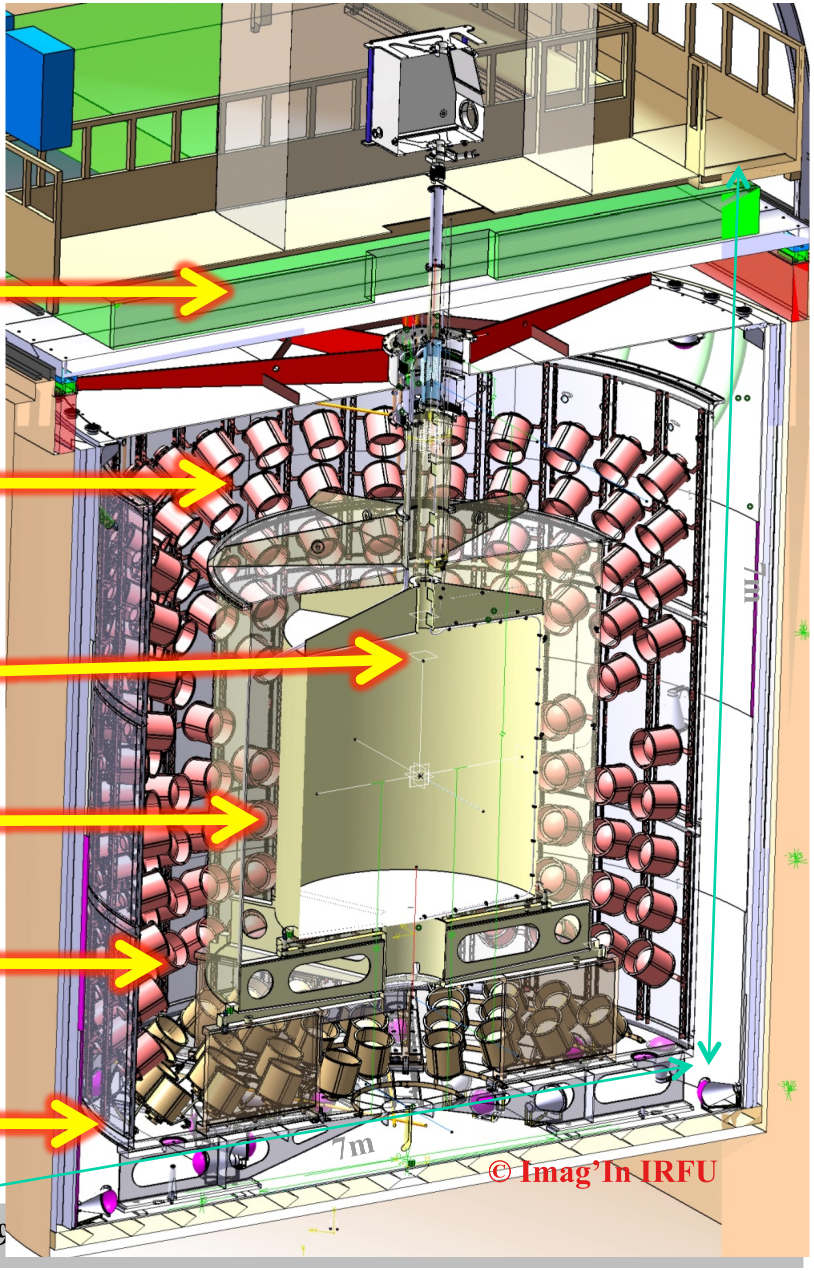
outer veto

detector

old Chooz site
➔ available
➔ for ~ free

Detector Design

New 4-region detector concept of the Double Chooz Collaboration:



© Imag'In IRFU

Outer Muon Veto (400mm plastic scintillator strips)

390 inner 10'' PMTs @ buffer vessel

Target: 10.3 m^3 Gd-doped scintillator in acrylic vessel (8 mm)

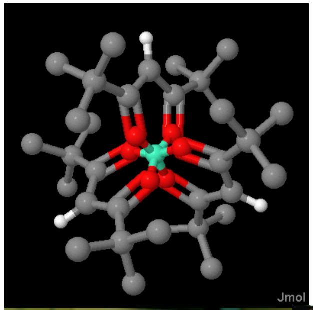
Gamma catcher: 22.3 m^3 scintillator in acrylic vessel (12mm)

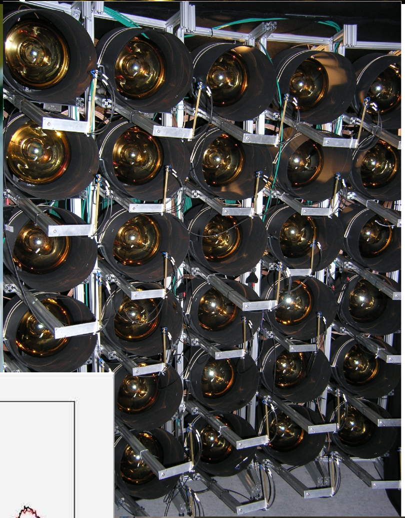
Buffer: 110 m^3 mineral oil in stainless steel vessel (3mm)

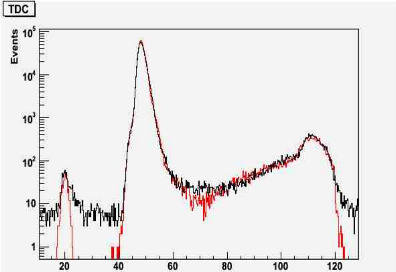
Inner muon veto: 90 m^3 scintillator in steel vessel equipped with 78 PMTs

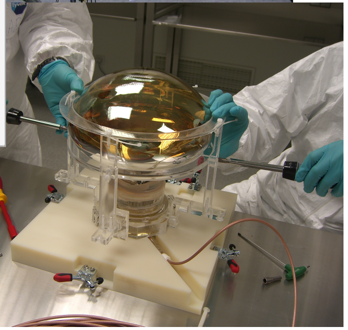
Development

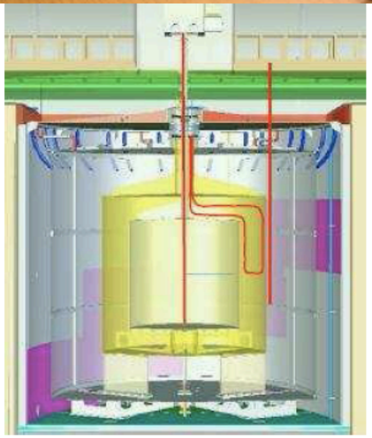
- Extensive scintillator R&D and testing (>4y)
- Detector optimization
- Low level background glas
  ➔ PMT radiopurity singles < 5Bq/det
- Full PMT characterization & calibration
- Electronics (FE, TB, TMB, …)
- Calibration systems
- Analysis tools

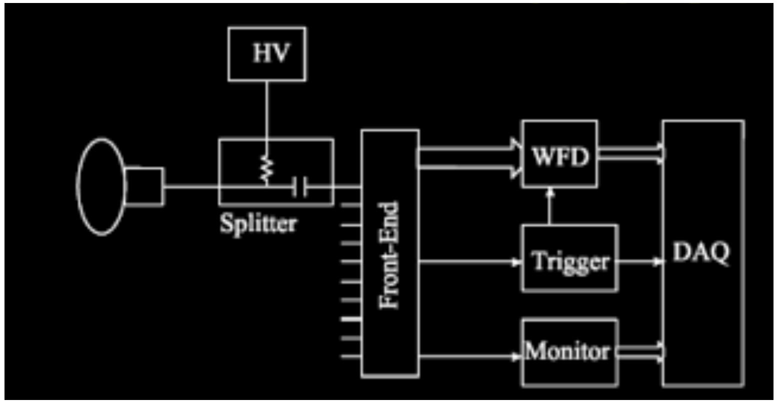












Far Detector Construction

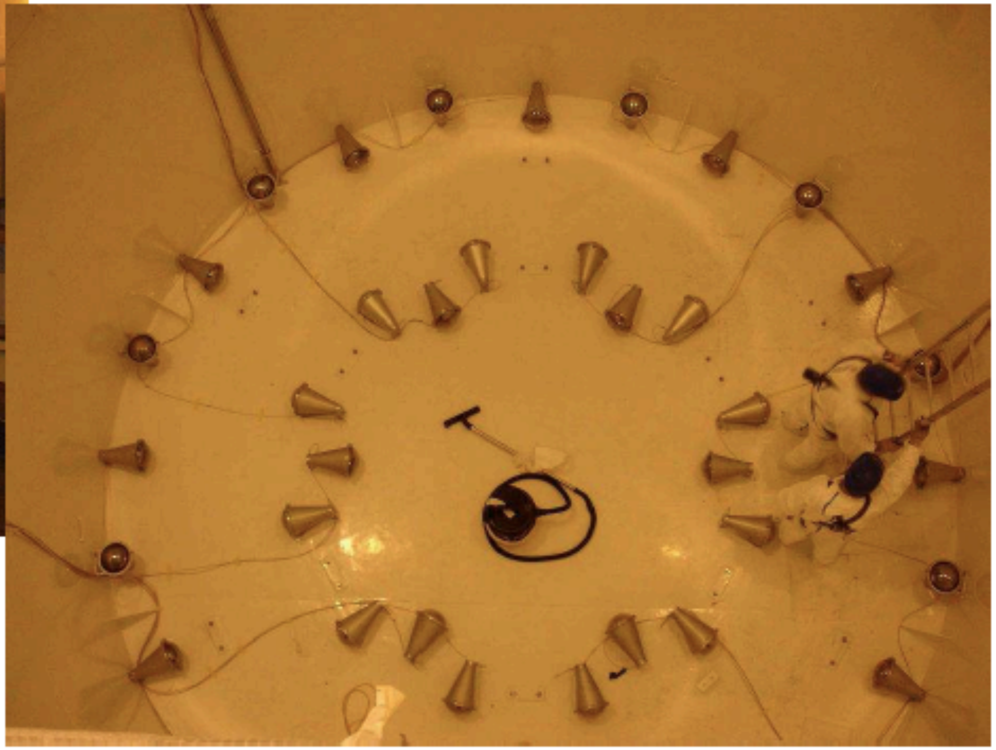
Pit refurbishment ➔ detector construction

October 2008

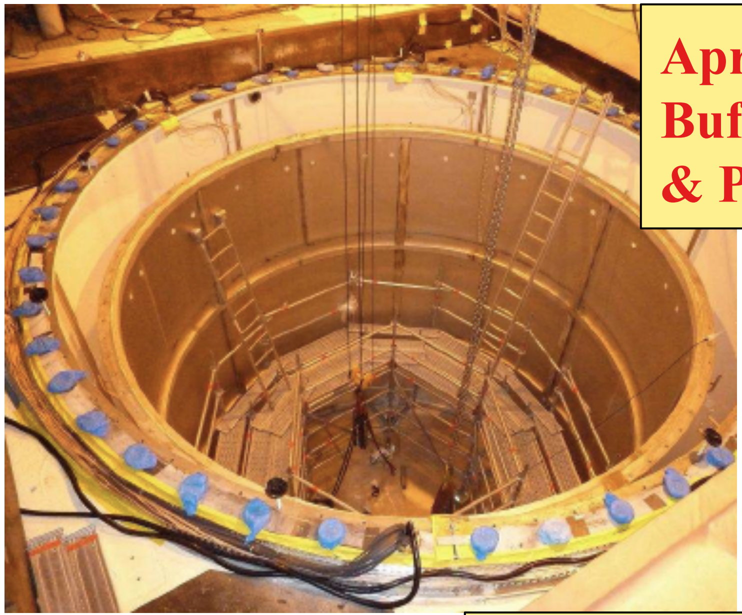
shield: 15cm
de-magnetzed
iron

Far Detector Construction

February 2009:
Inner veto PMTs installed

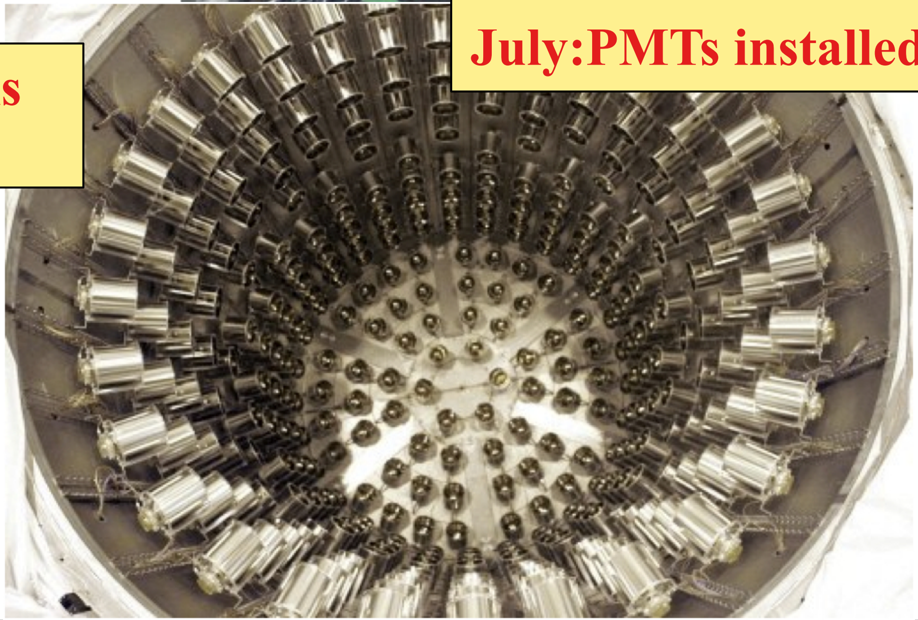


Far Detector Construction



April / May:
Buffer tank
& PMT installation

July:PMTs installed



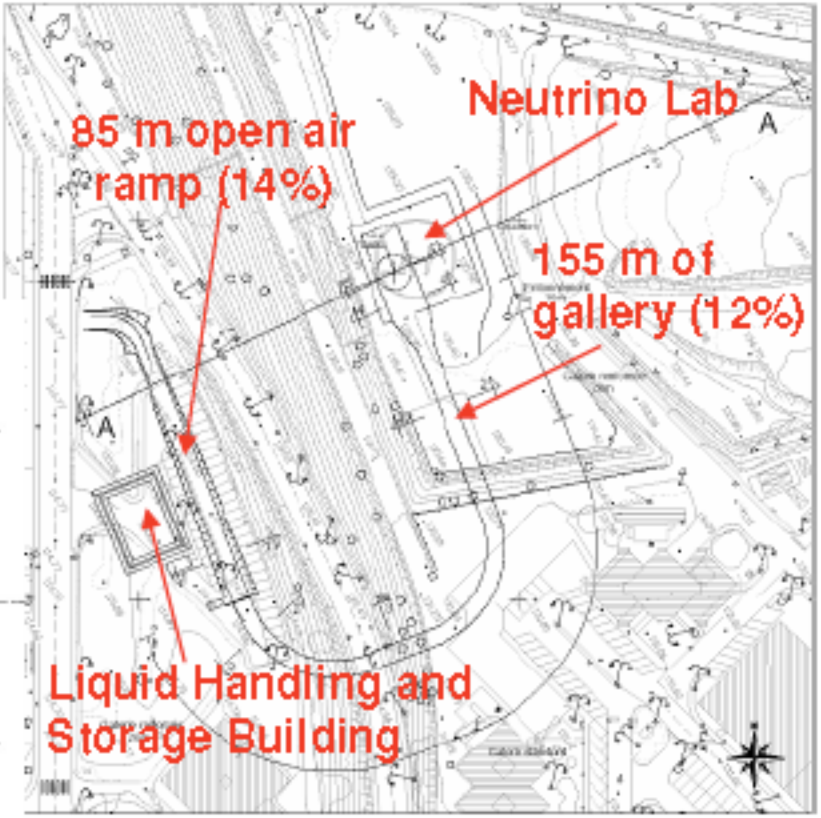
Aug:acrylic vessels
➔ installation

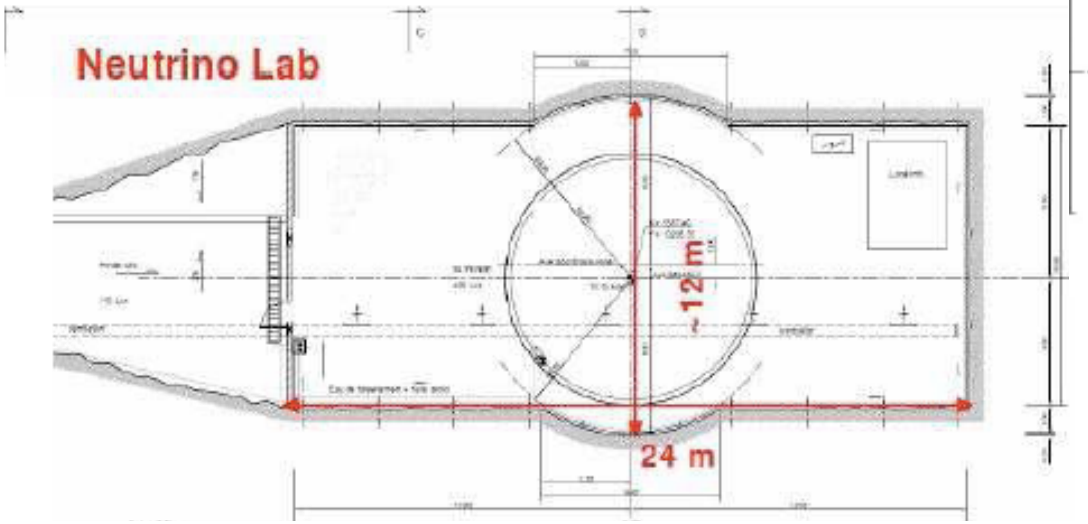
Schedule

- Far detector instalation will be finished in the end of 2009
  - upper lid: inner veto and buffer PMTs
  - electronics
  - filling system
- Filling and commissioning early 2010
- Outer veto in April 2010 (not a must for running)
- 4 month shutdown of one reactor for re-fueling
- Maybe a stop of both reactors for a few weeks
  ←→ background w/o reactor
- Running with far detector
  ←→ significantly improved Chooz experiment
- Installation of near detector
  → data taking 2011

Near Detector: New Neutrino Lab

- Agreement wth EdF and French agencies signed
- Constructed end of 2010
  ➔ 2nd detector
  ➔ data taking





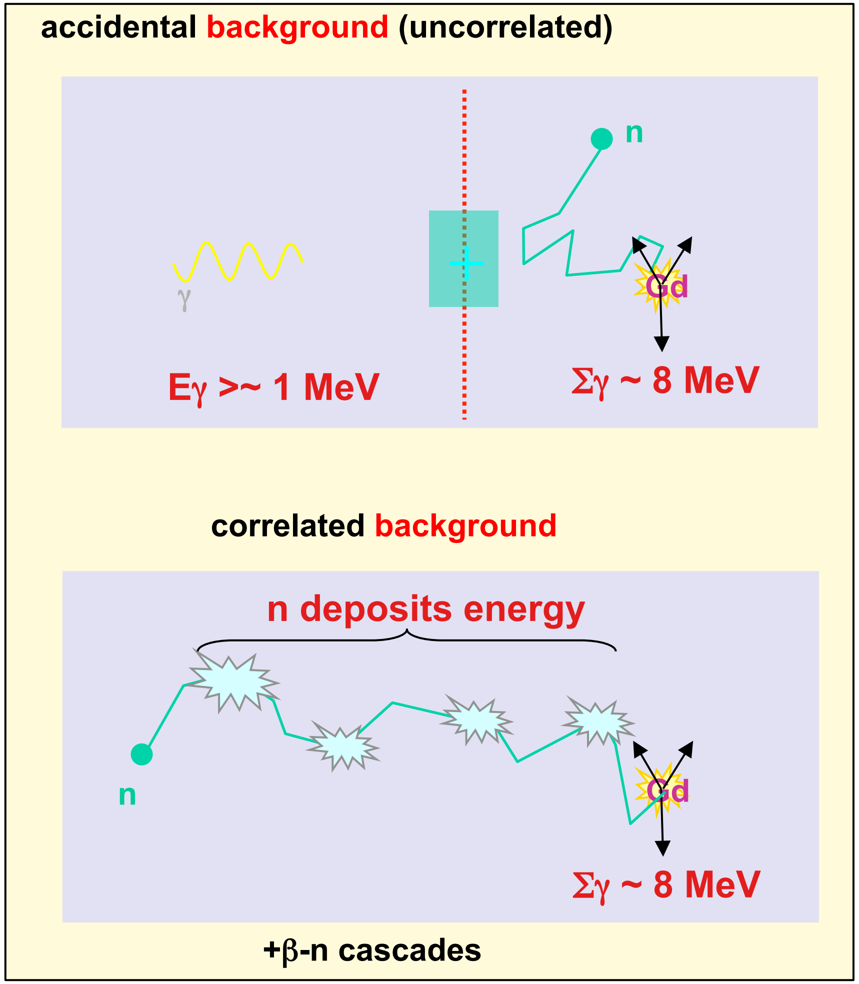
Correlated and Uncorrelated Backgrounds

Accidentals:

- **e$^+$-like signal:** radioactivity from materials and surrounding rock
- **n signal:** from cosmic m spallation, thermalized in detector and captured on Gd
- **n signal:** from other radioactive events

Correlated:

- fast n (by cosmic m) recoil on p (low E) and captured on Gd
- long-lived (^{9}Li, ^{8}He) β-decaying isotopes induced by μ

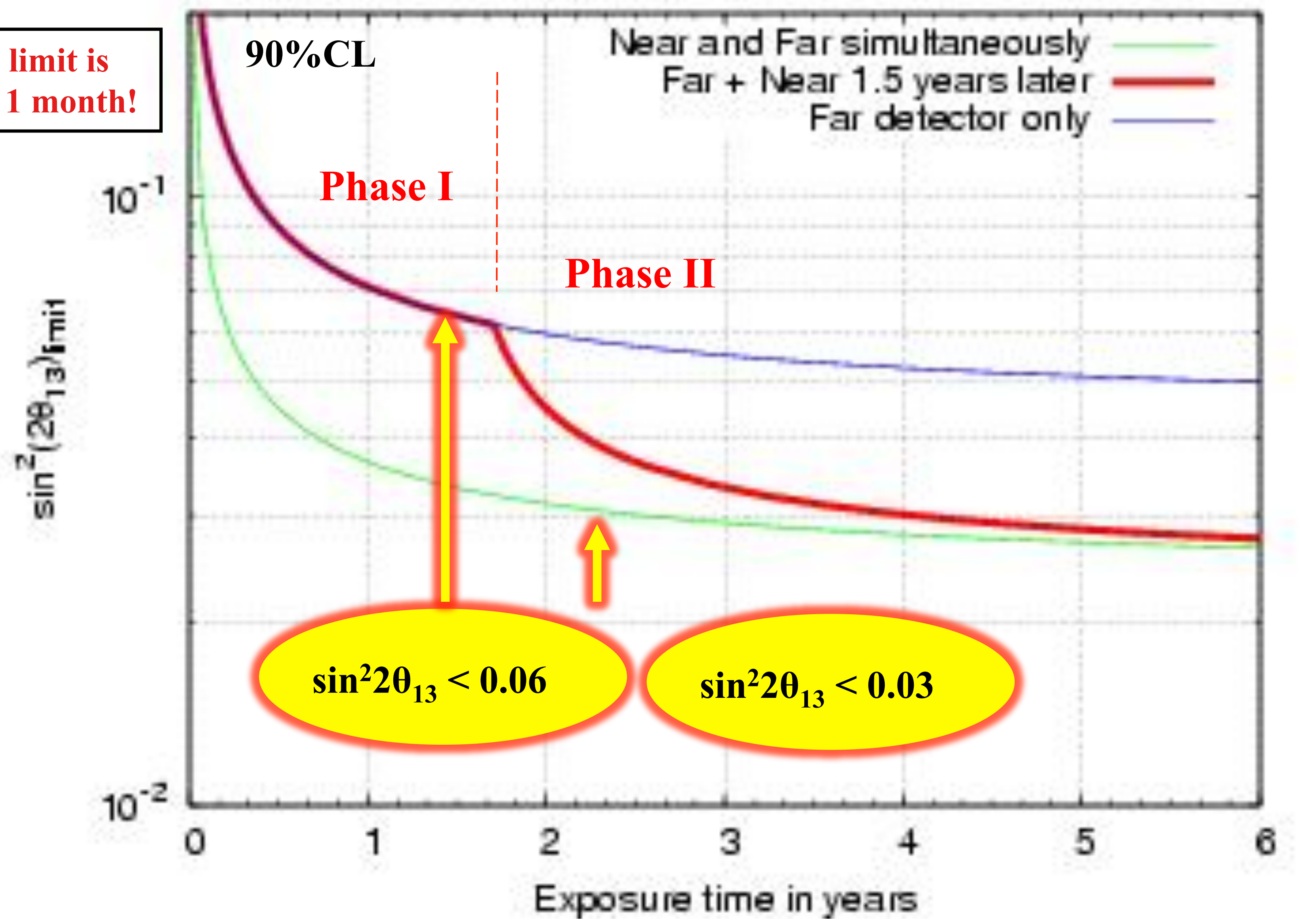


Systematics

		Chooz	Double Chooz (relative)	
Reactor-induced	ν flux and σ	1.9 %	<0.1 %	Two ''identical'' detectors, Low bkg
	Reactor power	0.7 %	<0.1 %	
	Energy per fission	0.6 %	<0.1 %	
Detector - induced	Solid angle	0.3 %	<0.1 %	Distance measured @ 10 cm + monitor core barycenter
	Target Mass	0.3 %	0.2 %	Same weight sensor for both det.
	Density	0.3 %	<0.1 %	Accurate T control (near/far)
	H/C ratio & Gd concentration	1.2 %	<0.2%	Same scintillator batch + Stability
	Spatial effects	1.0 %	<0.1 %	''identical'' Target geometry & LS
	Live time	few %	0.25 %	Measured with several methods
Analysis	From 7 to 3 cuts	1.5 %	0.2 - 0.3 %	(see next slide)
	Total	2.7 %	< 0.6 %	(Total ~0.45% without contingency ….)

Sensitivity over Time

CHOOZ limit is
reached in 1 month!



Phase I

Phase II

$\sin^2 2\theta_{13} < 0.06$

$\sin^2 2\theta_{13} < 0.03$

The Role of Reactor Experiments in the Era of Precision Oscillations

2 flavour approximations:

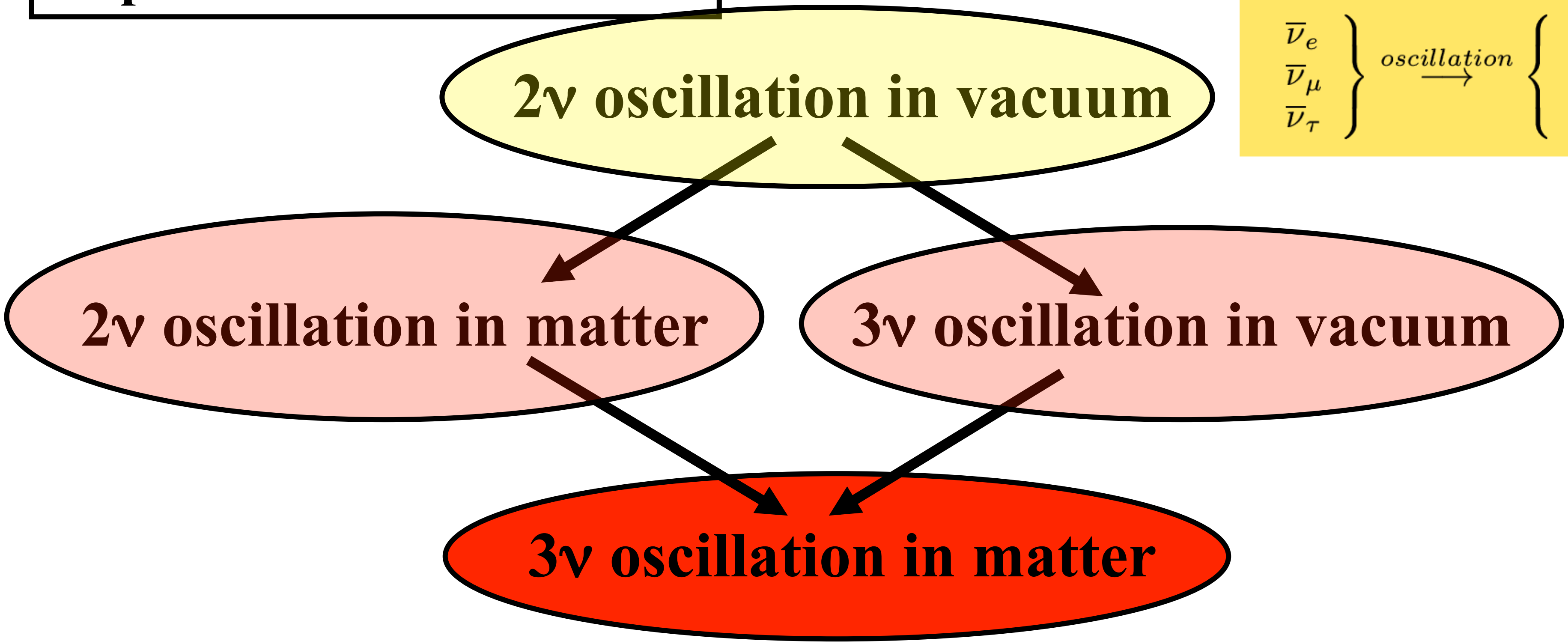
$P_{ab} = \sin^2(2\theta)\ \sin^2(\Delta m^2 L/4E)$

$P_{aa} = 1 - P_{ab}$

➔ **precision not sufficient**

$$\left.\begin{array}{c}\nu_e\\ \nu_\mu\\ \nu_\tau\end{array}\right\}\overset{oscillation}{\longrightarrow}\left\{\begin{array}{c}\nu_e\\ \nu_\mu\\ \nu_\tau\end{array}\right.$$

$$\left.\begin{array}{c}\overline{\nu}_e\\ \overline{\nu}_\mu\\ \overline{\nu}_\tau\end{array}\right\}\overset{oscillation}{\longrightarrow}\left\{\begin{array}{c}\overline{\nu}_e\\ \overline{\nu}_\mu\\ \overline{\nu}_\tau\end{array}\right.$$



2ν oscillation in vacuum

2ν oscillation in matter

3ν oscillation in vacuum

3ν oscillation in matter

Theree Flavour Oscillation Physics

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

x Majorana-CP-phases

S_{13} → 3 flavour effects
→ S_{13} → δ

matter effects

3 flavour-oscillations

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

$$P(\nu_{e_l} \to \nu_{e_m}) = \underbrace{\delta_{lm} - 4\sum_{i>j} \mathrm{Re} J_{ij}^{e_l e_m} \sin^2 \Delta_{ij}}_{P_{CP}} \underbrace{-2\sum_{i>j} \mathrm{Im} J_{ij}^{e_l e_m} \sin 2\Delta_{ij}}_{P_{\cancel{CP}}}$$

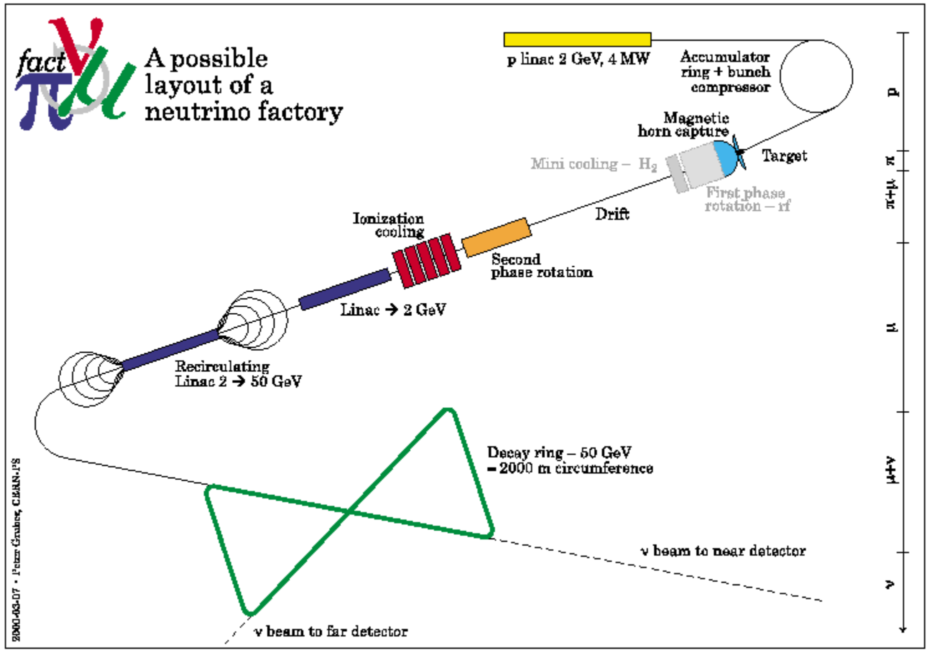
+ matter effects
→ sgn(Δm^2)

→precision neutrino physics
→ θ_{13} & leptonic CP violation

Different Neutrino Beams

A) conventional ν-beams from targets ➔ intense superbeams

B) neutrino factories



C) radioactive β-bemas

- Pure ν_e or $\overline{\nu}_e$ beam from radioactive decay, $\gamma \simeq 100$

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

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

↳ correlations & degeneracies, matter effects

Simulation of Future Experiments

- select a realistic setup (beam, detector, baseline, ...)
- simulate ➔ physics potential

Source ⊗ **Oscillation** ⊗ **Detector**

Source

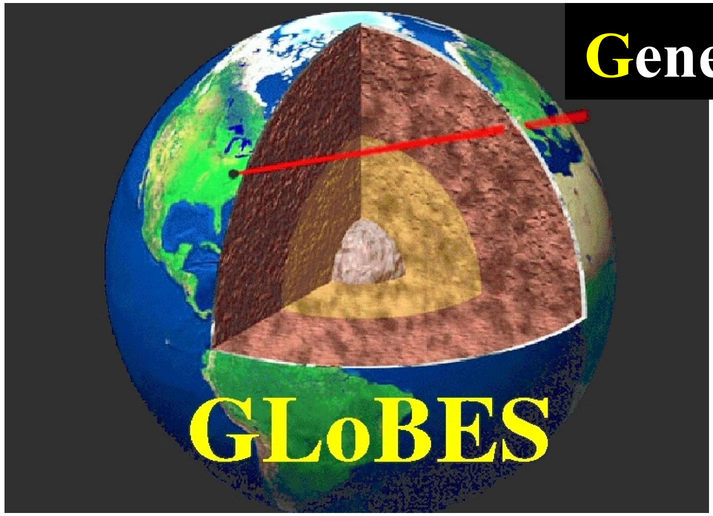
- neutrino energy E
- flux and spectrum
- flavour composition
- contamination
- symmetric $\nu/\overline{\nu}$ operation

Oscillation

- oscillation channels
- realistic baselines
- MSW matter profile
- degeneracies
- correlations

Detector

- effective mass, material
- threshold, resolution
- particle ID (flavour, charge, event reconstruction, ...)
- backgrounds
- x-sections (at low E)



General Long Baseline Experiment Simulator

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

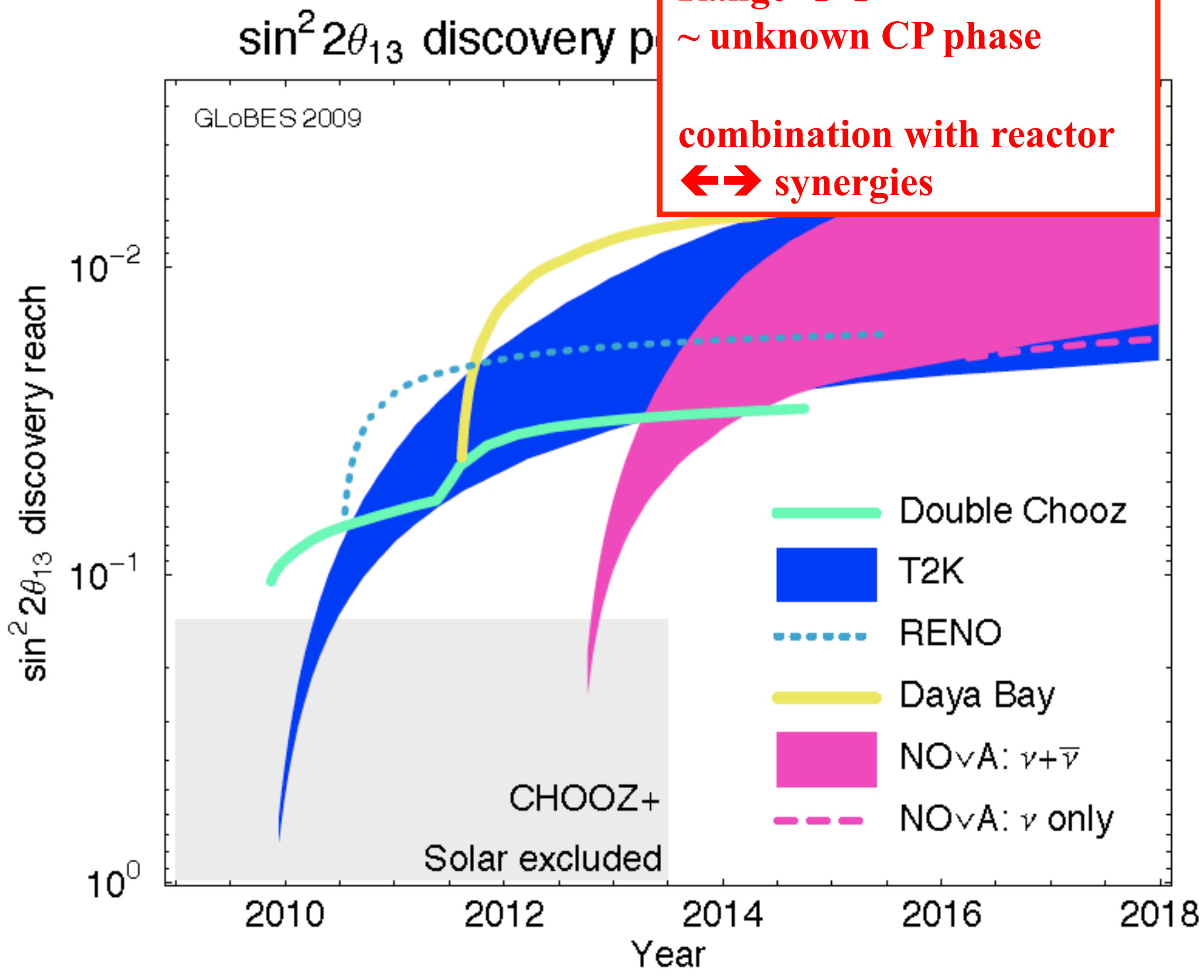
http://www.mpi-hd.mpg.de/~globes

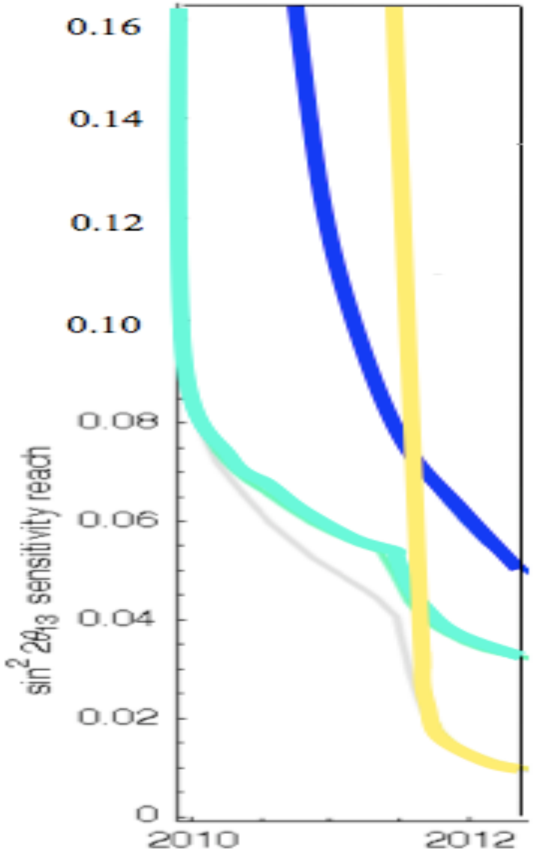
Huber, Kopp, ML, Winter

θ_{13} – Now and in the Future

Range ←→
~ unknown CP phase

combination with reactor
←→ synergies



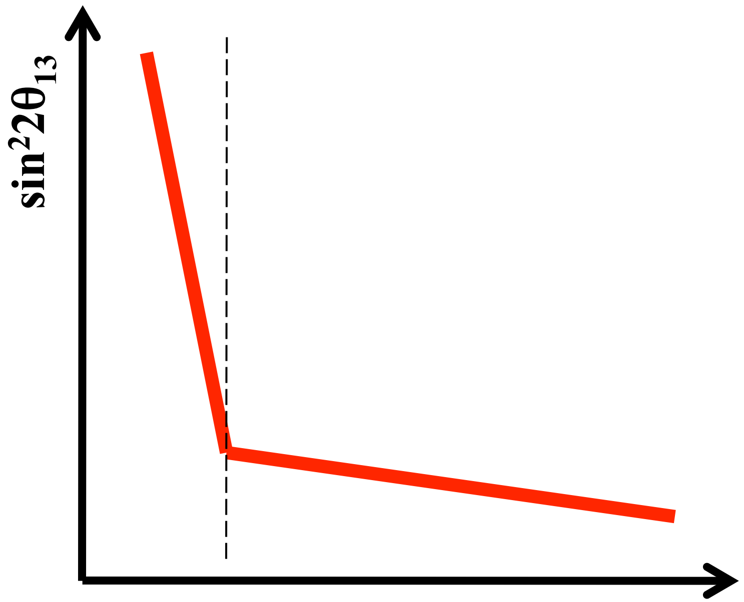


Huber, ML, Schwetz, Winter, arXiv:0907.1896

a linear scale – next years: significant improvements

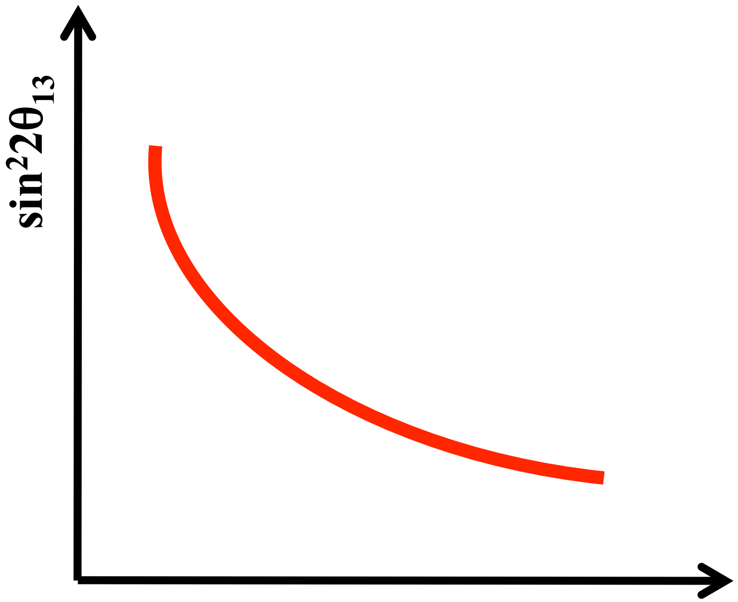
Critical Issues in Sensitivity Projections

Reactors:



- initially fast improvement
  ➔time critical
- later: GW x t x time
  ➔ size wins ; important: stability

Beams: ⇔ T2K:



- initially fast improvement
  ➔time critical
- later: ramping of MW x time
  ➔ important: steady increase
  ➔ how fast 5y x 0,75MW ?
  ➔ ramping & target stability

Why is θ_{13} so important?

- theoretical reason:

  ➔ teach us about origin of flavour, masses, mixings, CP
- practical reason:

  ➔ next generation experiments ⇄ value of θ_{13}

  ➔ super-beam, beta-beam, neutrino factory, …
- further reasons:

  ➔ better understanding of

    - nuclear physics processes (reactor, background)
    - plutonium content ⇄ proliferation, IAEA
    - scintillators for future AP projects

The larger Picture: GUTs

Gauge unification suggests that some GUT exists

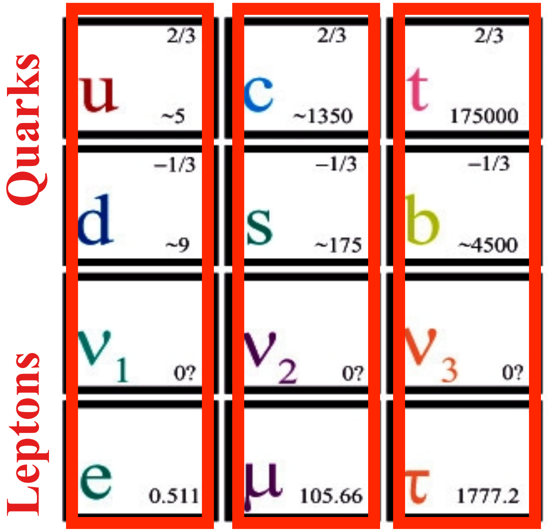
Requirements:

gauge unification

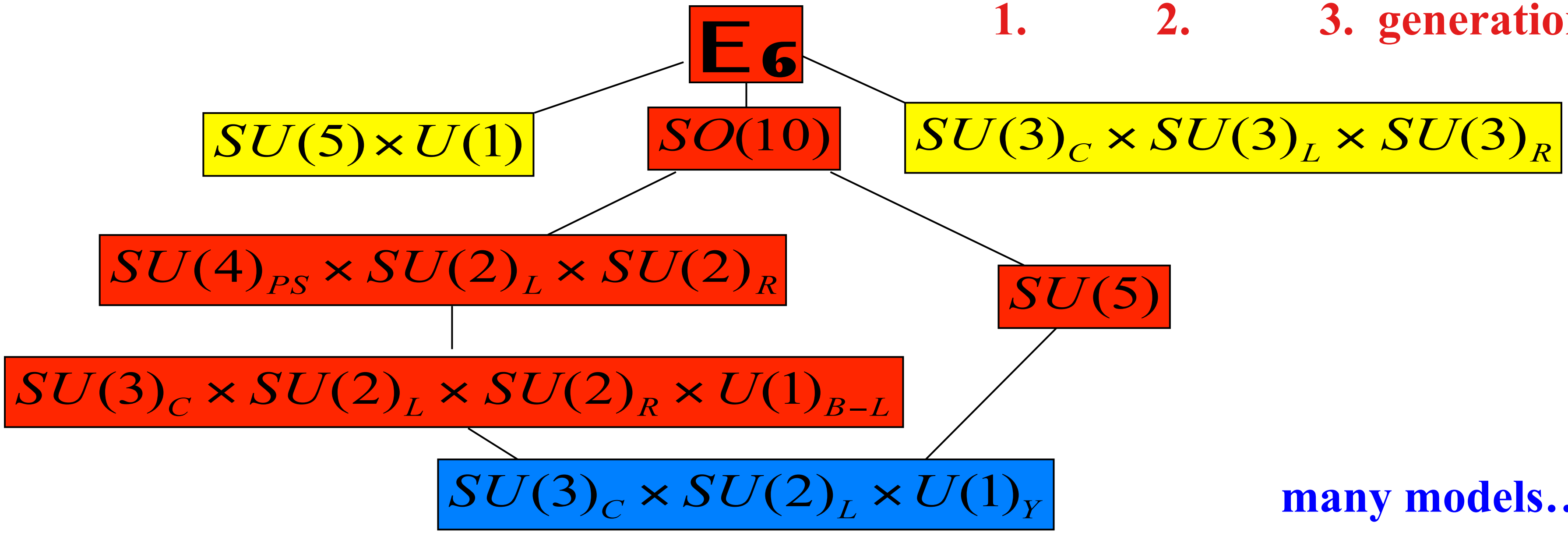
particle multiplets ⇔ ν_R

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

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

$SO(10)$

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

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

$SU(5)$

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

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

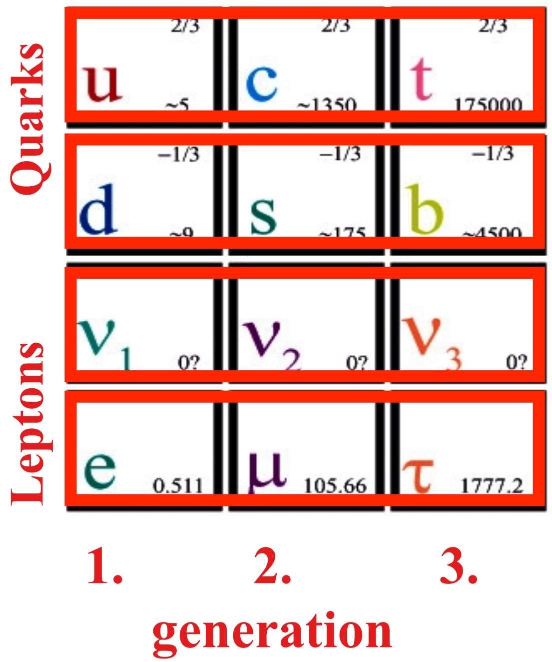
many models…

Flavour Unification

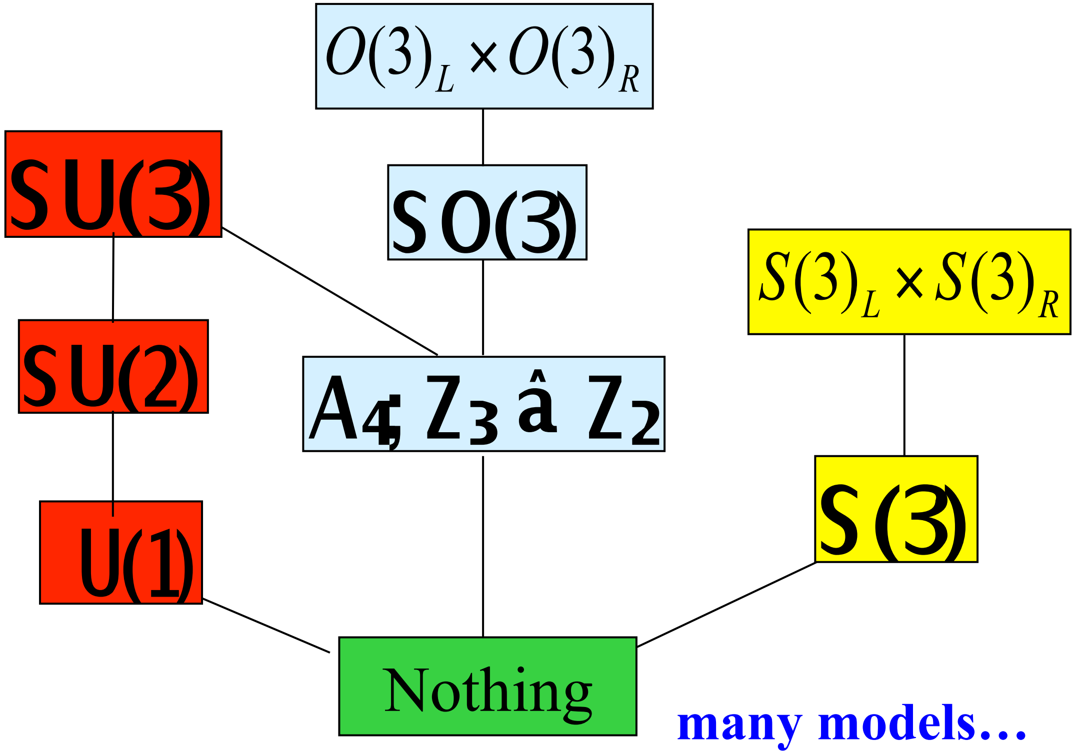
- so far no understanding of flavour, 3 generations
- apparant regularities in quark and lepton parameters

➔ flavour symmetries (finite number for limited rank)

➔ symmetry not texture zeros



Examples:



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

SU(3)

SO(3)

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

SU(2)

$A_4, Z_3 \times Z_2$

S(3)

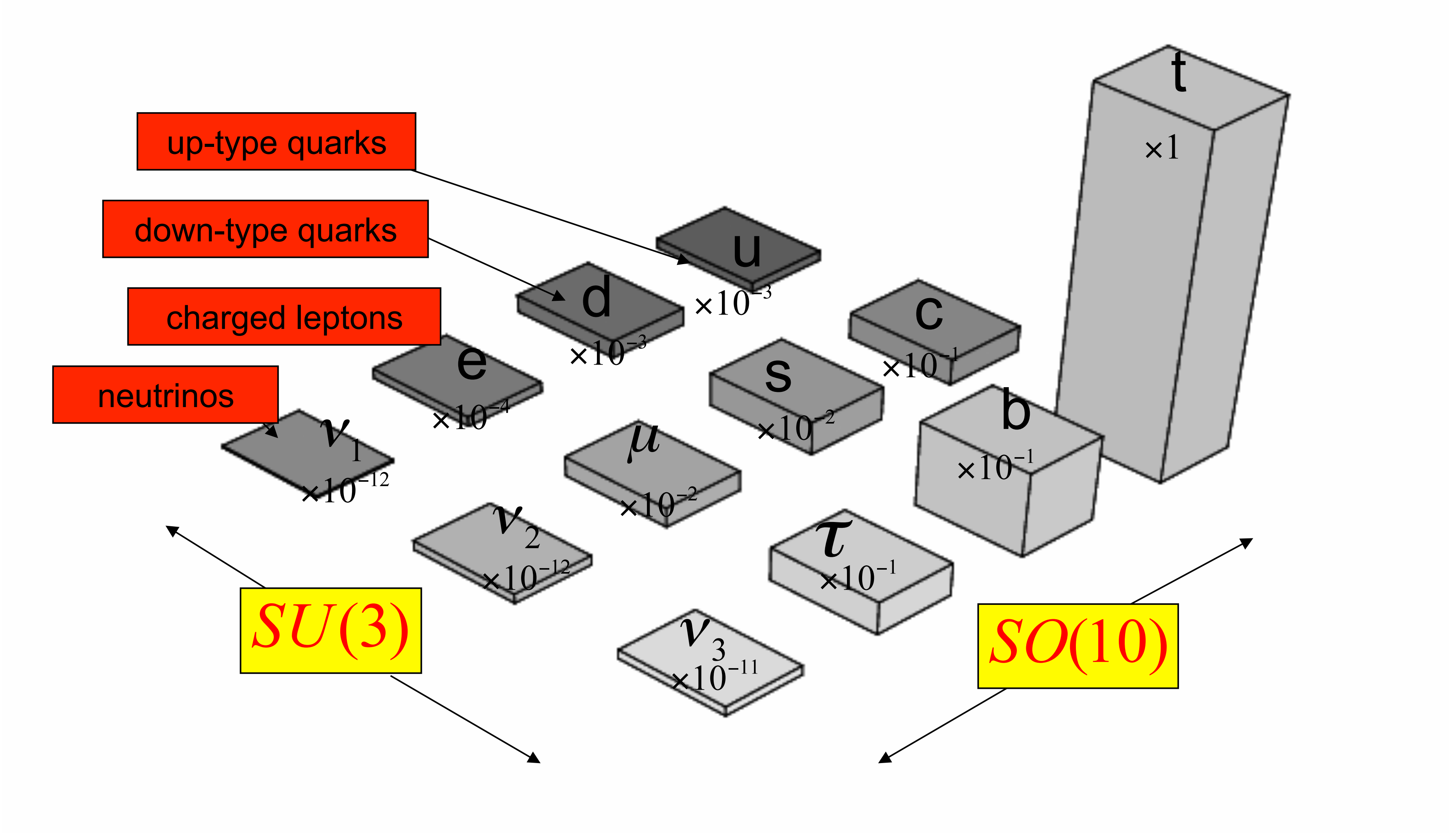
U(1)

Nothing

many models…

GUT *and* Flavour Unification

Example: SO(10) x SU(3)



GUT ⊗ Flavour Challenges

- **Difficulty grows with**

  - size of discrete flavour symmetry

  - size of the GUT group

  ➔ so far only a few viable models

  e.g. SO(10) ⊗ S4 **Hagedorn, ML, Mohapatra**

  ➔ limited number of possibilities

  ➔ phenomenological success non-trivial

  ➔ embedding into GUT ⊗ continuous group unlikely

  Adulpravitchai, Blum, ML

Aims: Distinguish models by future precision & learn about origin of flavour, masses, mixings

Conclusions

- Double Chooz is the first next generation reactor neutrino experiment to improve or measure θ_{13}
- Good theoretical reasons to expect a signal
- Installation of far detector far advanced
- Data taking planned to start early 2010 with FD

➔ $\sin^2 2\theta_{13} < 0.06$ in 1.5 years @ 90%CL *or* oscillation

- Data taking with both detectors 2011

➔ $\sin^2 2\theta_{13} < 0.03$ in 3 years @ 90%CL