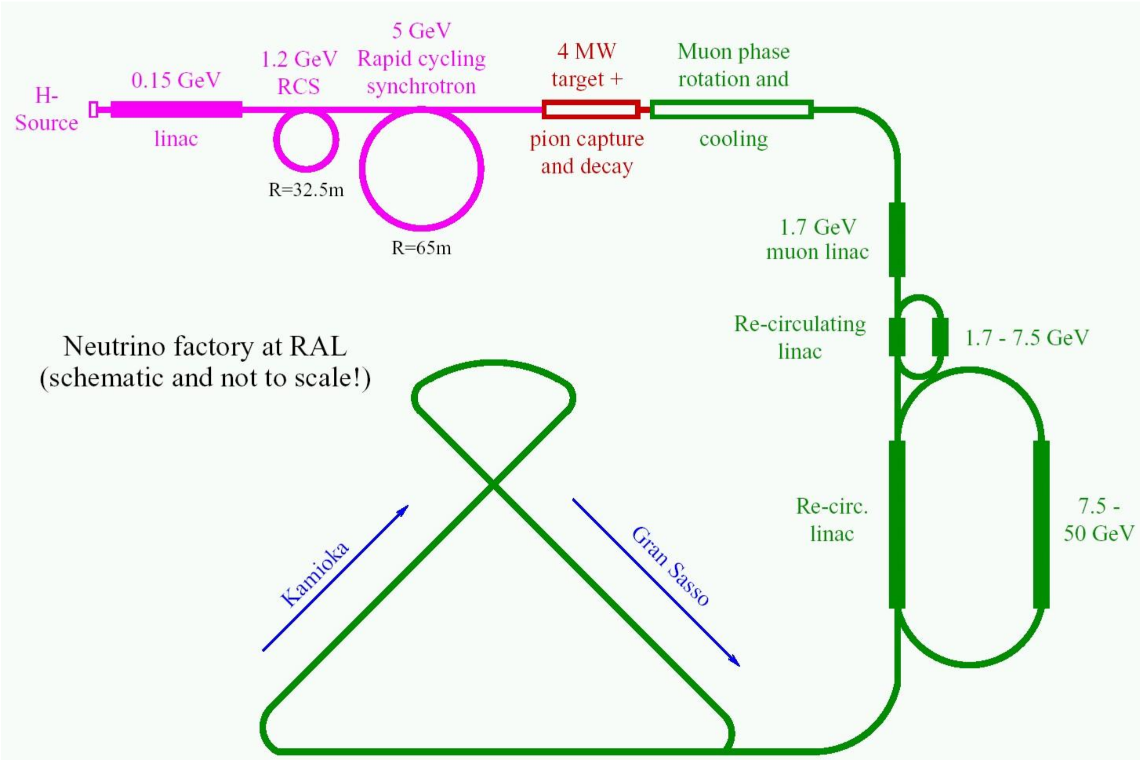
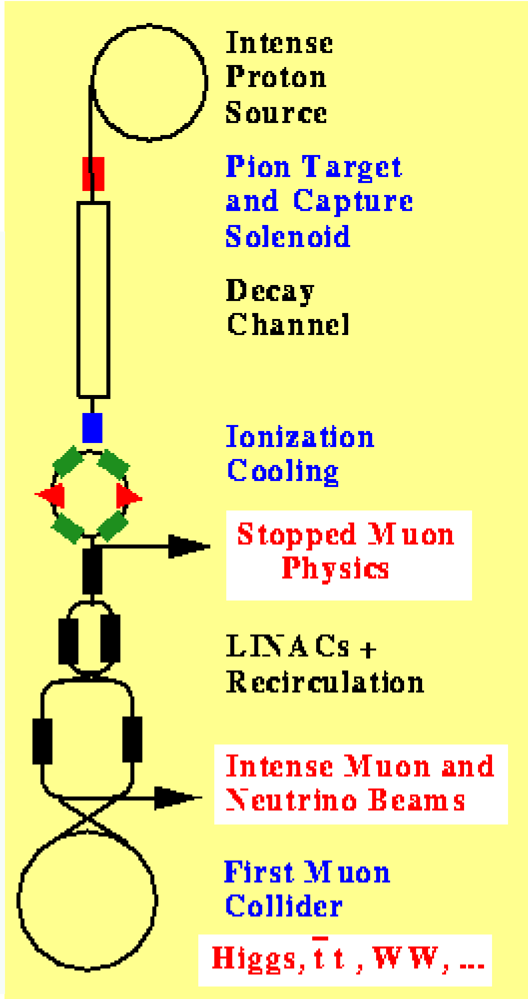
Neutrino Factory Physics

Steve King (Southampton)





Oscillation

- Neutrino physics has surprised us all
- Many discoveries in the last decade:
- Atmospheric ν_μ are converted to ν_τ (SK) (98)
- Solar ν_e are converted to either ν_μ or ν_τ(SNO) (02)
- Only the LMA solution left for solar neutrinos (Homestake+Gallium+SK+SNO) (02)
- Reactor anti-ν_e disappear/reappear (KamLAND) (04)
- Accelerator ν_μ disappear (K2K 04 , MINOS 06)

Revolution

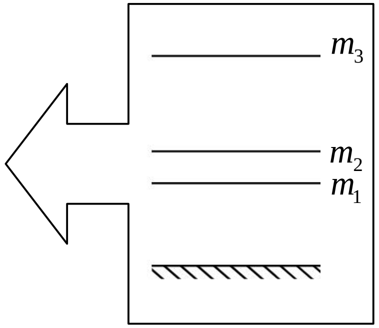
- Lepton Flavor is not conserved
- Neutrinos have tiny masses, not very hierarchical
- Neutrinos mix a lot
- At least 7 new parameters for SM
- Quite unlike quark mass and mixing
- Of all fermions, neutrinos are least understood
- Yet they play an essential role in the Universe $n_\nu \sim n_\gamma >> n_e$ and their tiny mass may indicate New Physics BSM at very high energies

Three neutrino mass and mixing

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Standard Model states

Neutrino mass states



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

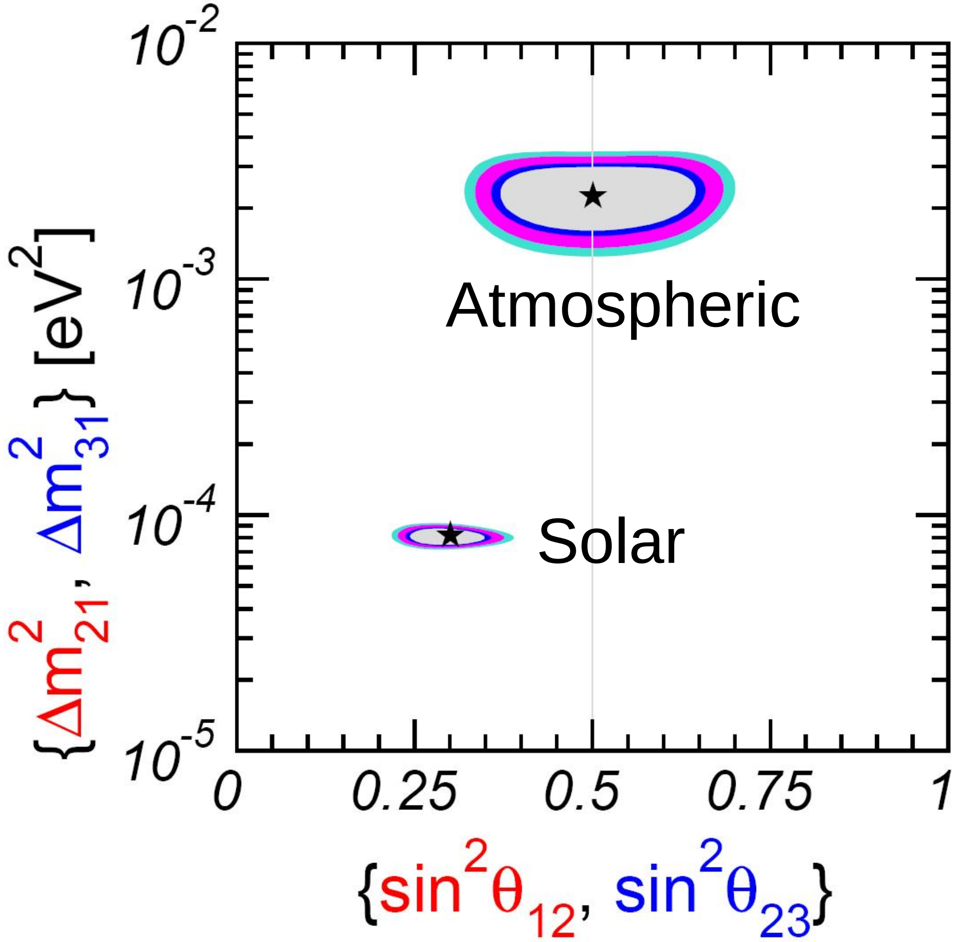
Atmospheric | Reactor | Solar | Majorana

Oscillation phase δ

Majorana phases α_1, α_2

3 masses + 3 angles + 1(3) phase(s) = 7(9) new parameters for SM

Latest global fit for atmospheric & solar oscillations



. Maltoni, T. Schwetz, M. A. Tortola and J. W. F. Valle,

Latest version 19th Oct 07

- Latest SSM
- SNO salt data
- K2K
- Latest MINOS results

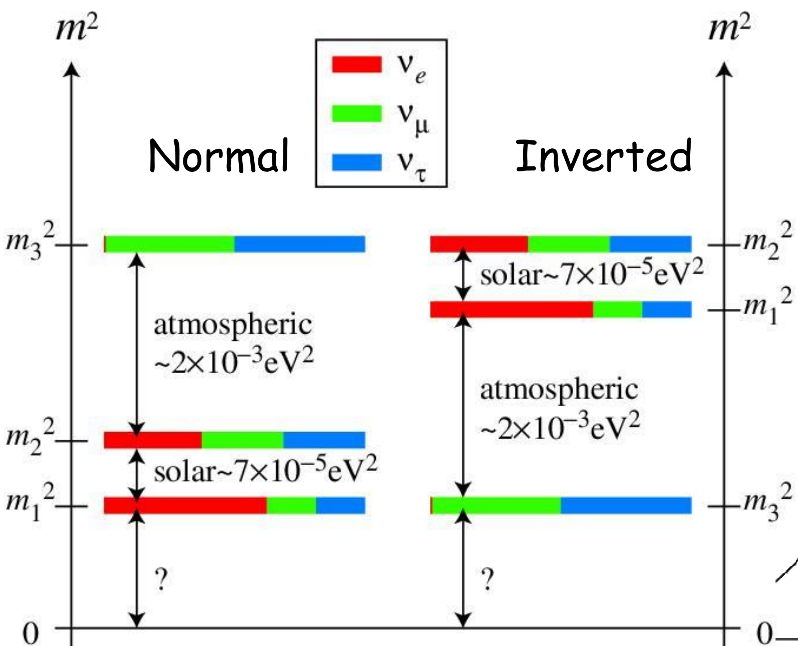
Neutrino mass squared splittings and angles

parameter	best fit	3σ range
Δm^2_{21} $[10^{-5}\ \mathrm{eV}^2]$	7.9	7.1–8.9
Δm^2_{31} $[10^{-3}\ \mathrm{eV}^2]$	2.6	2.0–3.2

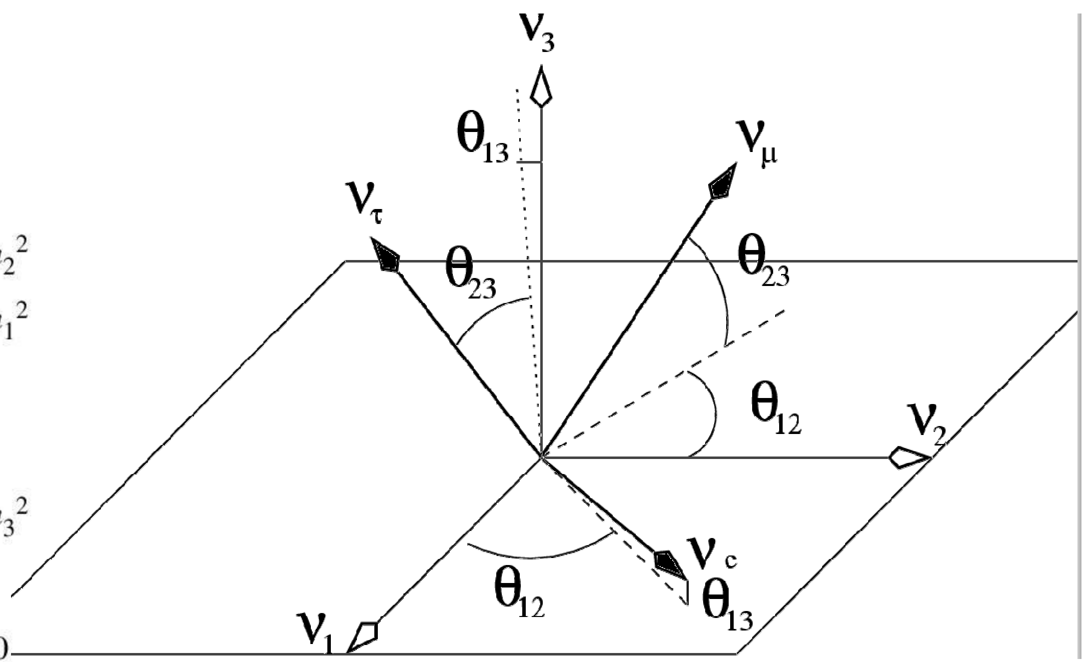
Valle et al

$$\theta_{12} = 33^\circ \pm 5^\circ$$
$$\theta_{23} = 45^\circ \pm 10^\circ$$
$$\theta_{13} < 13^\circ$$

3 σ errors



Absolute neutrino mass scale?



Tri-bimaximal mixing (TBM)

Harrison, Perkins, Scott

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\theta_{12} = 35^\circ, \qquad \theta_{23} = 45^\circ, \qquad \theta_{13} = 0^\circ.$$

c.f. data $\theta_{12} = 33^\circ \pm 5^\circ, \theta_{23} = 45^\circ \pm 10^\circ, \ \theta_{13} < 13^\circ$

- Current data is consistent with TBM
- But no convincing reason for exact TBM – expect deviations

Useful to Parametrize lepton mixing matrix in terms of deviations from tri-bimaximal mixing

SFK **arXiv:0710.0530**

$$s_{13} = \frac{r}{\sqrt{2}}, \quad s_{12} = \frac{1}{\sqrt{3}}(1+s), \quad s_{23} = \frac{1}{\sqrt{2}}(1+a)$$

$$0 < r < 0.22, \; -0.11 < s < 0.04, \; -0.12 < a < 0.13.$$

r = reactor   s = solar   a = atmospheric

$$U \approx \begin{pmatrix} \sqrt{\frac{2}{3}}(1-\frac{1}{2}s) & \frac{1}{\sqrt{3}}(1+s) & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+s-a+re^{i\delta}) & \frac{1}{\sqrt{3}}(1-\frac{1}{2}s-a-\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1+a) \\ \frac{1}{\sqrt{6}}(1+s+a-re^{i\delta}) & -\frac{1}{\sqrt{3}}(1-\frac{1}{2}s+a+\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1-a) \end{pmatrix}$$

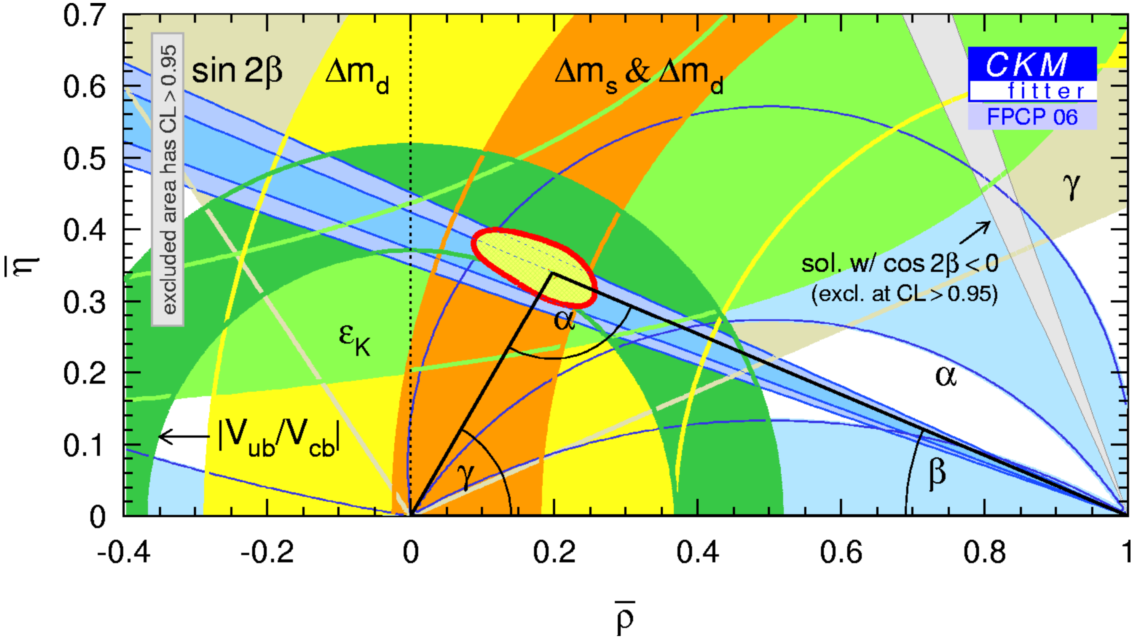
Present data is consistent with r,s,a=0 →tri-bimaximal

c.f. Wolfenstein for quarks

$$V \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

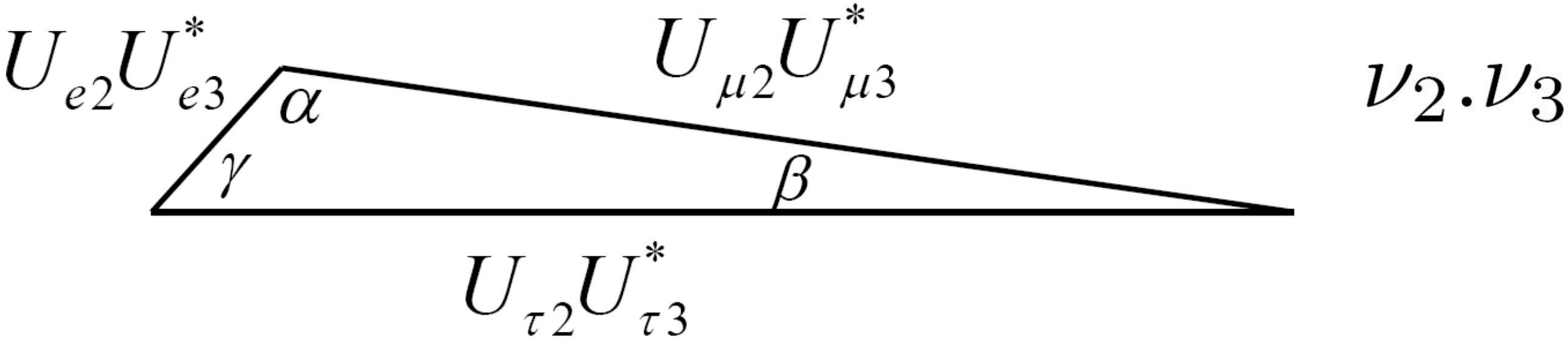
$$\lambda \approx 0.227$$

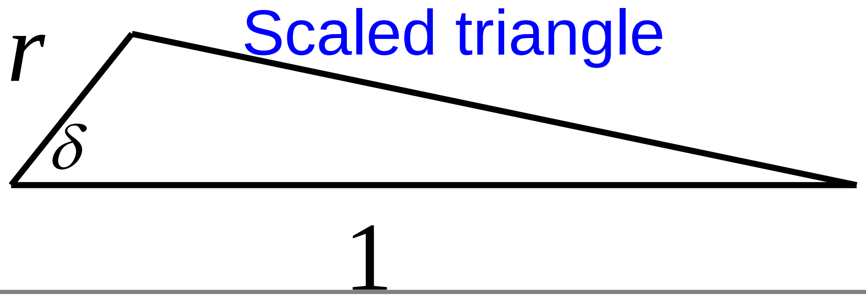
Quark UT is very well determined



In the case of leptons UT is unknown

$$U \approx \begin{pmatrix} \sqrt{\frac{2}{3}}(1-\frac{1}{2}s) & \frac{1}{\sqrt{3}}(1+s) & \frac{1}{\sqrt{2}}re^{-i\delta} \\ -\frac{1}{\sqrt{6}}(1+s-a+re^{i\delta}) & \frac{1}{\sqrt{3}}(1-\frac{1}{2}s-a-\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1+a) \\ \frac{1}{\sqrt{6}}(1+s+a-re^{i\delta}) & -\frac{1}{\sqrt{3}}(1-\frac{1}{2}s+a+\frac{1}{2}re^{i\delta}) & \frac{1}{\sqrt{2}}(1-a) \end{pmatrix}$$





Neither r nor δ is measured – UT could be a straight line!

Two main challenges facing neutrino physics:

- Measure the neutrino masses

(m_1, m_2, m_3 scale, ordering, nature)

- Measure the neutrino mixings

(the deviations from tri-bimaximal mixing r,s,a and the CP phase δ)

Long-baseline accelerator experiments vs. reactor experiments

E.Falk

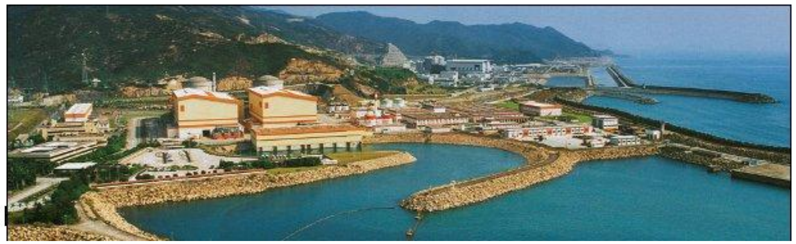
- Long-baseline accelerator experiments:
  - Look for appearance ($\nu_\mu \to \nu_e$) in pure ν_μ beam vs. *L* and *E*
  - Near detector to measure background ν_es (beam + mis-id)

T2K:
$\langle E_\nu \rangle$ = 0.7 GeV
L = 295 km

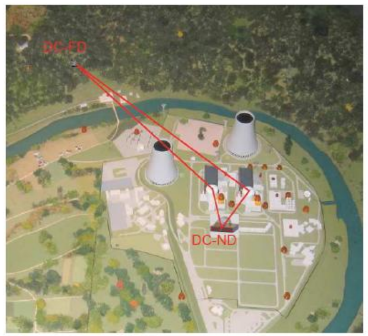
NOνA:
$\langle E_\nu \rangle$ = 2.3 GeV
L = 810 km

- Reactor experiments:
  - Look for disappearance ($\overline{\nu}_e \to \overline{\nu}_e$) as a fnc of *L* and *E*
  - Near detector to measure unoscillated flux

Daya Bay



Double Chooz:
$\langle E_\nu \rangle$ = 3.5 MeV
L = 1050 m



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Oscillation formulae in terms of r,s,a

$$P_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta)$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

reactor $\left\{ P_{ee} = 1 - 2r^2 \sin^2 \Delta_{31} - \frac{8}{9}\Delta^2_{21} \right.$

Only sensitive to the reactor parameter r

LBL

$$\left\{ \begin{array}{lll} P_{\mu e} & = & r^2 \sin^2 \Delta_{31} + \frac{4}{9}\Delta^2_{21} + \frac{4}{3} r \Delta_{21} \sin \Delta_{31} \cos(\Delta_{31} + \delta) \\ P_{\mu\mu} & = & 1 - (1 - 4a^2) \sin^2 \Delta_{31} - \frac{2}{9}(1 + 3\cos 2\Delta_{31})\Delta^2_{21} \\ & + & \frac{2}{3}(1 - s - r\cos\delta)\Delta_{21} \sin 2\Delta_{31}. \end{array} \right.$$

Sensitive to r,s,a

Oscillation formulae in terms of r,s,a

(including matter effects)

$$\Delta = \Delta_{31}, \; \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$A = \frac{VL}{2\Delta}$$

$$V \approx 7.56 \times 10^{-14} \rho \, Y_e$$

$$Y_e \approx 0.5$$

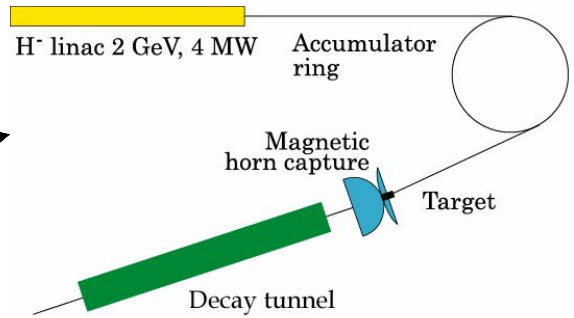
$$\rho \approx 4.5 \text{ g/cm}^3$$

$$\begin{aligned} P_{\mu e} &= \frac{4}{9}\alpha^2 \frac{\sin^2 A\Delta}{A^2} + r^2 \frac{\sin^2 (A-1)\Delta}{(A-1)^2} \\ &+ \frac{4}{3} r\alpha \cos(\Delta + \delta) \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)}. \end{aligned}$$

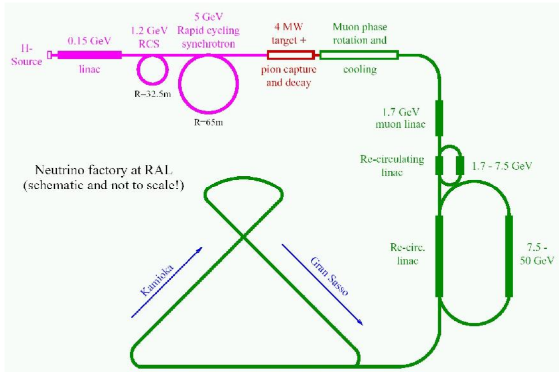
For a list of formulae in terms of r,s,a see SFK **arXiv:0710.0530**

Future LBL Options:

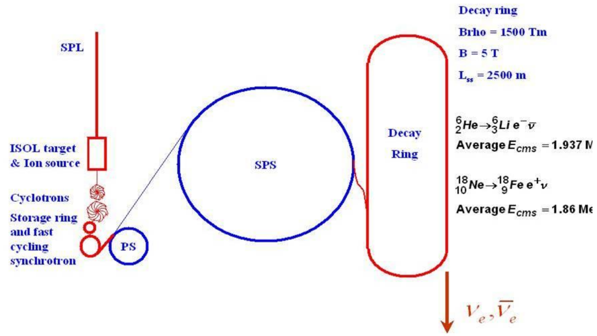
- Second generation super-beam: CERN, FNAL, BNL, J-PARC II



- Neutrino Factory



- Beta-beam

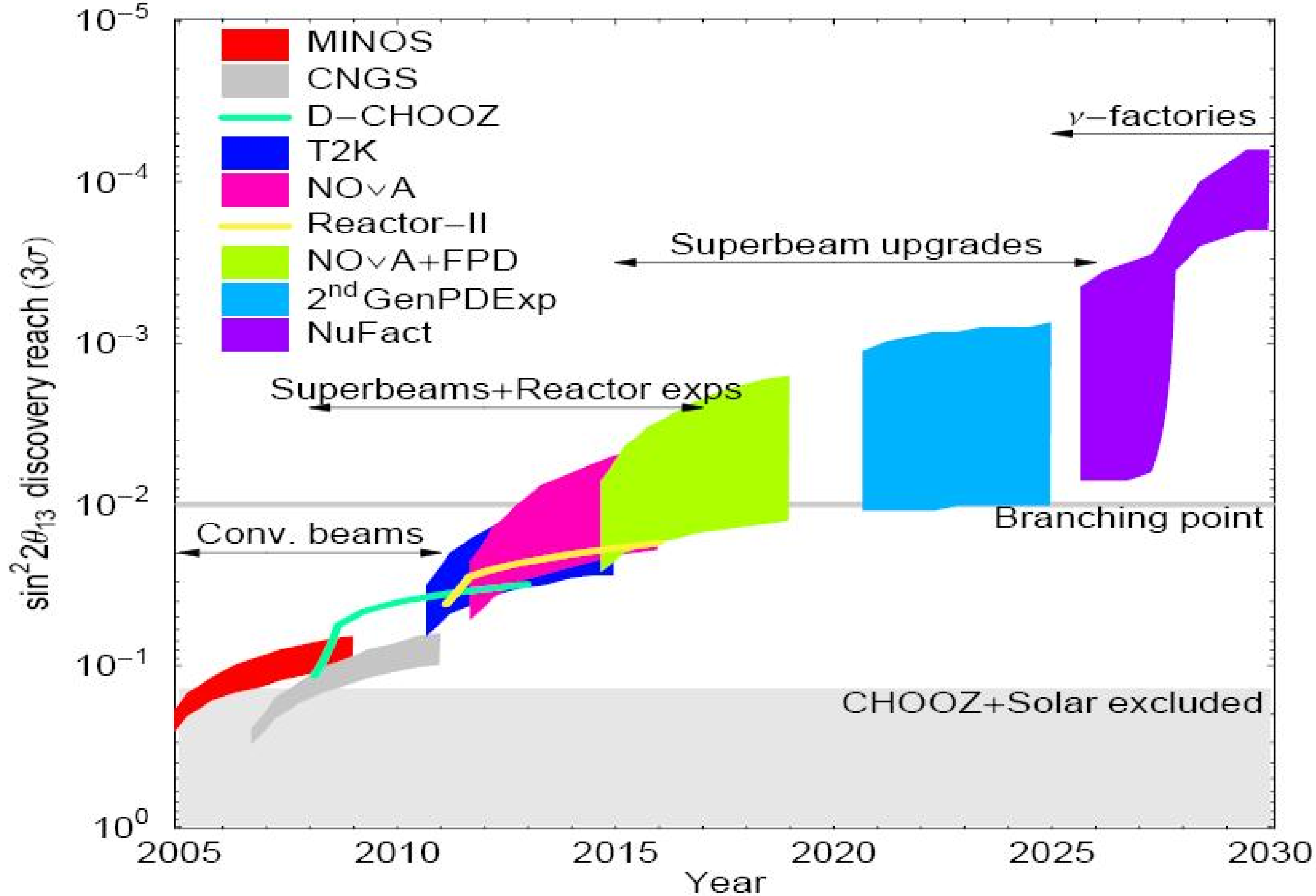


Which one(s) to go for? → ISS

NF can study all ν_e and ν_μ channels

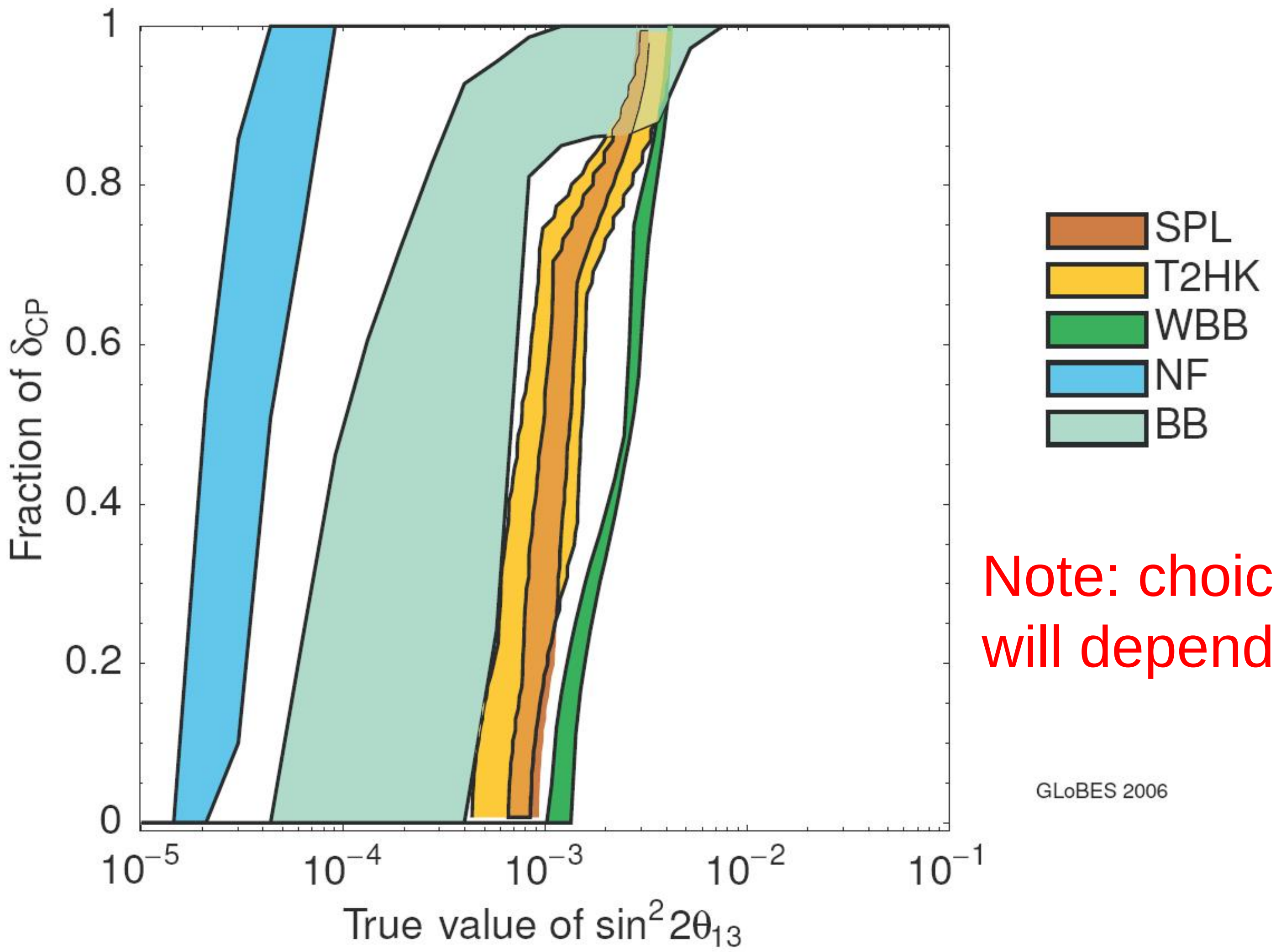
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

Prospects to measure θ_{13}



Prospects to measure θ_{13}

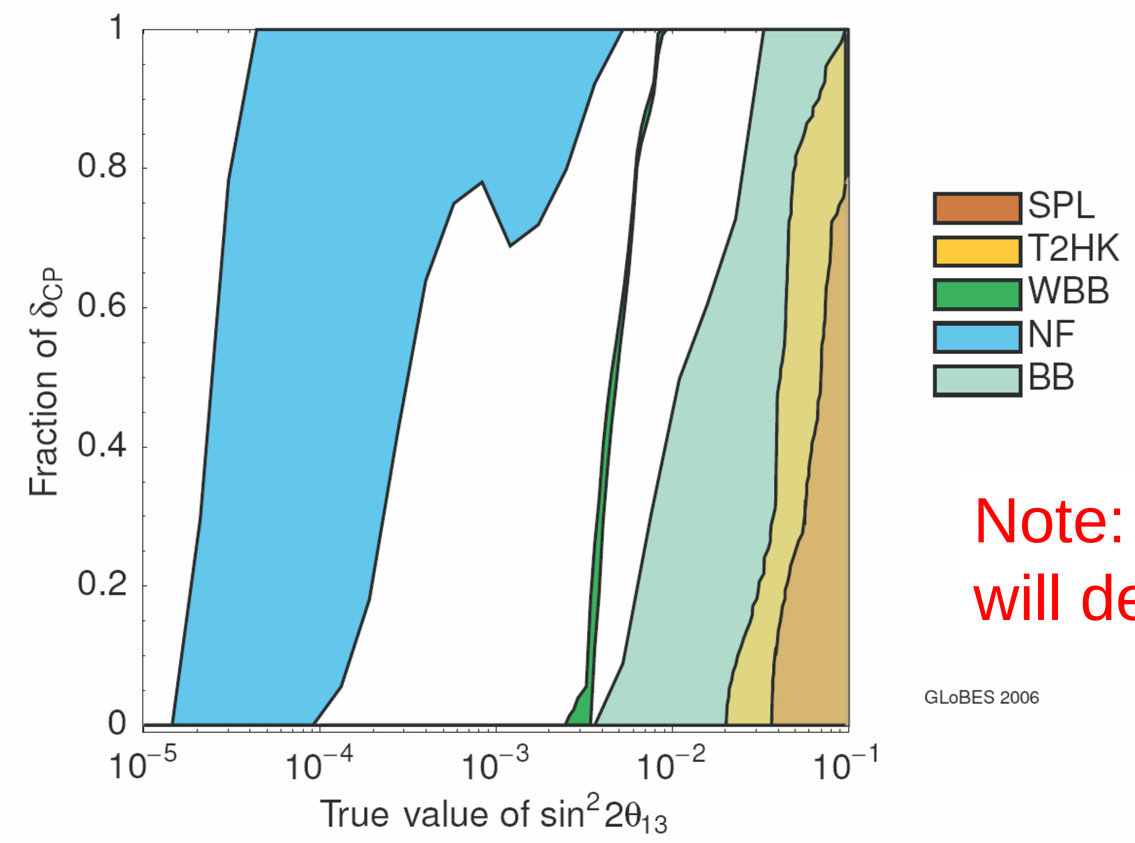
ISS Scoping Study 06



Note: choice of facility will depend on θ_{13}

Prospects to measure the pattern of ν masses

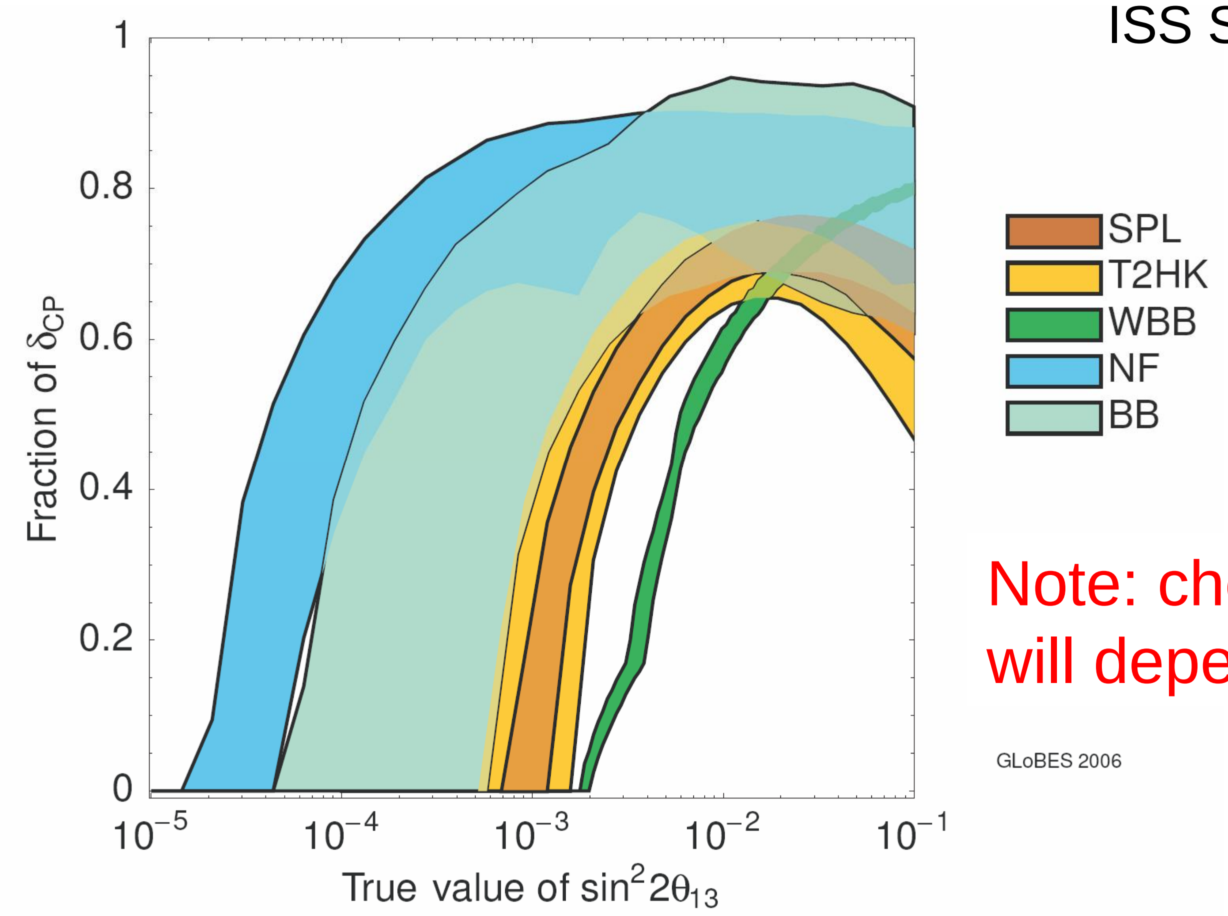
Sensitivity to the Sign of Δm_{23}^2 ISS Scoping Study 06



Note: choice of facility will depend on θ_{13}

Prospects to measure CP Violation

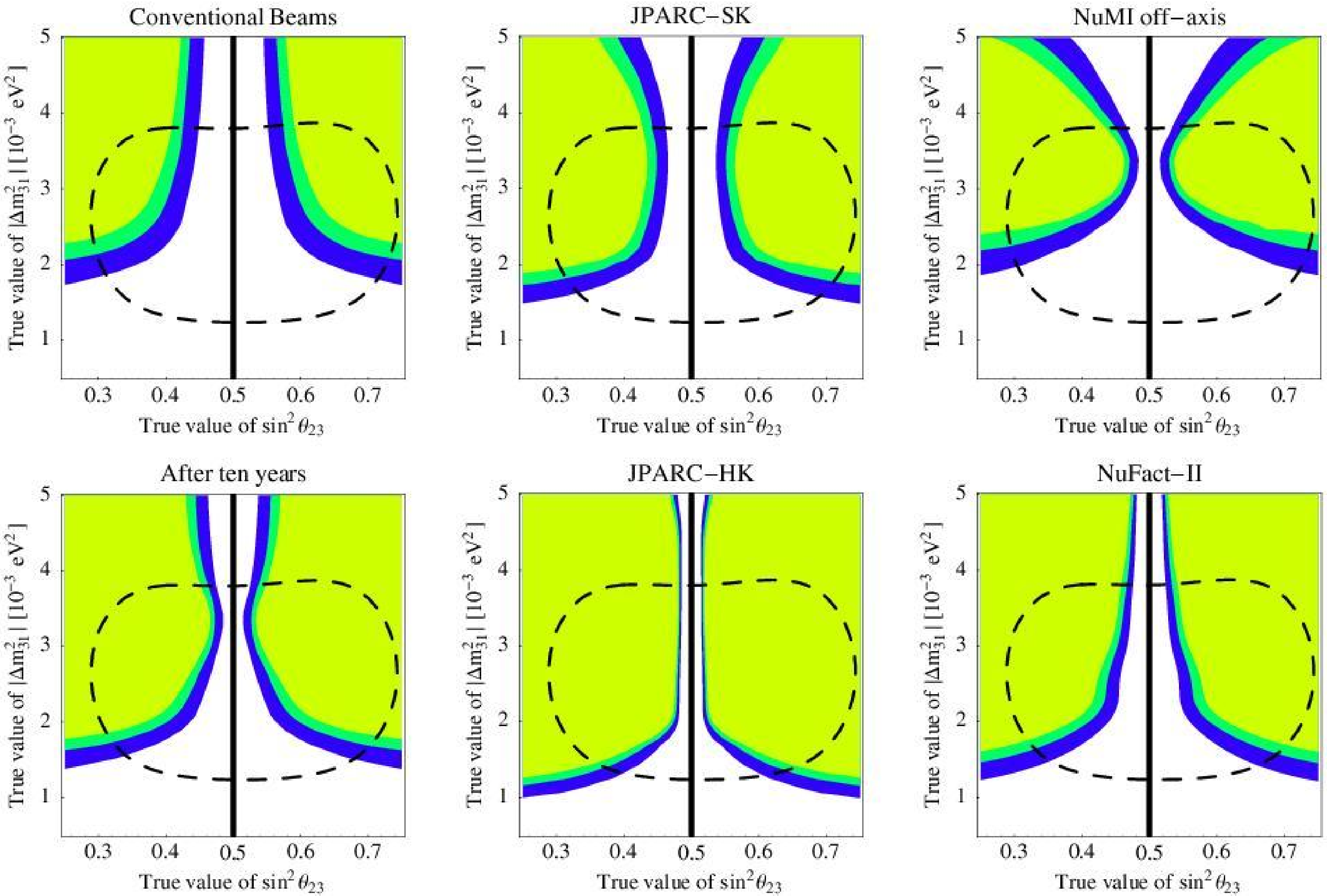
ISS Scoping Study 06



Note: choice of facility will depend on θ_{13}

Prospects to measure a = $s_{23}^2 - 0.5$

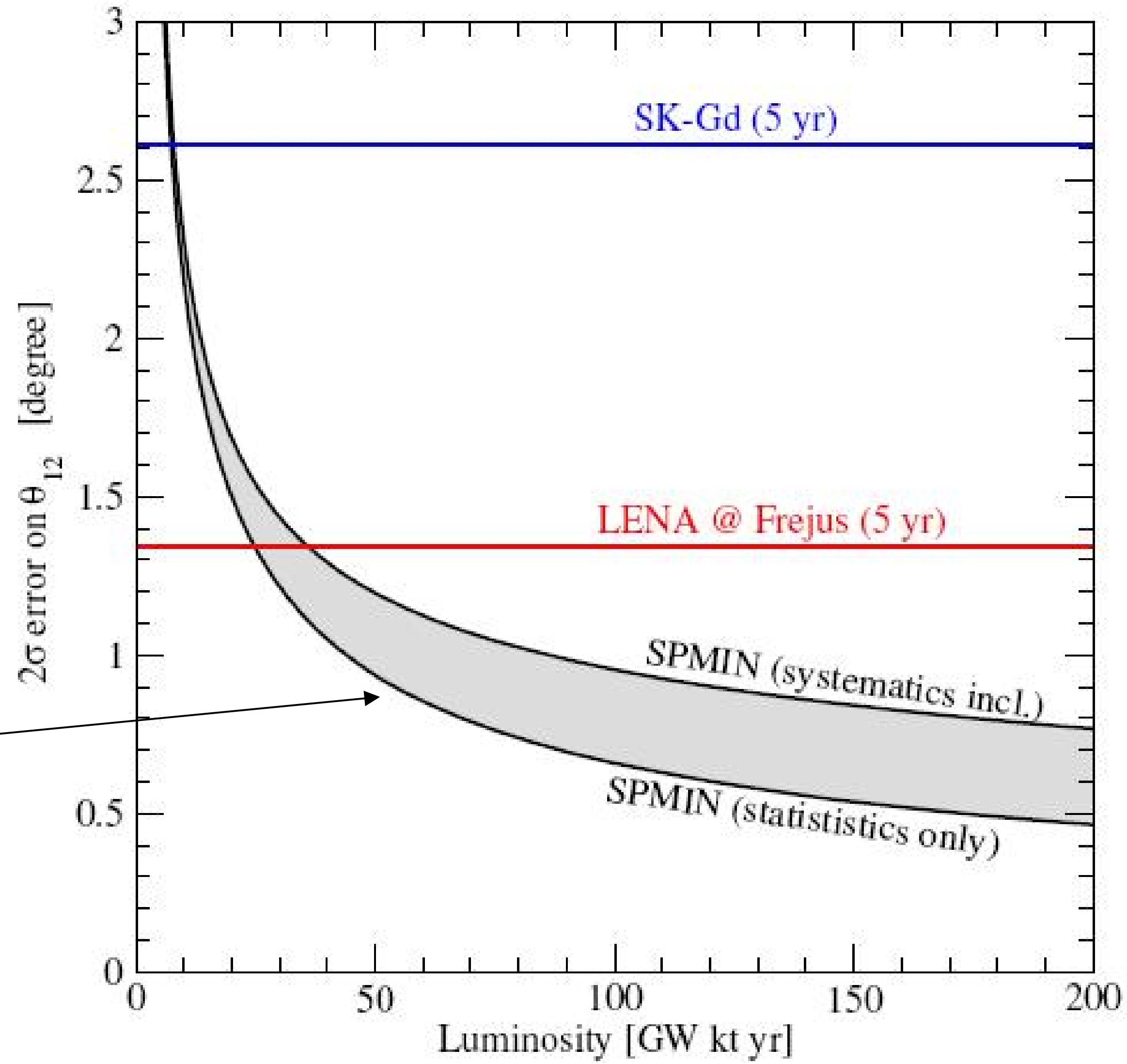
S. Antusch, M. Huber, J. Kersten, T. Schwetz, W. Winter



Prospects to measure the deviation of θ_{12} from 35^o

SPMIN=reactor experiment at the first Survival Probability Minimum

Present 2 σ error



Implications for physics and cosmology

- Origin of tiny neutrino mass

  Extra dimensions, See-saw mechanism, SUSY
- Unification of matter, forces and flavour

  GUTs, Family Symmetry, Strings,…
- Did neutrinos play a role in our existence?

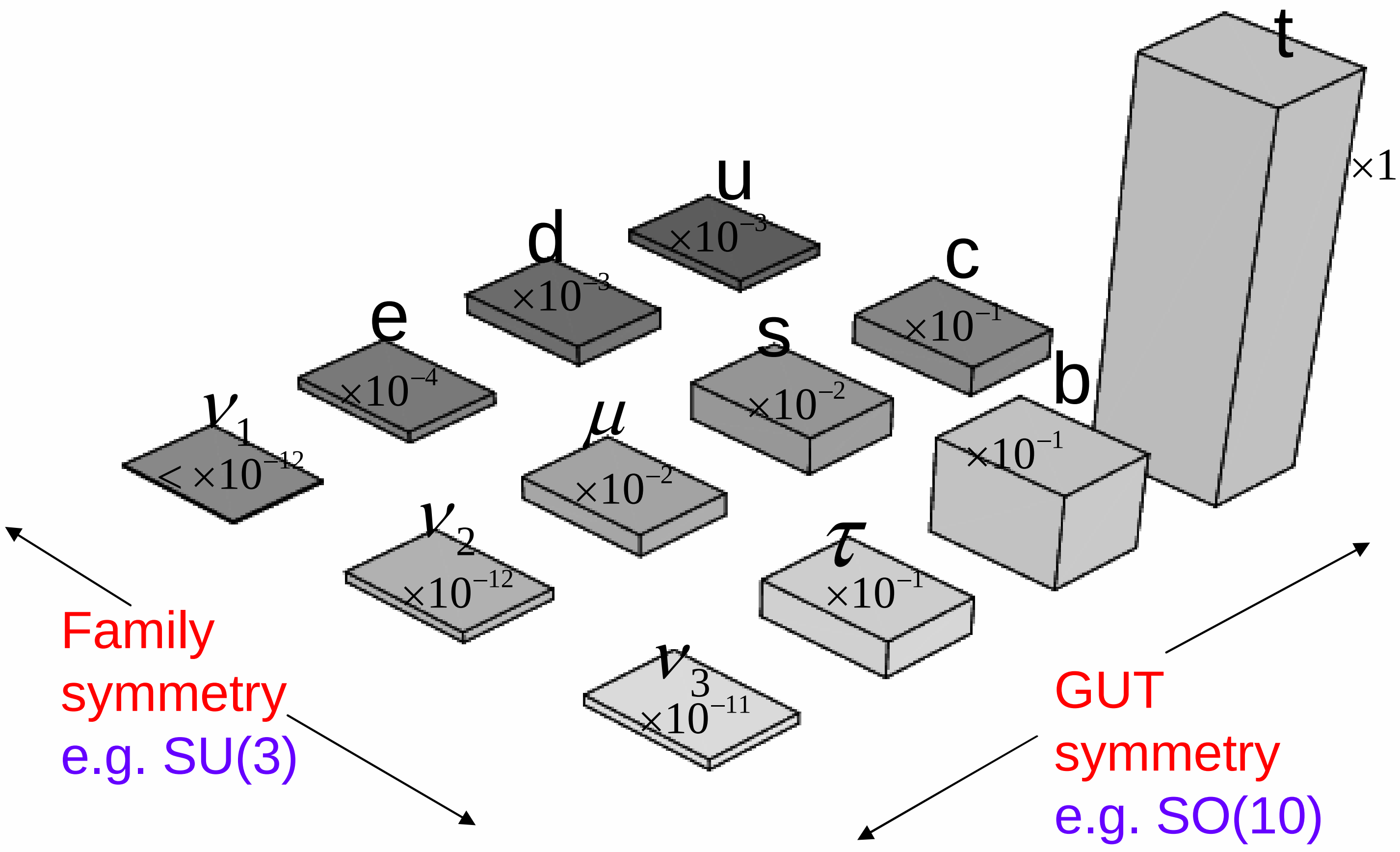
  Leptogenesis
- Did neutrinos play a role in forming galaxies?

  Hot/Warm Dark matter component
- Did neutrinos play a role in birth of the universe?

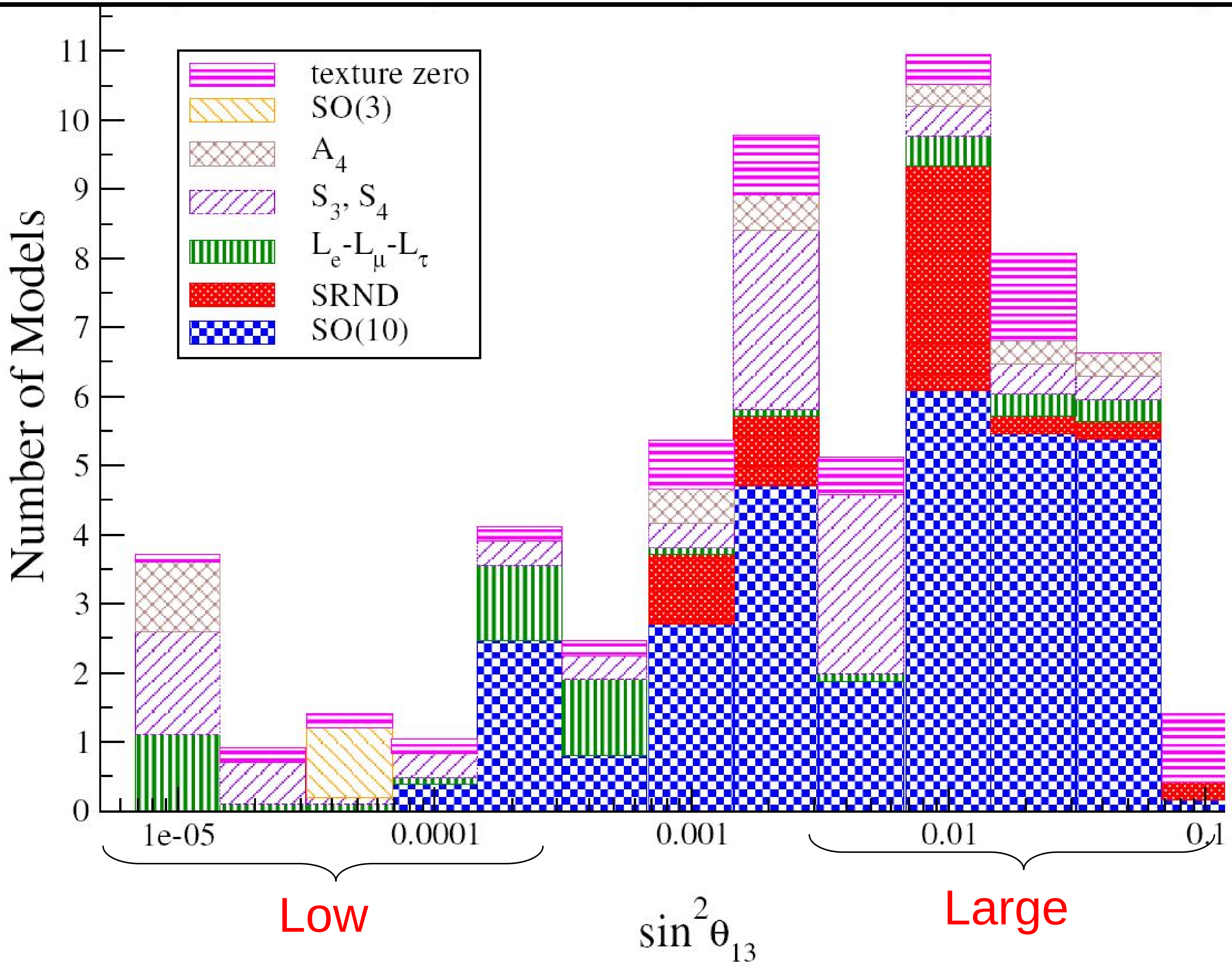
  Sneutrino inflation
- Can neutrinos shed light on dark energy? $\Lambda \sim m_\nu^4$

Cosmology session

Are neutrinos telling us something about unification of matter, forces and flavour?



Survey of predictions for θ_{13} Albright and Chen



Two challenging predictions

Cabibbo

$$\theta_{13}^{o} \approx \frac{\theta_C^{o}}{3\sqrt{2}} \approx 3^{\circ}$$

$$\sin^2 2\theta_{13} \approx 10^{-2}$$

Bjorken,Pakvasa,SFK…

$$\theta_{12}^{o} - 35^{o} \approx \theta_{13}^{o} \cos\delta$$

Sum rule

SFK, Antusch,Masina,…

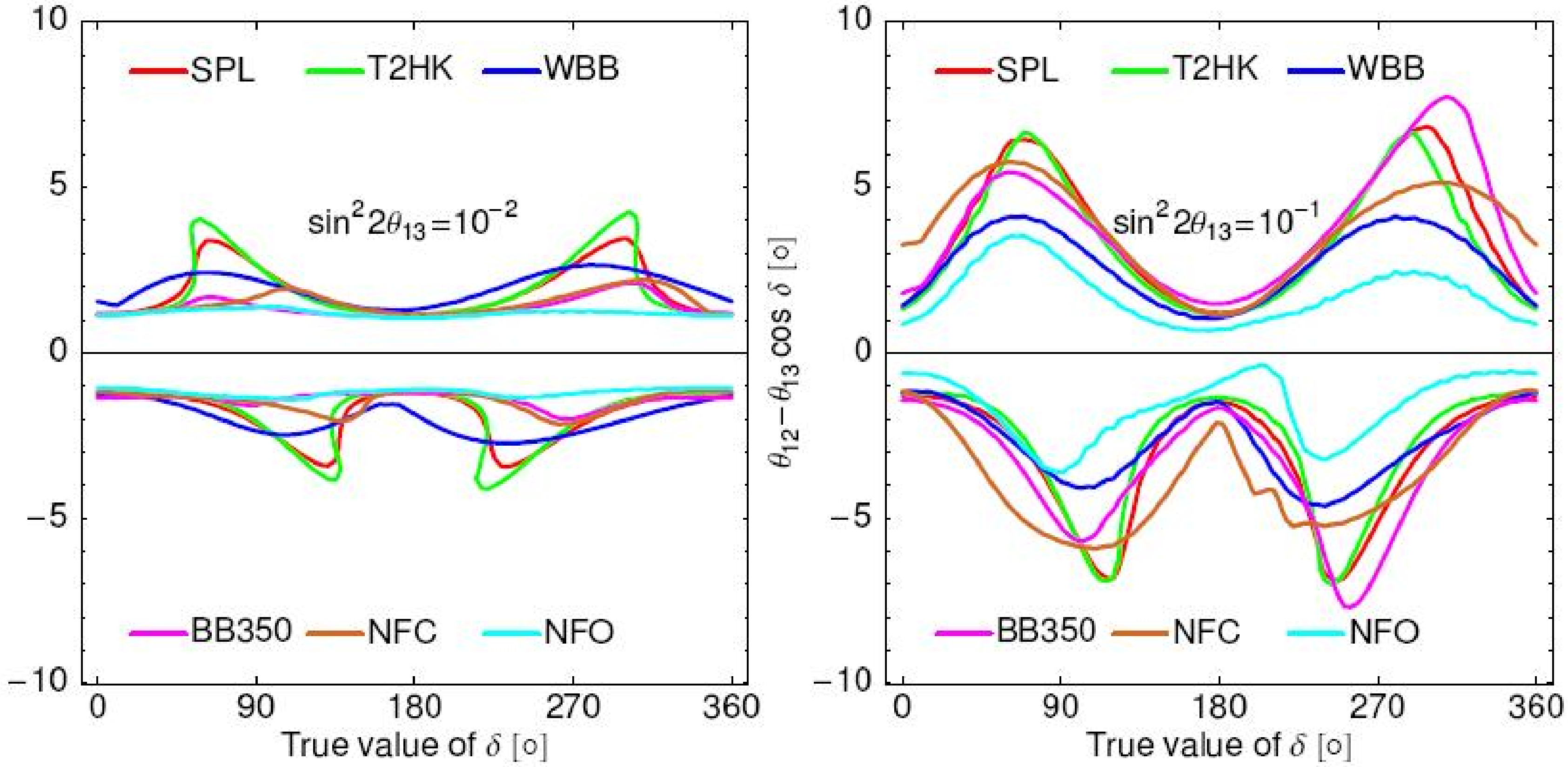
In the TBM parametrization these are recast as

$$s \approx r\cos\delta \qquad\qquad r \approx \lambda / 3$$

Solar Reactor CP phase Reactor Wolfenstein

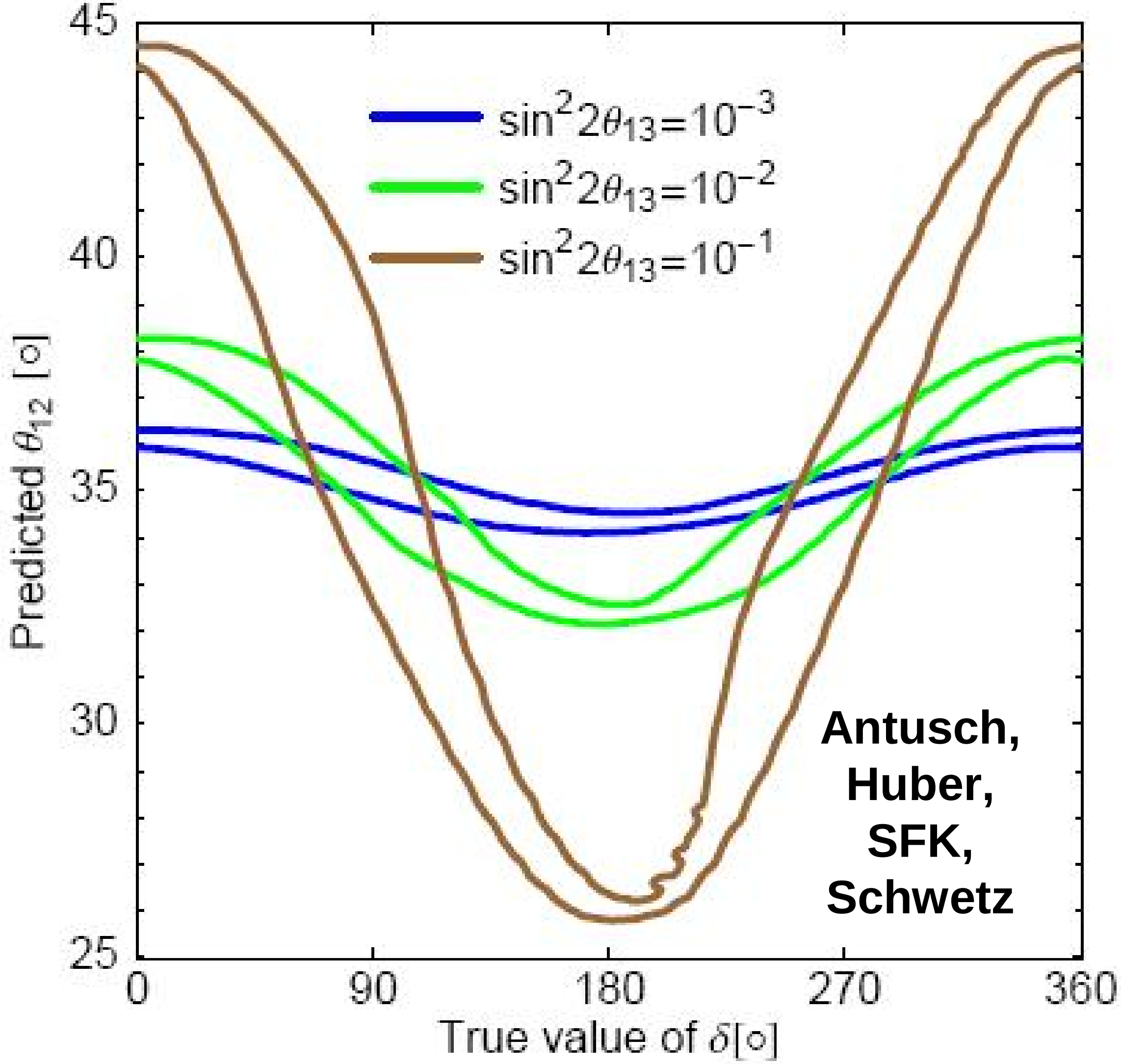
Prospects to measure sum rule combination $\theta_{13} \cos \delta$

3σ error in degrees on $\theta_{13}\cos\delta$



Antusch, Huber, SFK, Schwetz

Sum rule $\theta_{12}^{o} \approx 35^{\circ} + \theta_{13}^{o} \cos\delta$



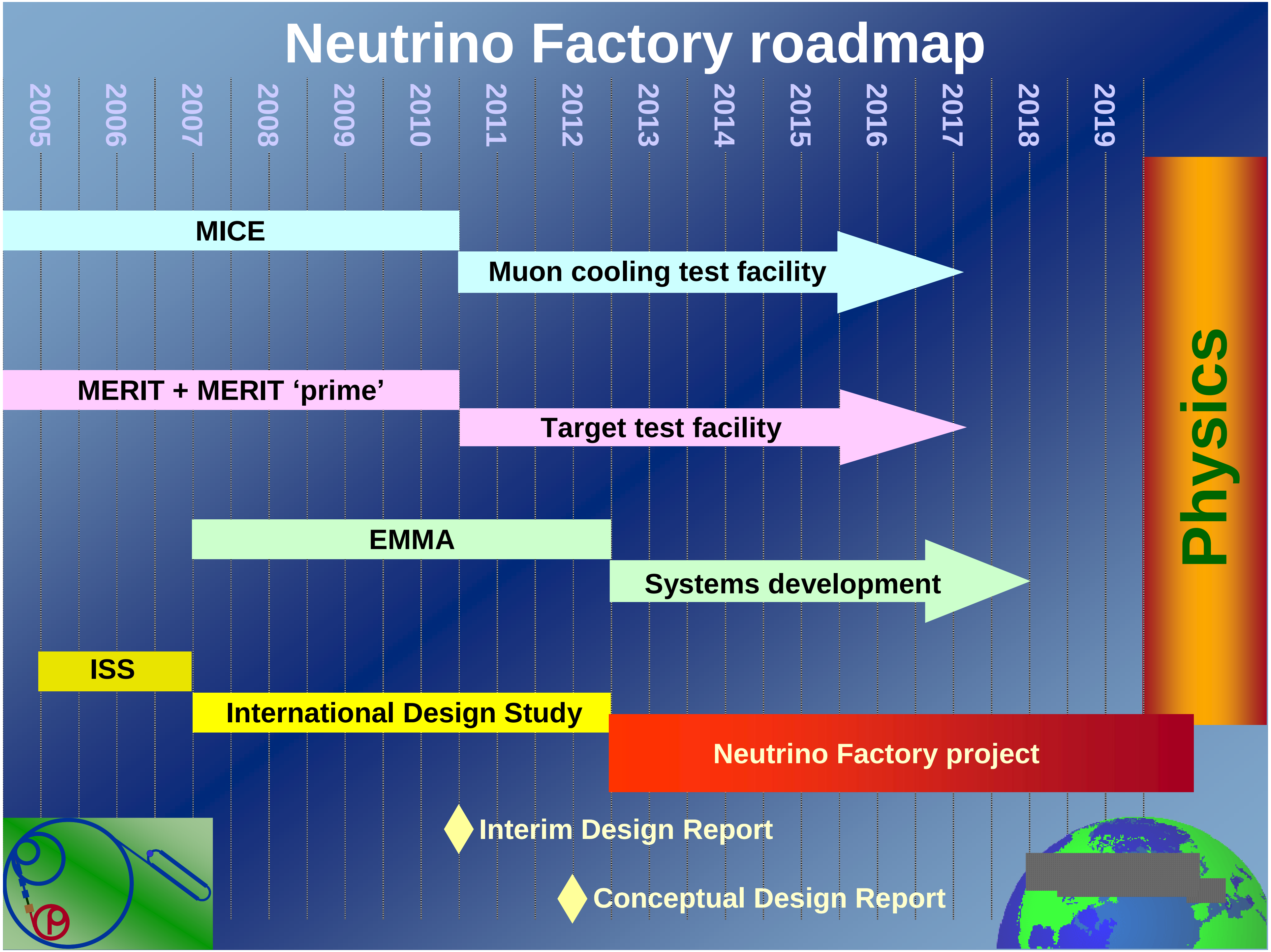
Bands show 3 σ error for an optimized neutrino factory determination of $\theta_{13}\cos\delta$

Current 3σ

$$\theta_{12} = 33^{\circ} \pm 5^{\circ}$$
$$\theta_{23} = 45^{\circ} \pm 10^{\circ}$$
$$\theta_{13} < 13^{\circ}$$

Conclusion

- **1998-2007 has been the golden age of neutrino oscillations – neutrino mass and mixing (beyond SM)**
- **Implications for origin of matter and the Universe**
- **Implications for GUTs and Flavour Models leading to testable predictions e.g. sum rule**
- **Goal of next generation of oscillation experiments is to show that the deviations from TBM r,s,a are non-zero**
- **Challenge for future is to accurately measure r,s,a and δ to relate them to each other and to the Wolfenstein λ**
- **This will not be easy, but, comparing the current options, the neutrino factory emerges as the machine of choice**


Neutrino Factory roadmap
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
MICE
Muon cooling test facility
MERIT + MERIT 'prime'
Target test facility
EMMA
Systems development
ISS
International Design Study
Neutrino Factory project
Physics
Interim Design Report
Conceptual Design Report