Neutrino Oscillation Physics

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CIEMAT, 24 October 2008

The neutrino

The most curious elementary particle
and the one that gave us more surprises

is still a perfect unknown

...because it only interacts weakly

three active neutrinos only

+ the possibility of sterile neutrinos

Flavour mixing
(oscillations)

→

Massive Neutrinos

First evidence of Physics beyond
the Standard Model

Flavour Mixing

ν_e

ν_μ

ν_τ

weak eigenstates

$$\nu_{\alpha L} = \sum_{k=1}^{n} U_{\alpha k} \nu_{kL}$$

m_1

m_2

m_3

mass eigenstates

θ_{23} | θ_{13}, δ_{CP} | θ_{12} | α_1, α_2

PMNS mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric neutrinos

connection between solar and atmospheric

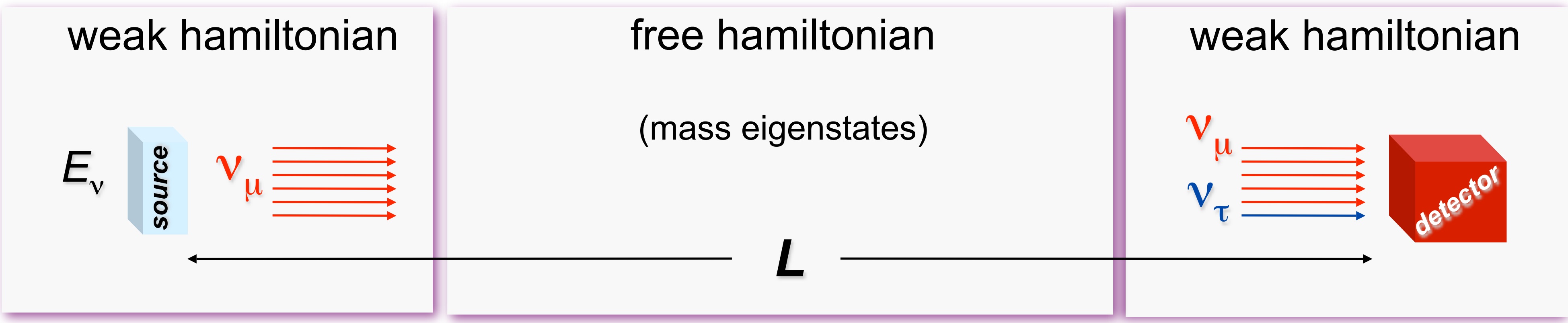
solar neutrinos

Majorana

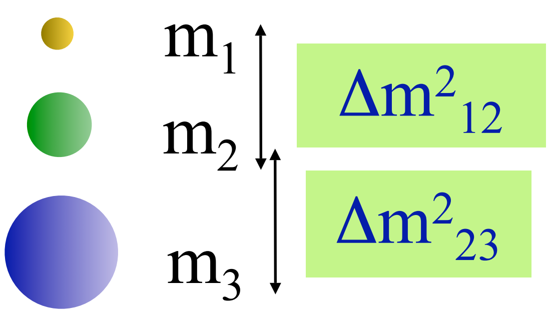
Dirac

Neutrino oscillations

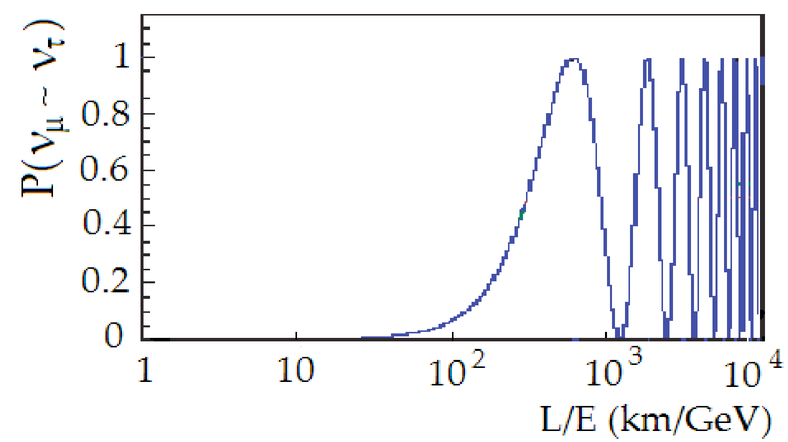
Requirements: Massive neutrinos & different masses



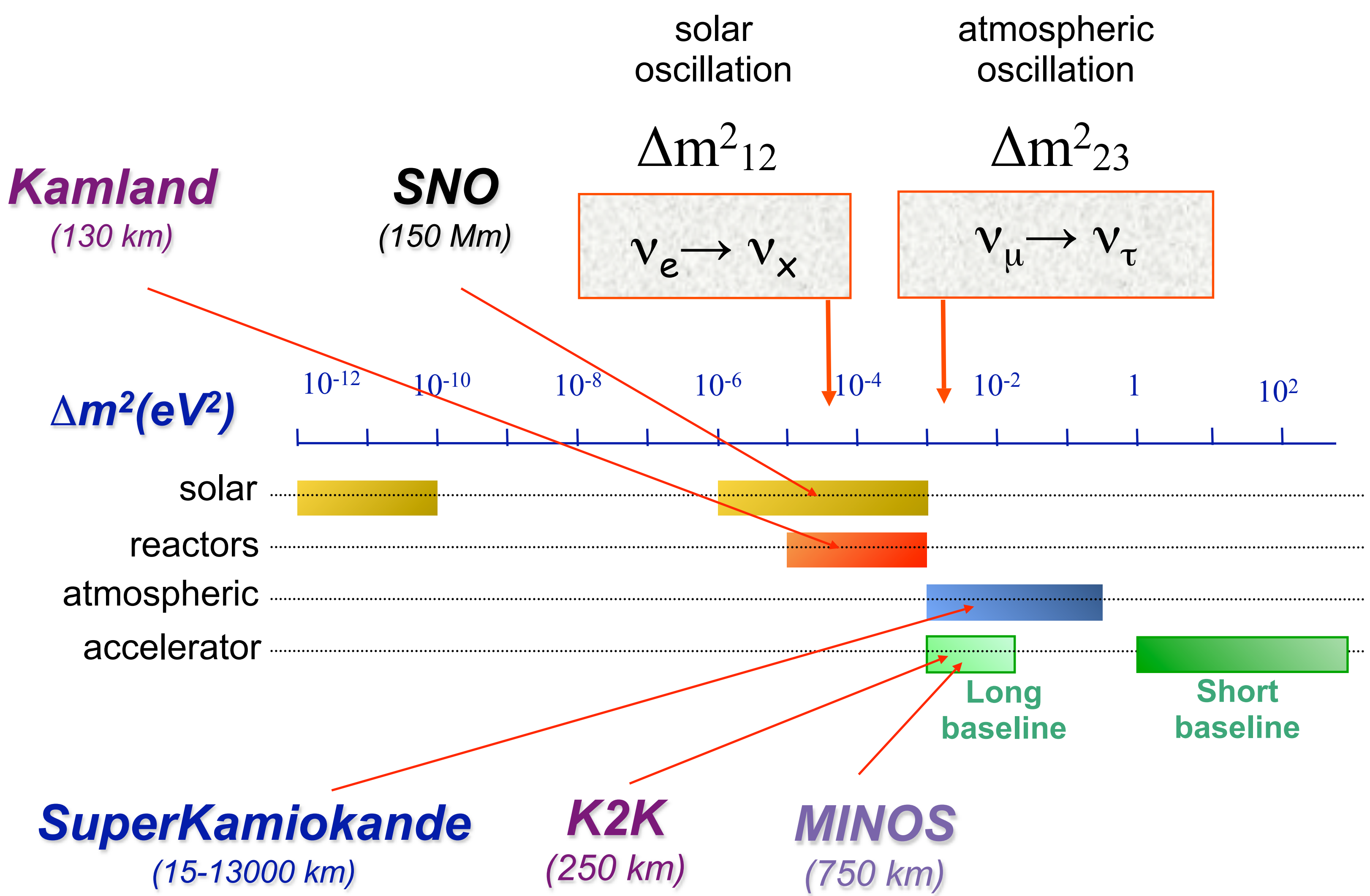
$$P_{\nu_\mu \nu_\tau} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4E_\nu}\right)$$



mass eigenstates



Experimental results I



Experimental results II

Errors from 10 to 30%

$$\Delta m^2_{21} = 7.67^{+0.22}_{-0.21}\ \left({}^{+0.67}_{-0.61}\right) \times 10^{-5}\ \mathrm{eV}^2\,,$$

$$\Delta m^2_{31} = \begin{cases} -2.37 \pm 0.15\ \left({}^{+0.43}_{-0.46}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(inverted hierarchy)}\,, \\ +2.46 \pm 0.15\ \left({}^{+0.47}_{-0.42}\right) \times 10^{-3}\ \mathrm{eV}^2 & \text{(normal hierarchy)}\,, \end{cases}$$

$$\theta_{12} = 34.5 \pm 1.4\ \left({}^{+4.8}_{-4.0}\right)\,,$$

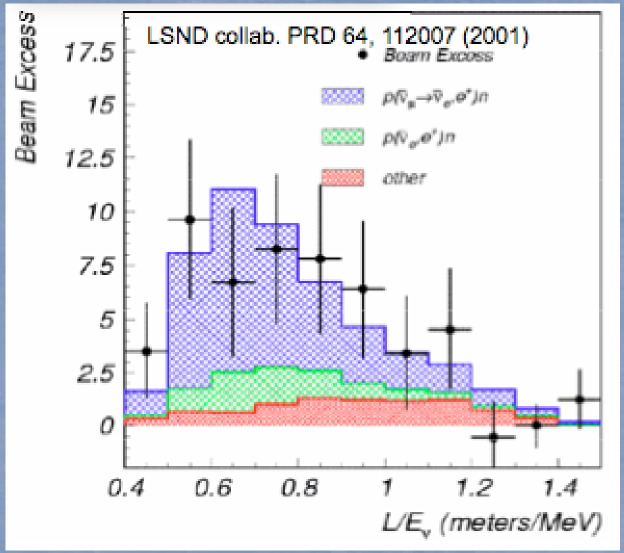
$$\theta_{23} = 42.3^{+5.1}_{-3.3}\ \left({}^{+11.3}_{-7.7}\right)\,,$$

$$\theta_{13} = 0.0^{+3.9}\ \left({}^{+9.0}\right)$$

Still missing

θ_{13}	sign(Δm^2_{23})
δ_{cp}	¿ $\theta_{23} = 45^o$?

Sterile neutrinos



LSND

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

L/E ~ 1

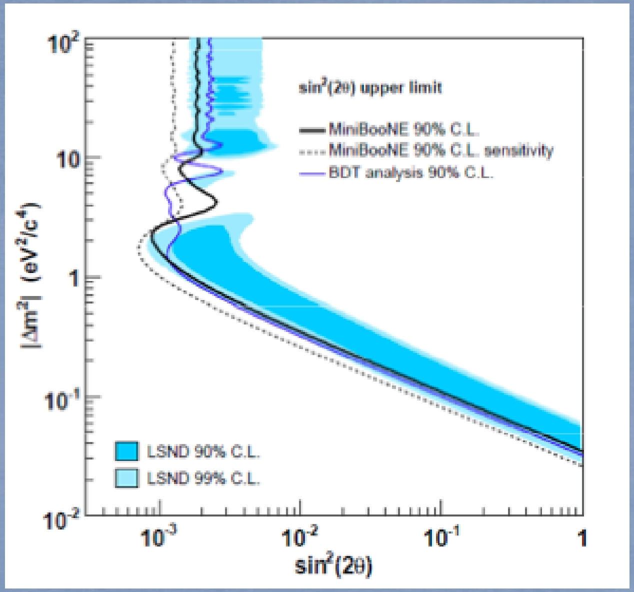
↓

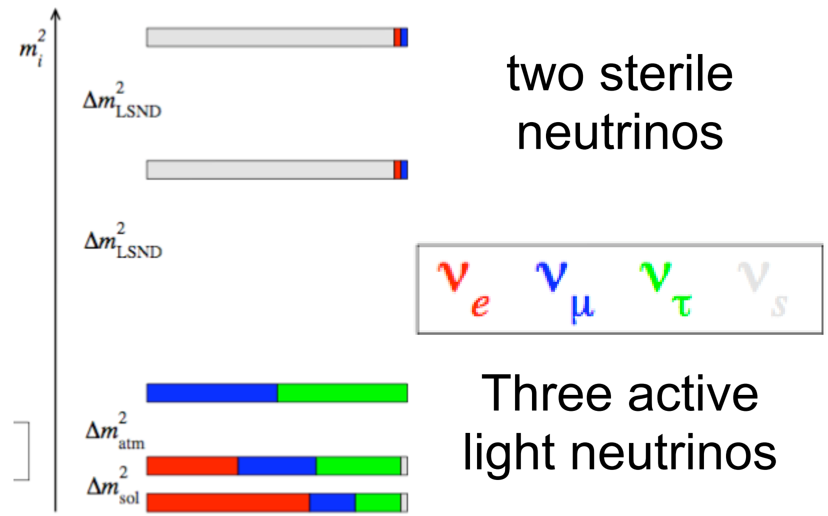
$\Delta m^2 \sim 1$ eV

Incompatible with all other experiments for 3 neutrinos only

MiniBooNE

Excludes the LSND result as two family oscillations





two sterile neutrinos

Three active light neutrinos

The θ_{13} quest

Oscillation length

$$P_{\nu_\mu \nu_\tau} = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L}{4\mathrm{E}_\nu}\right)$$

$$\frac{\Delta m^2 \cdot L}{4E_\nu} = \frac{\pi}{2} \longrightarrow L_{osc} = \frac{2\pi}{\Delta m^2}$$

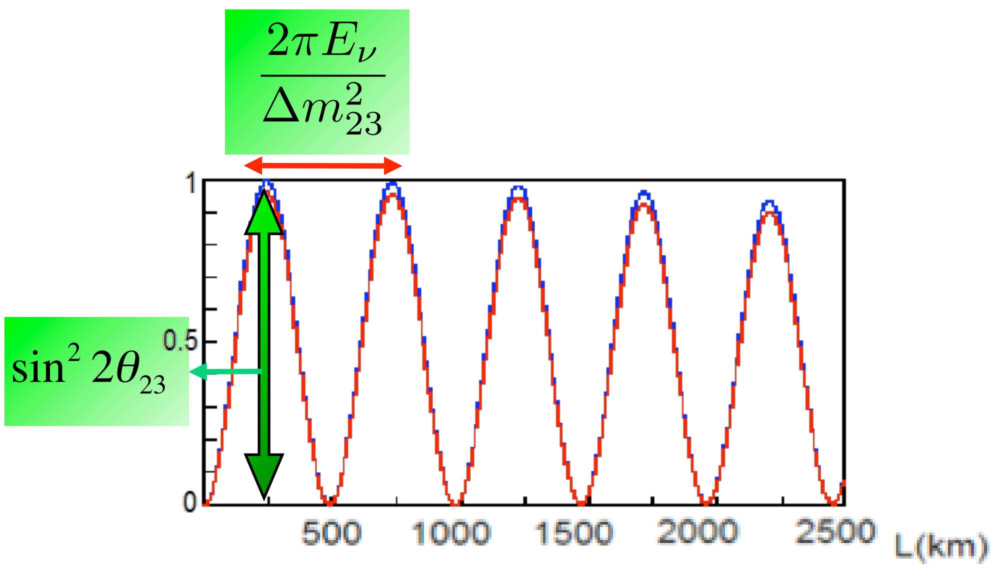
$$L_{osc}^{23} = \frac{2\pi}{\Delta m_{23}^2} \simeq 475\, Km$$

$$L_{osc}^{12} = \frac{2\pi}{\Delta m_{12}^2} \simeq 15500\, Km$$

Subdominant oscillation

	atmospheric	solar	interference
$P(\text{no }\nu_e) \simeq$	$P_{atm}(\theta_{23}, \lvert\Delta m^2_{23}\rvert)$		
$P(\nu_e) \simeq$	$\frac{sin^2 2\theta_{13}}{2} \cdot P_{atm}(\theta_{23}, \lvert\Delta m^2_{23}\rvert)$	$+ P_{sol}(\theta_{12}, \Delta m^2_{12})$	$\pm sin2\theta_{13} \cdot F_{solar} \cdot F_{atm}(sin2\theta_{23}, \lvert\Delta m^2_{23}\rvert) \cdot F(\delta_{cp}, \Delta m^2_{23})$

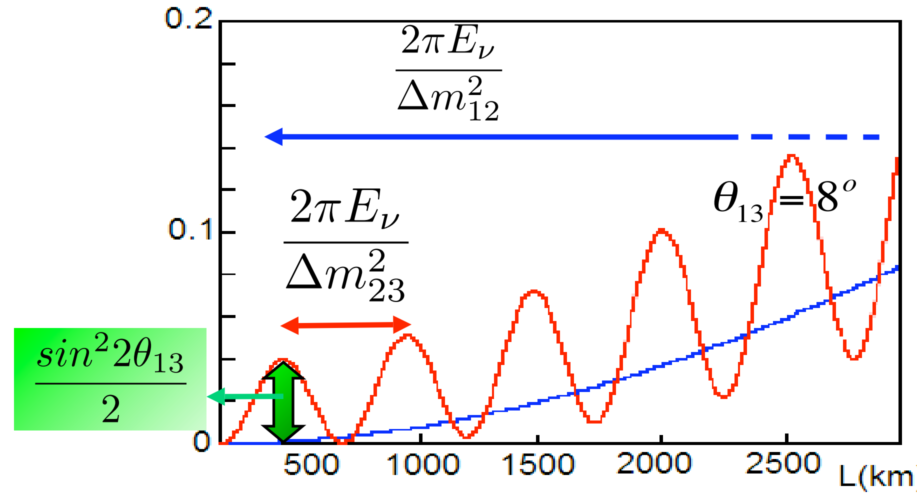
Dominant (no ν_e)



$\nu_\mu \rightarrow \nu_\tau$ OPERA

$\nu_\mu \rightarrow \nu_\mu$ MINOS

Subdominant (ν_e)



$\nu_e \rightarrow \nu_\mu$

$\nu_e \rightarrow \nu_\tau$

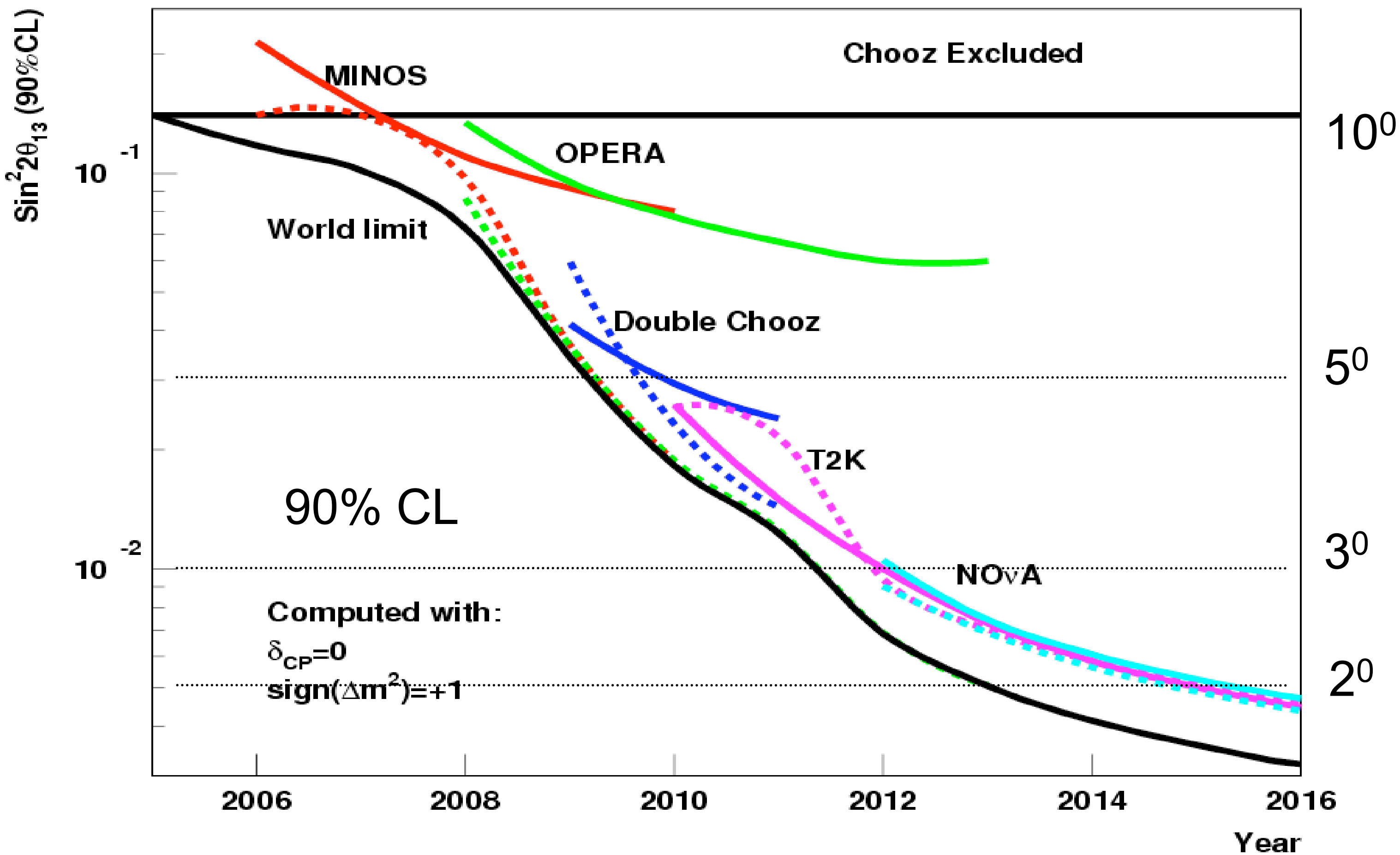
D-Chooz $\nu_e \rightarrow \nu_e$

$\nu_\mu \rightarrow \nu_e$ T2K NOvA

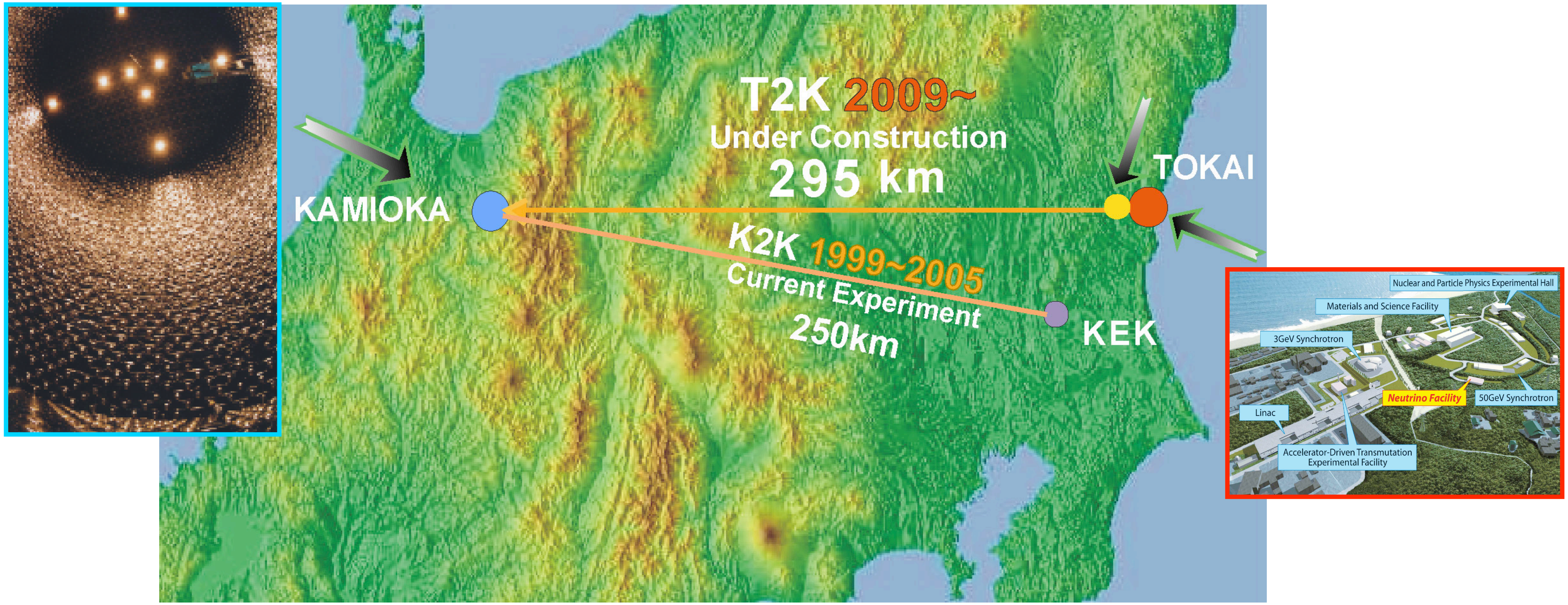
The θ_{13} quest

Subdominant oscillation:

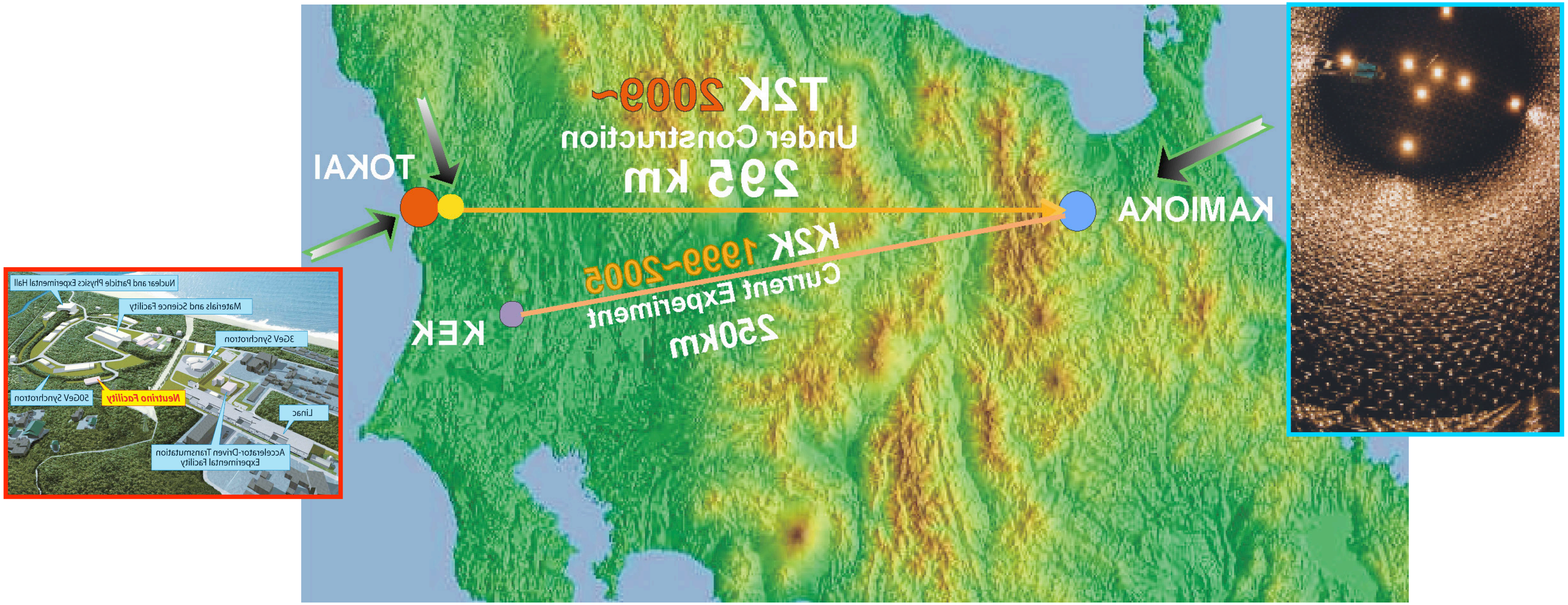
Accelerators	Reactors
$\nu_\mu \longrightarrow \nu_e$	$\overline{\nu}_e \longrightarrow \overline{\nu}_e$

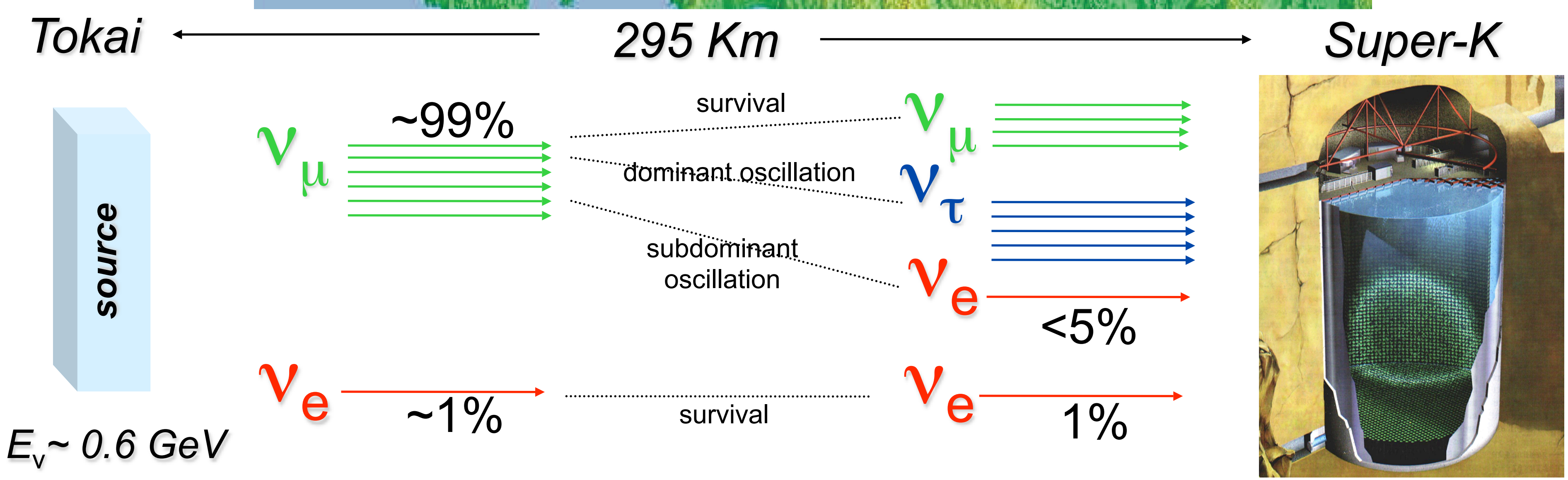


Super-beams I: T2K



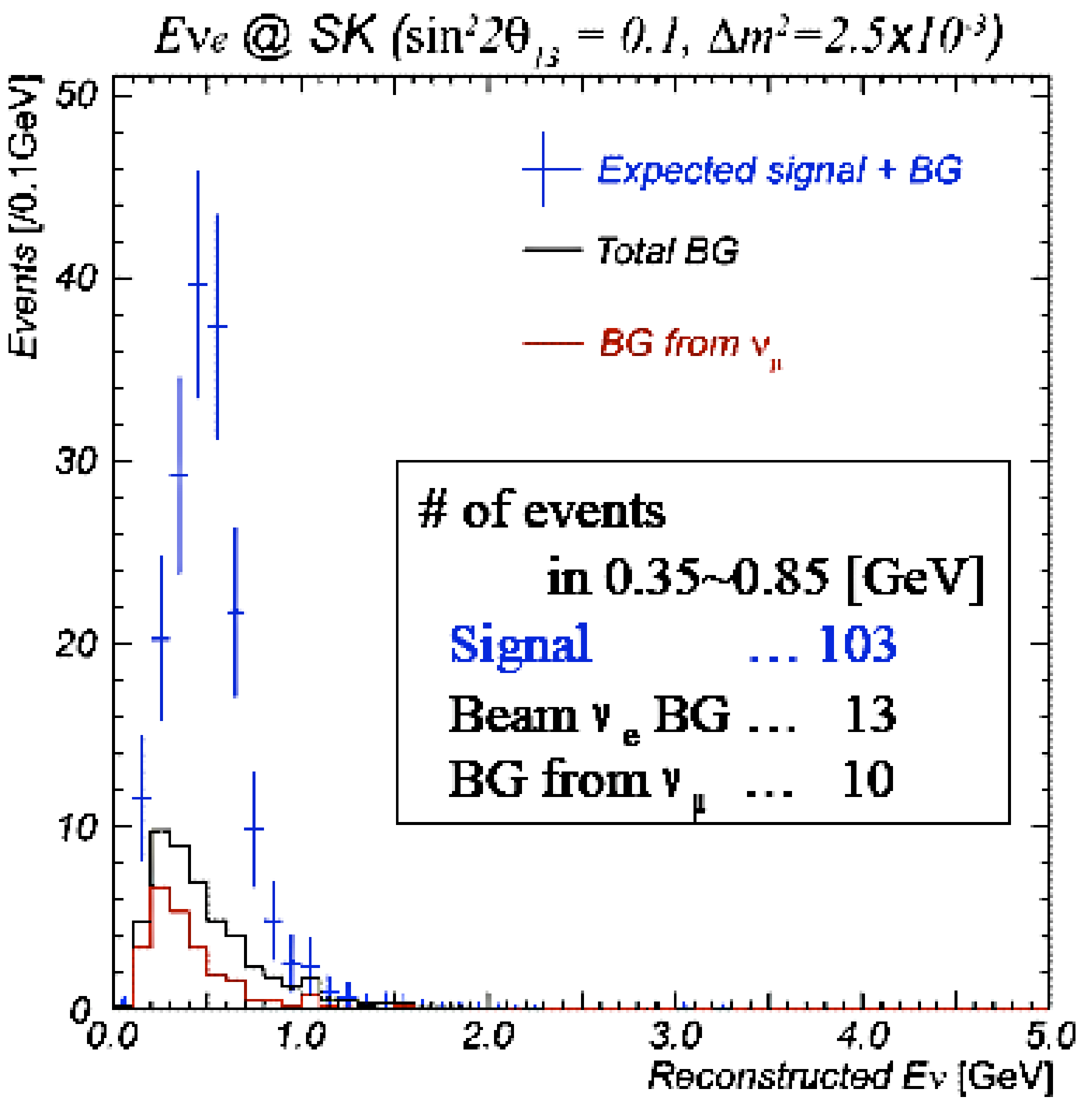
T2K: Tokai to Kamioka





T2K expected sensitivity

$\theta_{13} = 9^o$

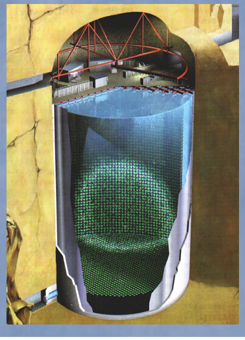


Current status $\theta_{13} < 10^o$

$\sin^2 2\theta_{13} < 0.15$

T2K 1st phase $\theta_{13} \sim 2.5^o$

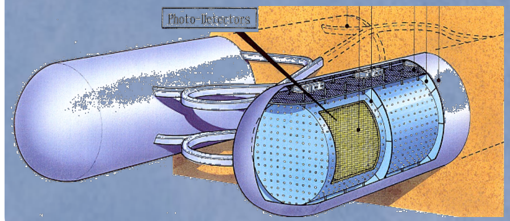
$\sin^2 2\theta_{13} \sim 10^{-2}$



Super-K (50 Kton)

T2K 2nd phase $\theta_{13} \sim 1^o$

$\sin^2 2\theta_{13} \sim 10^{-3}$



Hyper-K (500 Kton)

Reactor neutrinos

$n \rightarrow p + e^- + \overline{\nu}_e$ $E_\nu \sim$ MeV $L_{osc} \sim$ Km

atmospheric | **solar** | **interference**

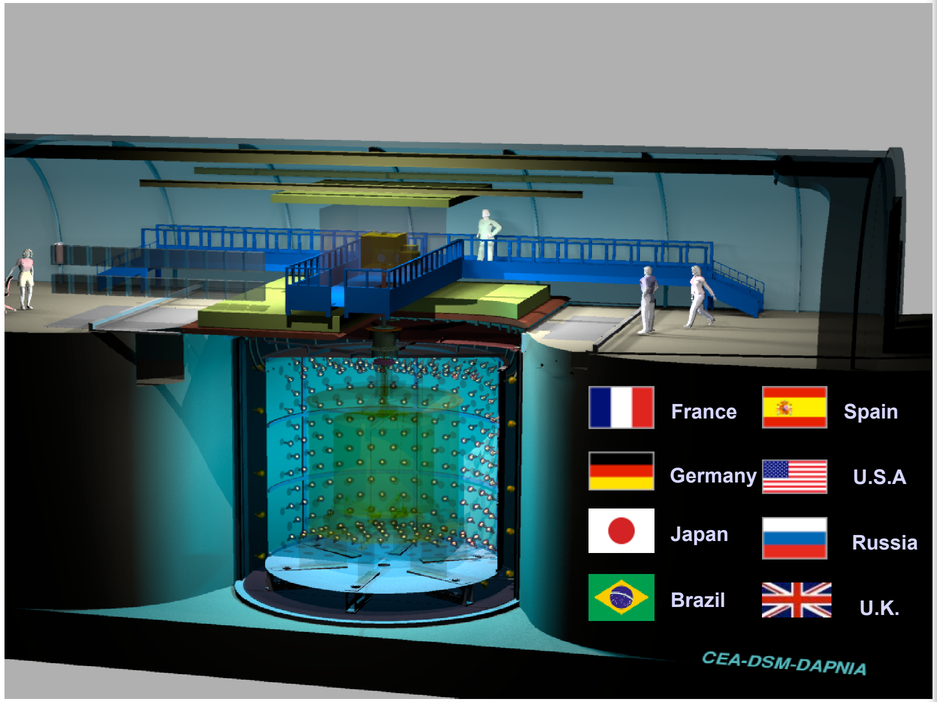
$$P(\nu_e) \simeq \frac{sin^2 2\theta_{13}}{2} \cdot P_{atm}(\theta_{23}, |\Delta m^2_{23}|) + P_{sol}(\theta_{12}, \Delta m^2_{12}) \pm sin2\theta_{13} \cdot F_{solar} \cdot F_{atm}(sin2\theta_{23}, |\Delta m^2_{23}|) \cdot F(\delta_{cp}, \Delta m^2_{23})$$

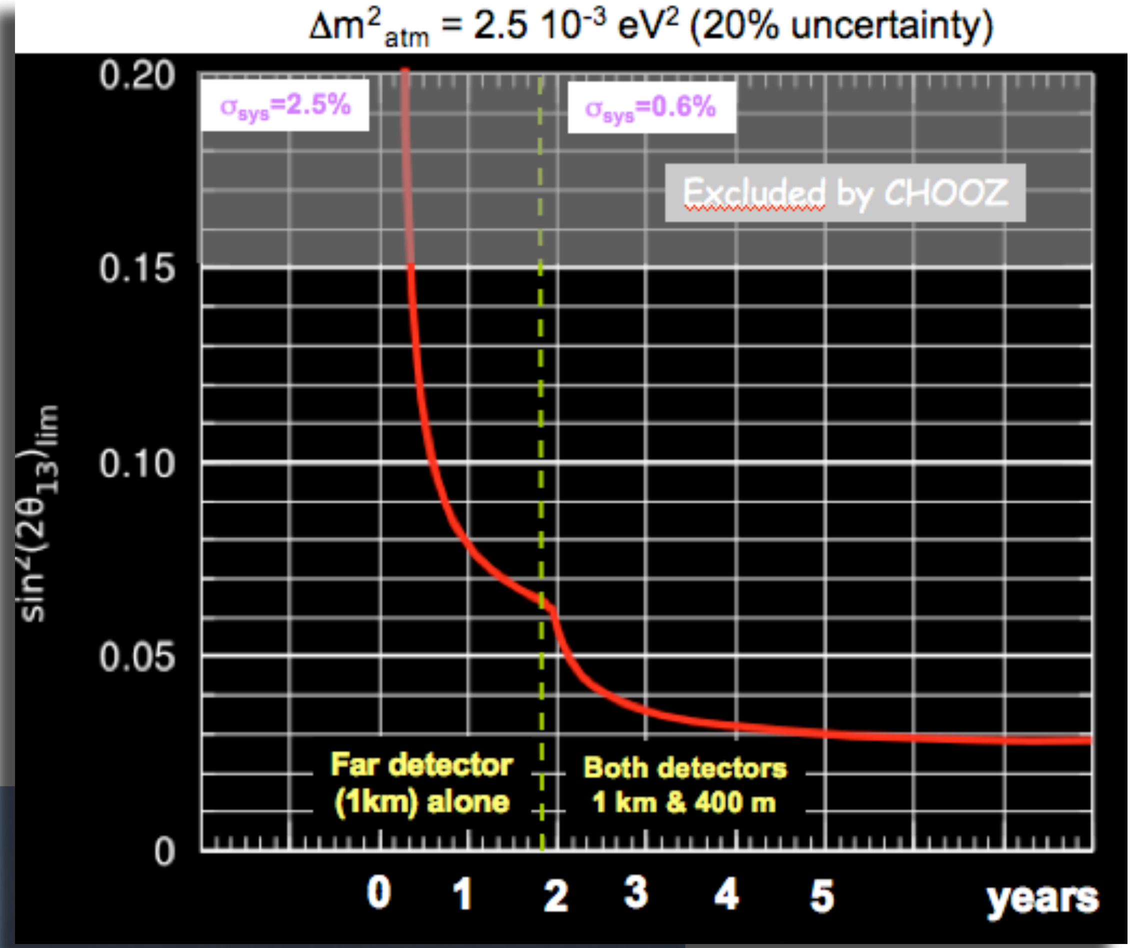
$$P_{\nu_e\nu_e} = 1 - P_{\nu_e\nu_\mu} - P_{\nu_e\nu_\tau} \simeq 1 - sin^2 2\theta_{13} \cdot sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$$

A clean probe of θ_{13}

- Below muon and tau production thresholds: **disappearance**
- Interference term cancels out: **no dependency δ_{cp}**
- Short baseline: **no dependence on mass hierarchy**

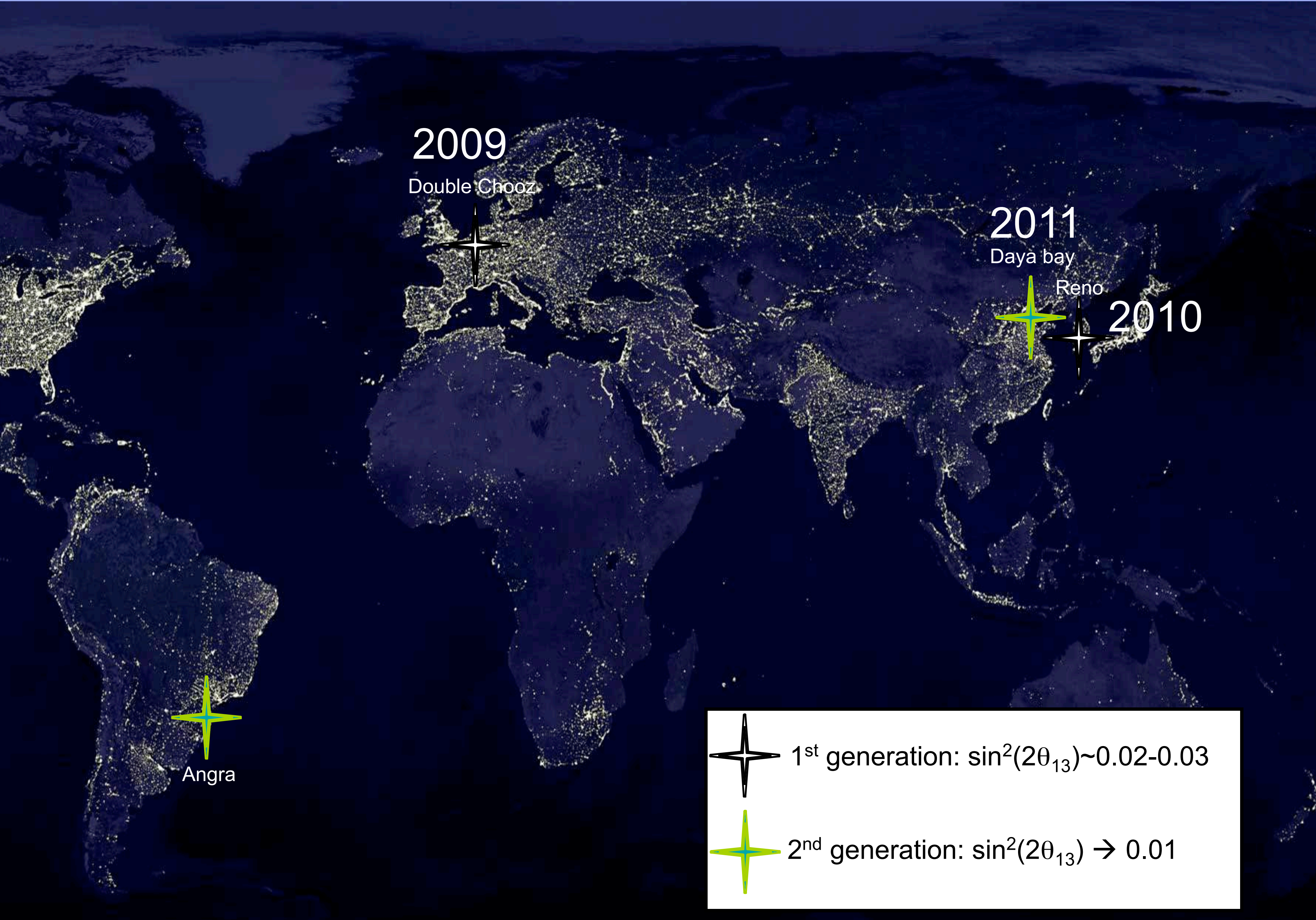
Double-Chooz





Timeline

- **2008-09:** Far detector construction and integration
- **Mid-2009:** Phase I data taking
- **2008-10:** near site and detector
- **2011:** Start of phase II data taking

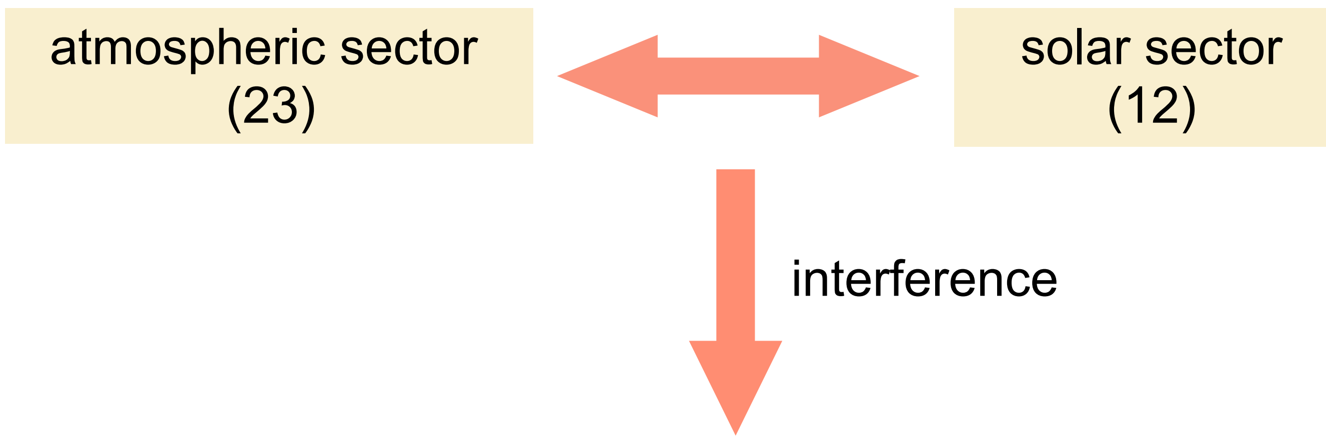


2009
Double Chooz
2011
Daya bay
Reno
2010
Angra
1st generation: $\sin^2(2\theta_{13})$~0.02-0.03
2nd generation: $\sin^2(2\theta_{13}) \rightarrow 0.01$

The path to leptonic CP violation

Beyond T2K and Double-Chooz

If Nature is generous T2K, D-Chooz, ... will observe the subdominant oscillation $\nu_\mu \rightarrow \nu_e$ ($\nu_e \rightarrow \nu_e$) and measure θ_{13}

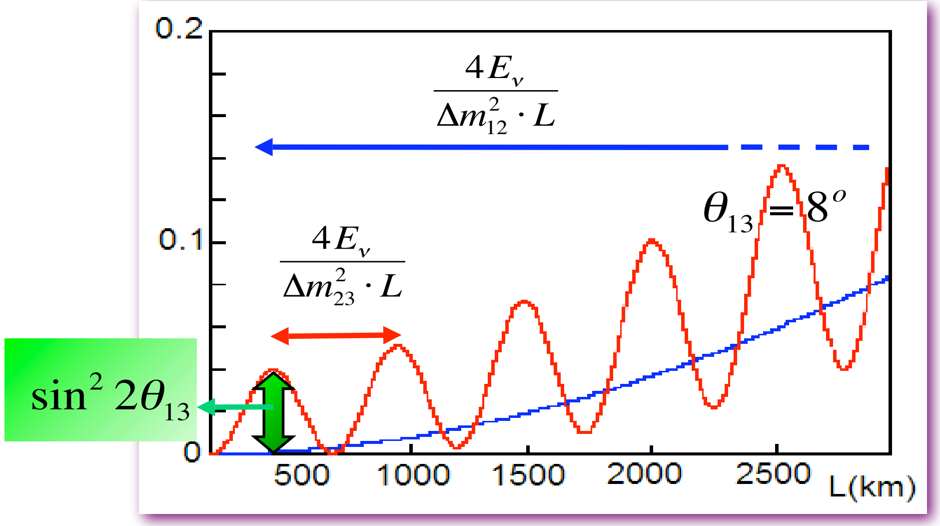


mass hierarchy	$\text{sign}(\Delta m^2_{23})$
CP violation	δ_{cp}

Studying the interference

However, observing a positive interference ($\theta_{13} \neq 0$) is one thing but studying different interference patterns is much more difficult

	atmospheric	**solar**	**interference**
$P(\text{no } \nu_e)$	$\simeq cos^2 2\theta_{13} \cdot P_{atm}(\theta_{23}, \lvert\Delta m^2_{23}\rvert)$		$\pm sin2\theta_{13} \cdot F_{solar} \cdot F_{atm}(sin2\theta_{23}, \lvert\Delta m^2_{23}\rvert) \cdot F(\delta_{cp}, \Delta m^2_{23})$
$P(\nu_e)$	$\simeq sin^2 2\theta_{13} \cdot P_{atm}(\theta_{23}, \lvert\Delta m^2_{23}\rvert)$	$+ P_{sol}(\theta_{12}, \Delta m^2_{12})$	



Correlations and degeneracies

atmospheric | interference | solar

$$P^{\pm}_{e\mu} = X^{\pm}_{\mu} \sin^2 2\theta_{13} + (Y^{\pm}_{c} \cos\delta \mp Y^{\pm}_{s} \sin\delta) \sin 2\theta_{13} + Z_{\mu}$$

Unknown parameters

θ_{13}	sign(Δm^2_{23})
δ_{cp}	¿ $\theta_{23} = 45^{o}$?

correlation of parameters → **degeneracies**

The attack of the clones

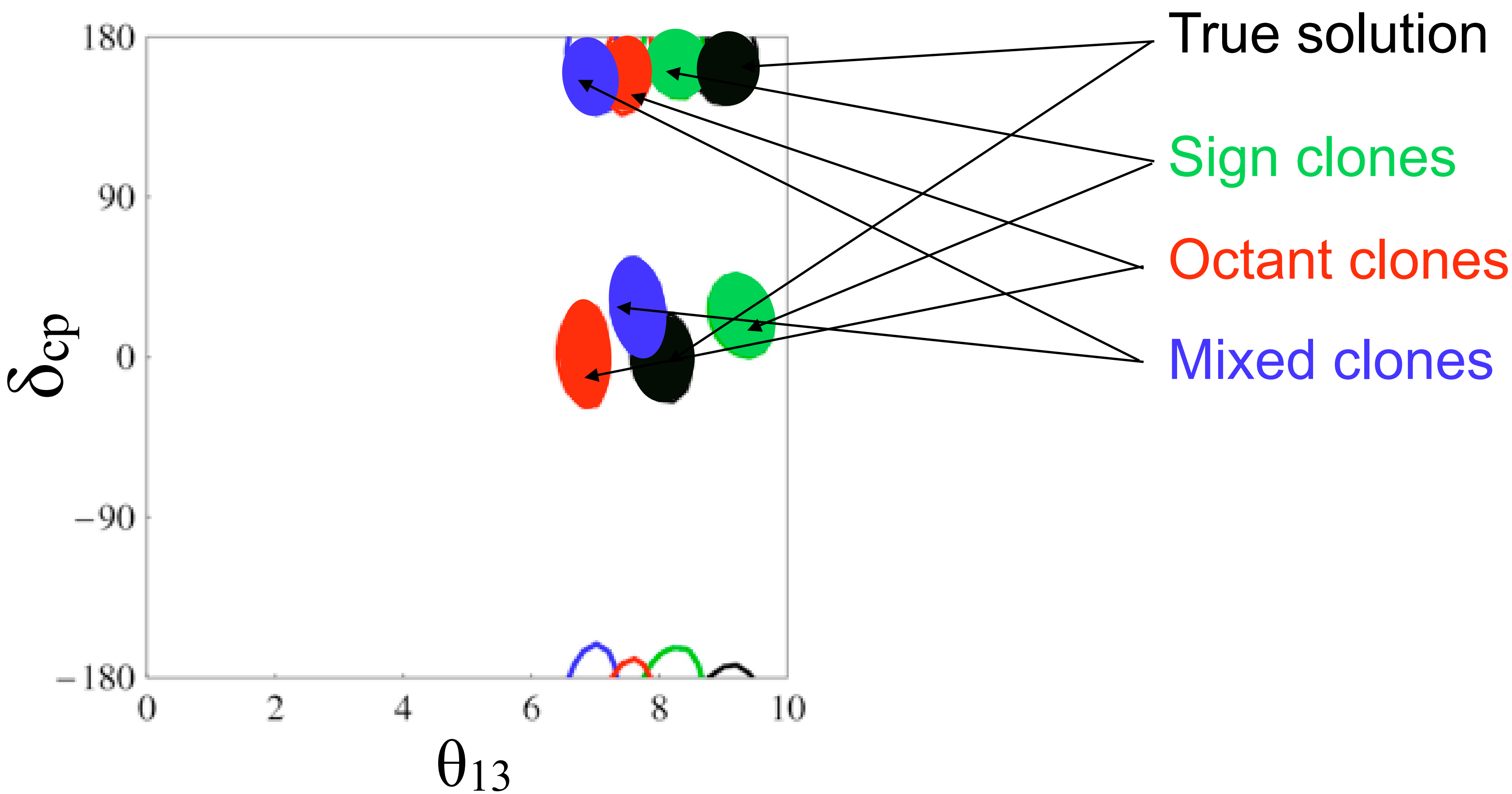
atmospheric | interference | solar

$$P_{e\mu}^{\pm} = X_{\mu}^{\pm} \sin^2 2\theta_{13} + (Y_c^{\pm} \cos\delta \mp Y_s^{\pm} \sin\delta) \sin 2\theta_{13} + Z_{\mu}$$

$\theta_{23}>45^o$ or $\theta_{23}<45^o$ octant

sign Δm^2_{23}

$\theta_{23}>45^o$ or $\theta_{23}<45^o$ octant



Solving degeneracies

degeneracy solvers

- several channels
- several energies
- several baselines

→

maximises the synergies with other Physics

- unitarity
- dark matter
- T violation
- CPT tests
- ...

Beam options

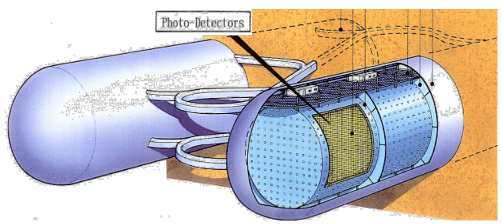
Super beams II

π^+

~99% ν_μ

~1% ν_e

< 5 GeV

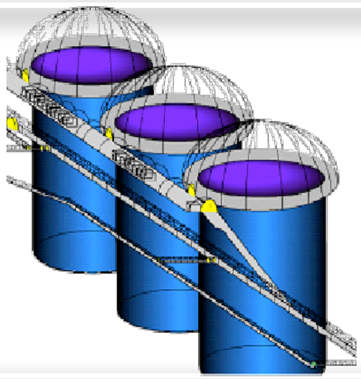


Beta beam

$^{18}_{10}Ne$

100% ν_e

< 5 GeV



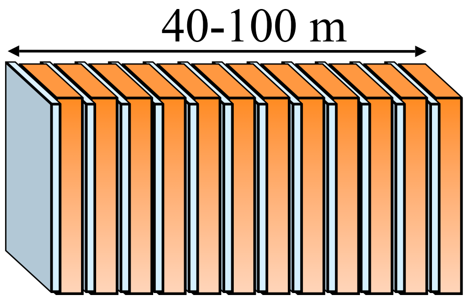
Neutrino factory

μ^+

50% $\bar{\nu}_\mu$

50% ν_e

<20-50 GeV



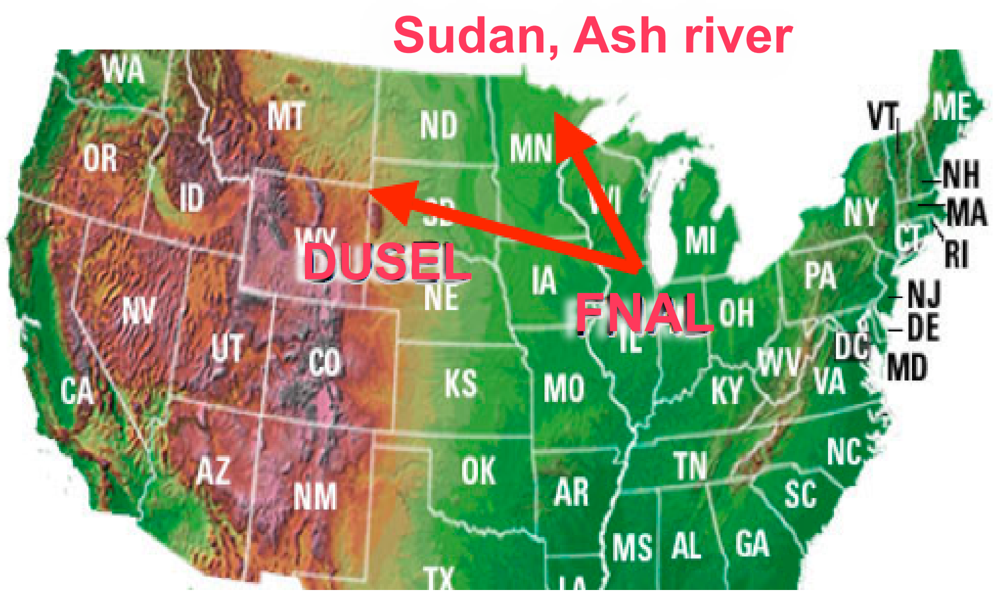
Super beams II

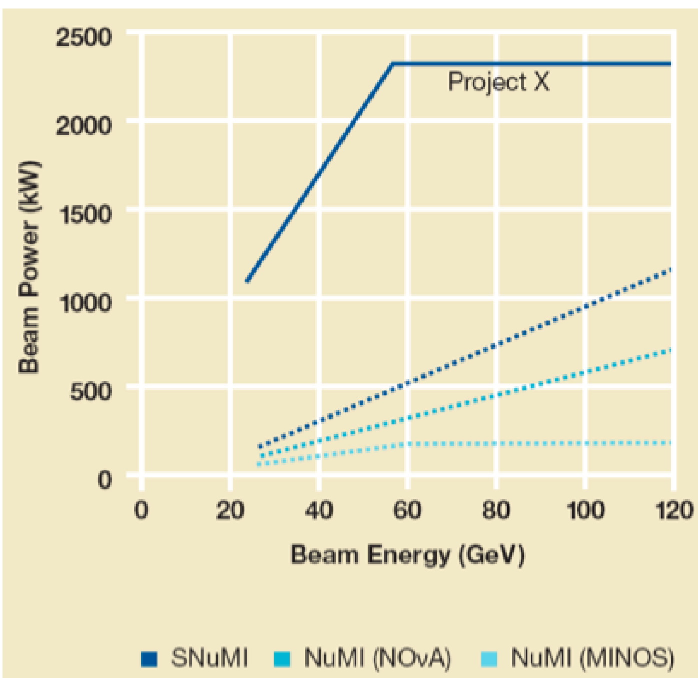
strategy

- More powerful beams (x 10)
- Bigger detectors (x 10)
- Longer distances to explore mass hierarchy (> 800 Km)

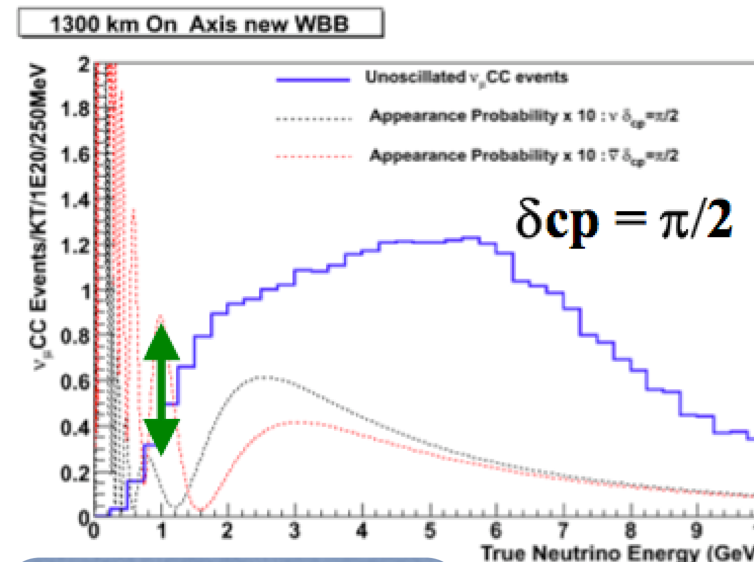
wide band beams versus off-axis beams

Fermilab programme

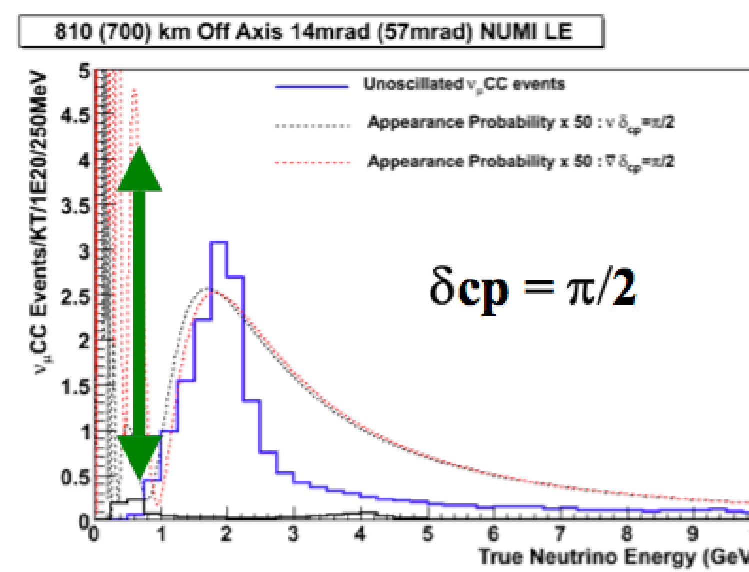




on-axis (Wide Band Beam)



off-axis beam

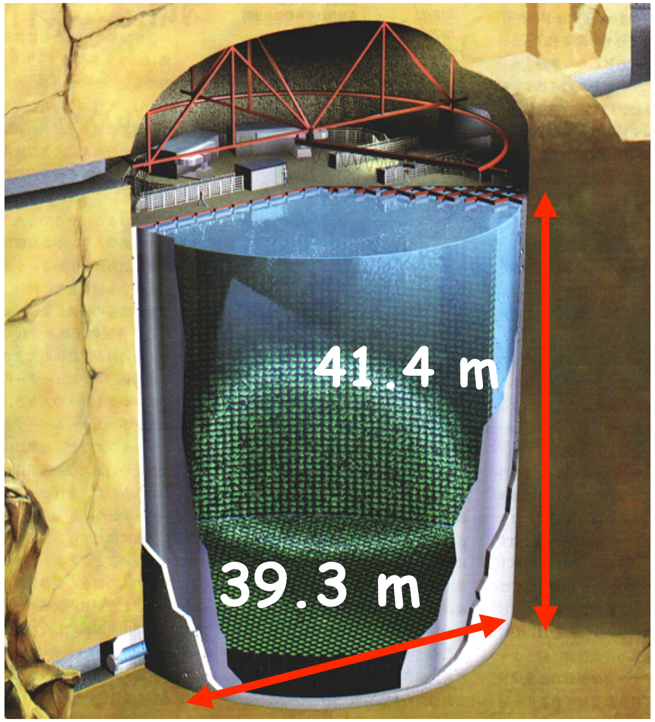


JPARC programme

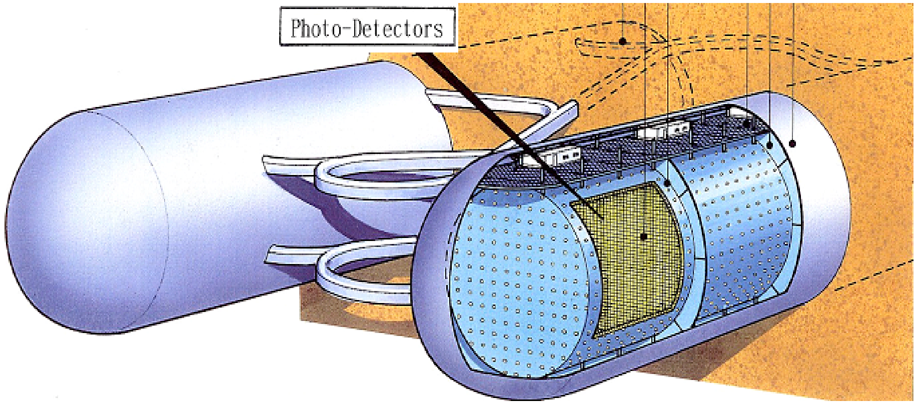
Linac : 181 MeV to 400 MeV

0.60MW
0.28 Hz → 0.91 MW
0.57 Hz → **1.66MW**
0.52 Hz

50 Kton

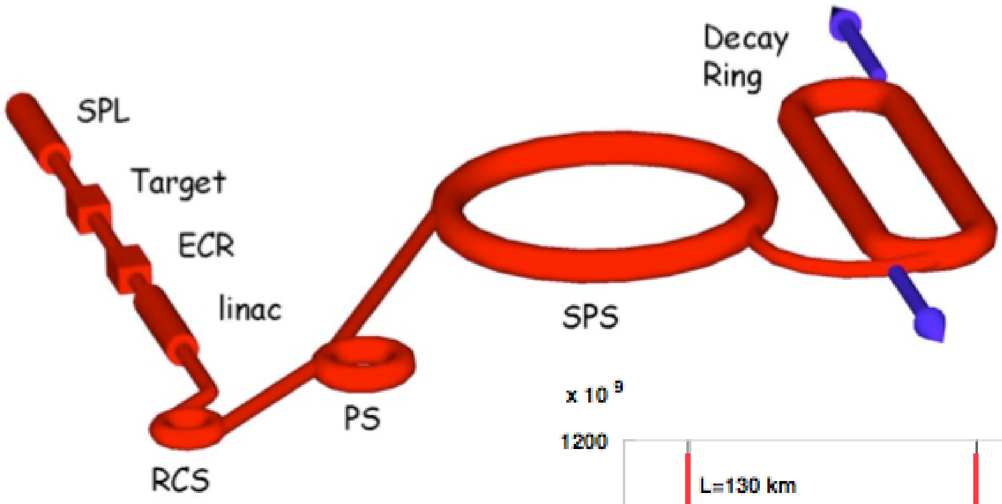


500 Kton

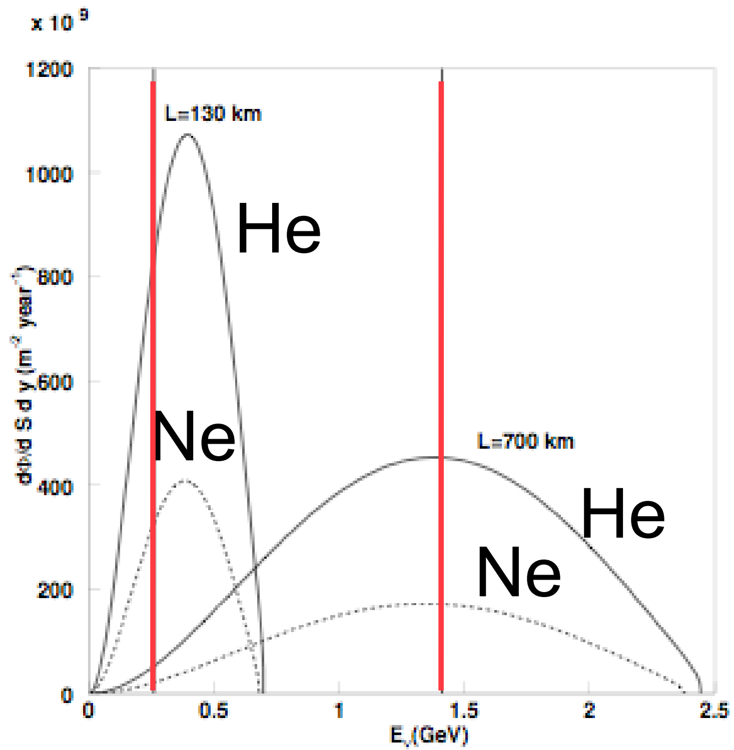


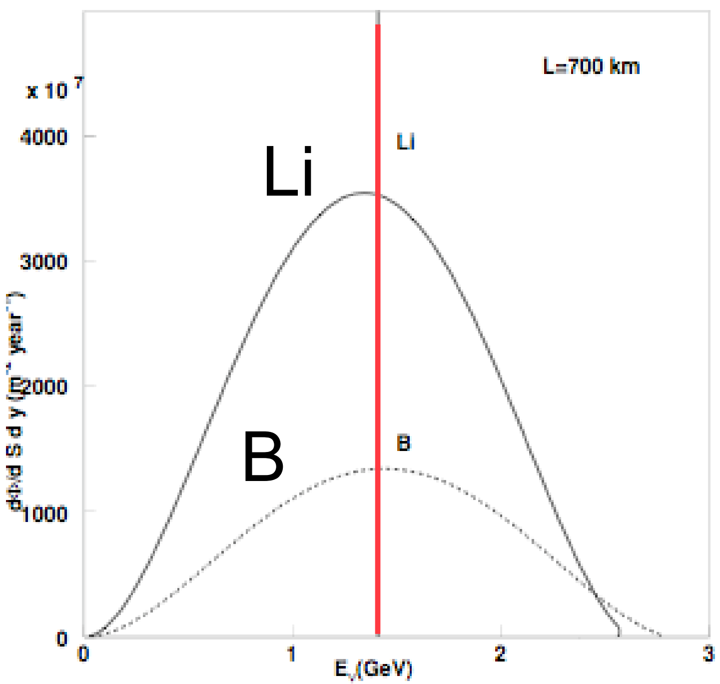
Beta beams

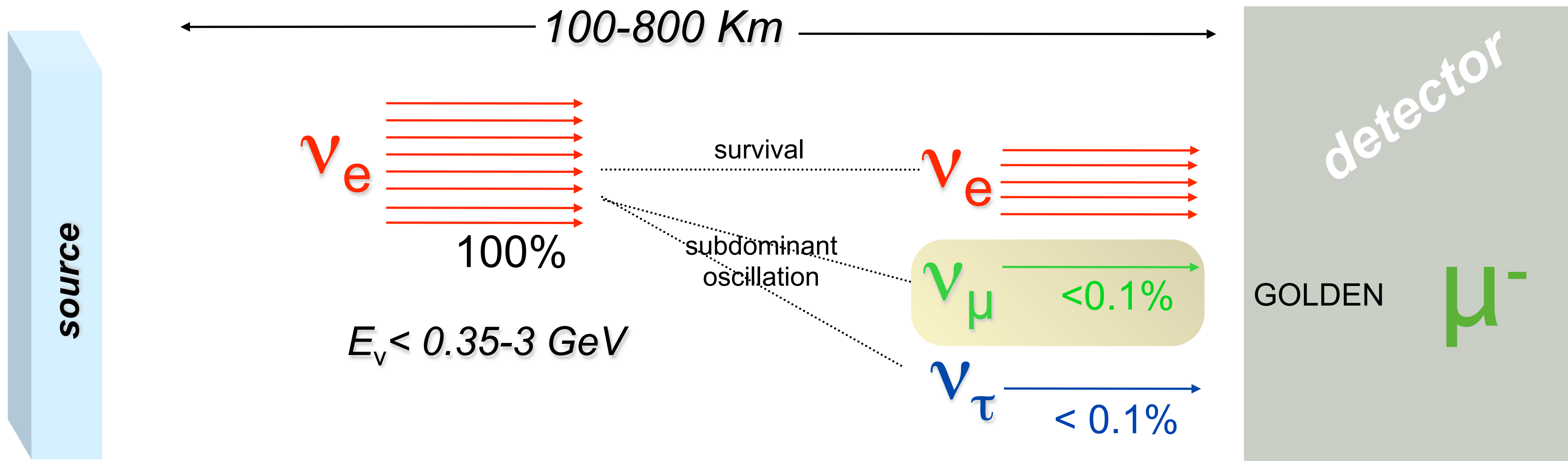
Pure ν_e beam → small beam systematics and backgrounds



Ion	γ	$L(km)$	$\bar{\nu}_e$ CC	ν_e CC	$\langle E_\nu \rangle (GeV)$
He/Ne	100	130	28.9	32.8	0.39/0.37
He/Ne	350	700	62.0	55.	1.35/1.3
Li/B	100	700	5.0	4.9	1.3/1.4

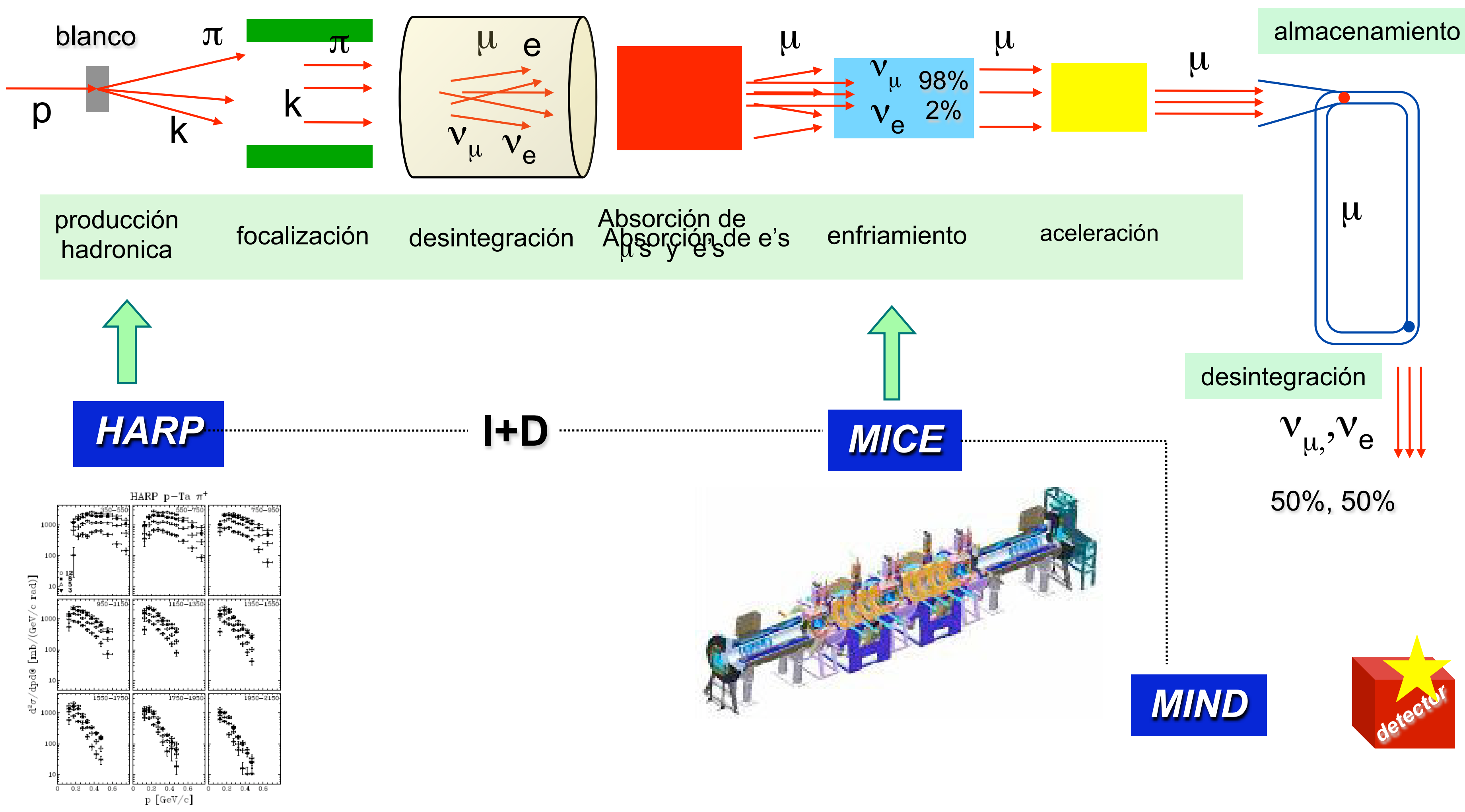




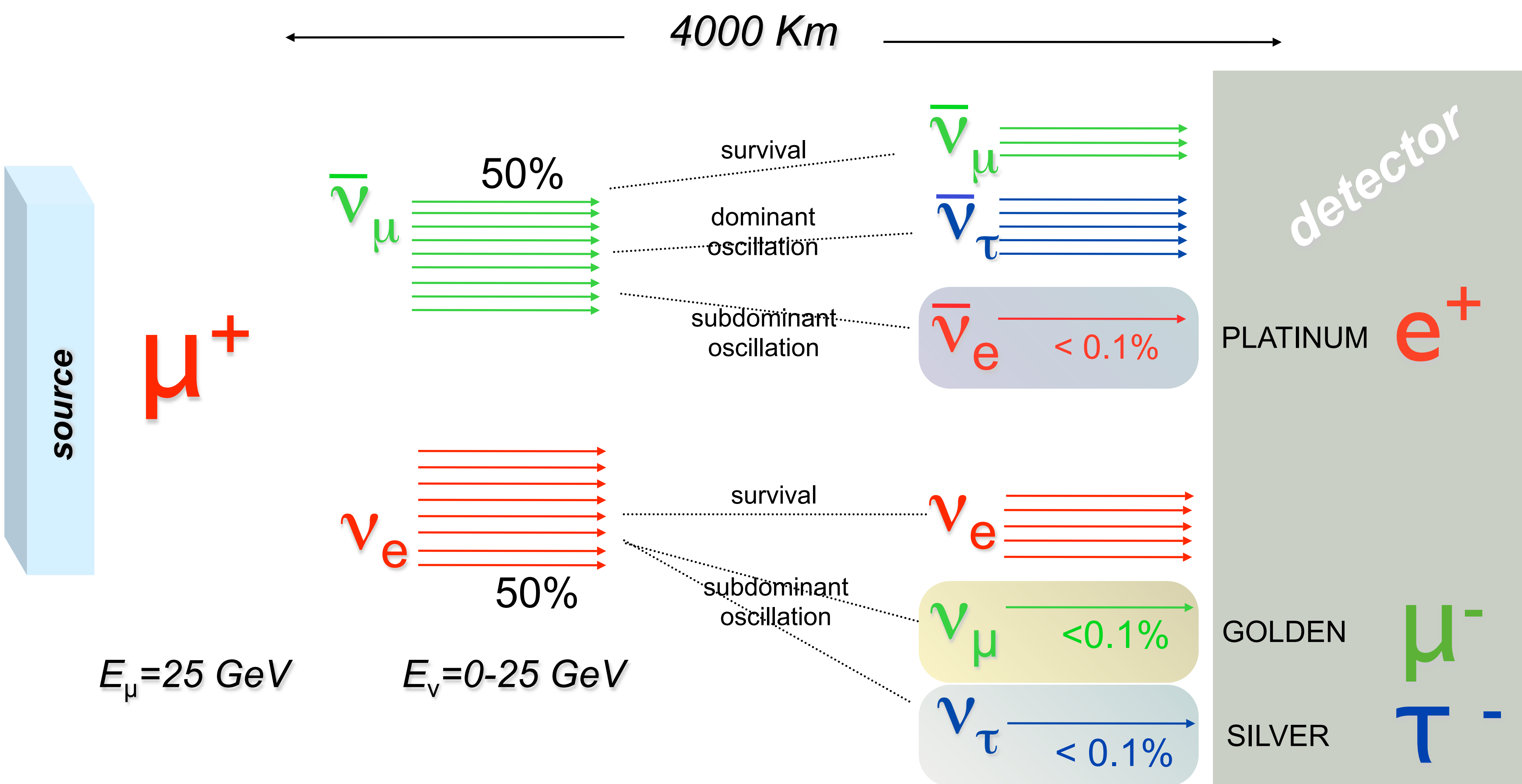


Relatively short baseline → small sensitivity to mass hierarchy

The neutrino factory



The neutrino factory



The ideal detector should be able to detect e,μ,τ and identify their charge

Oscillation channels

	atmospheric	interference	solar
golden	$P^{\pm}_{e\mu} = X^{\pm}_{\mu} \sin^2 2\theta_{13}$	$+ (Y^{\pm}_{c} \cos\delta \mp Y^{\pm}_{s} \sin\delta) \sin 2\theta_{13}$	$+ Z_{\mu}$
platinum	$P^{\pm}_{\mu e} = X^{\pm}_{\mu} \sin^2 2\theta_{13}$	$+ (Y^{\pm}_{c} \cos\delta \pm Y^{\pm}_{s} \sin\delta) \sin 2\theta_{13}$	$+ Z_{\mu}$
silver	$P^{\pm}_{e\tau} = X^{\pm}_{\tau} \sin^2 2\theta_{13}$	$- (Y^{\pm}_{c} \cos\delta \mp Y^{\pm}_{s} \sin\delta) \sin 2\theta_{13}$	$+ Z_{\tau}$

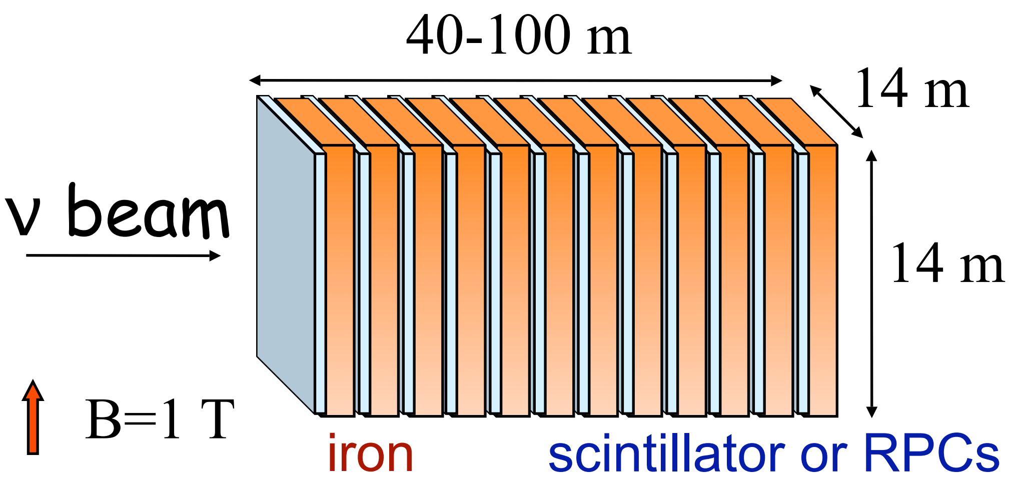
golden — Easy to detect muons and measure their charge

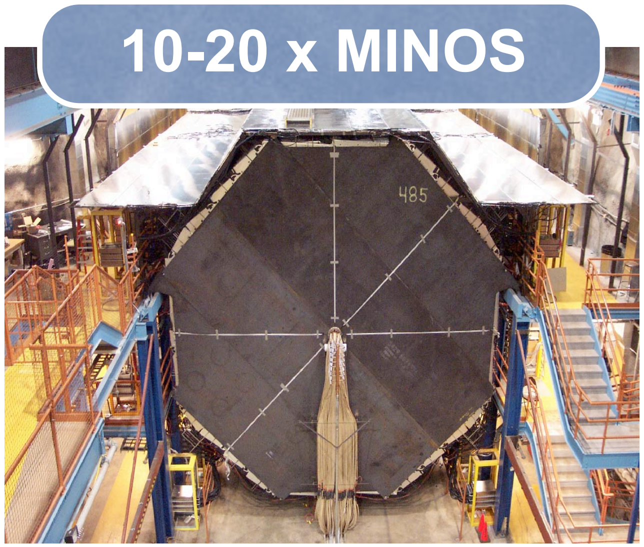
platinum — Electron charge identification is complicated

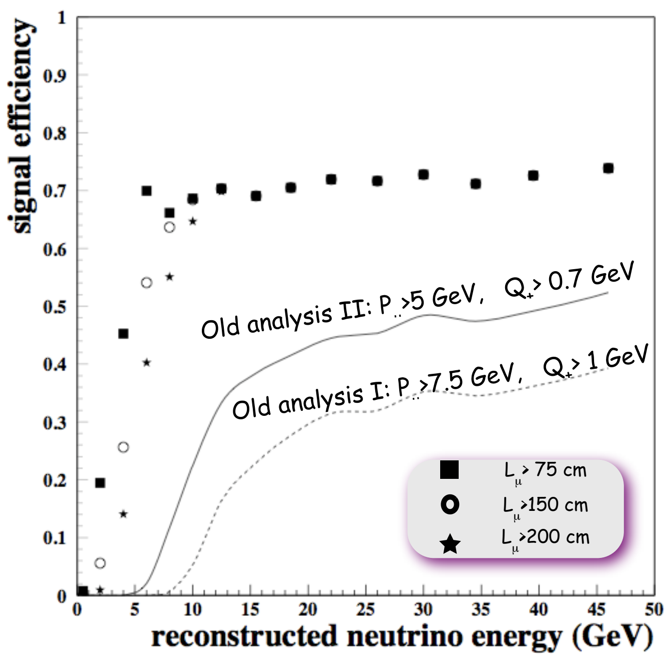
silver — Tau detection requires emulsions
Not all tau decay channels are useful

Statistically limited
Expensive

The golden detector: MIND







Energy threshold 3-5 GeV
Modest energy resolution
Insensitive to taus and electrons

→ **Maybe not sufficient**

Several channels

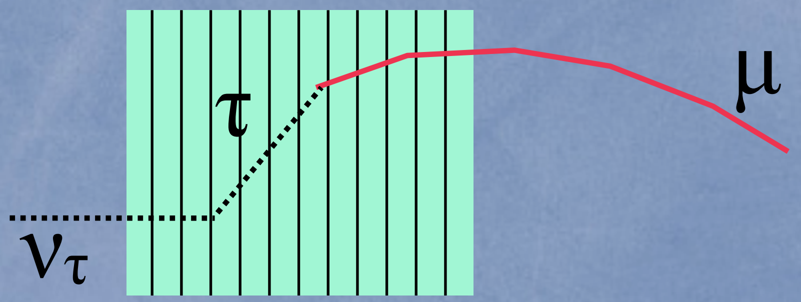
degeneracy solvers

- **several channels**
- several energies
- several baselines

- Expensive option
- It implies new detector technologies

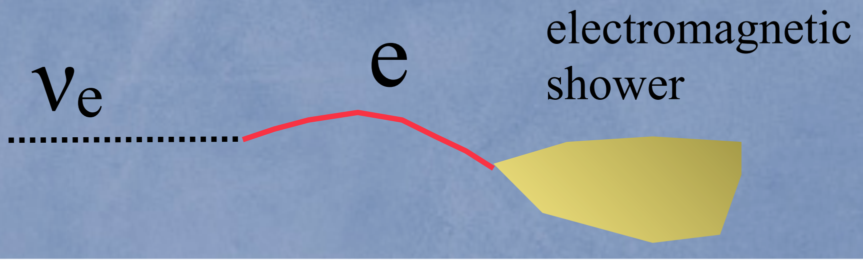
1. Detection of taus (silver channel)

- emulsions (OPERA-like)
- Baseline option is 15 Kton



2. Detection of electrons (platinum channel)

- emulsions
- liquid argon (in R&D phase)

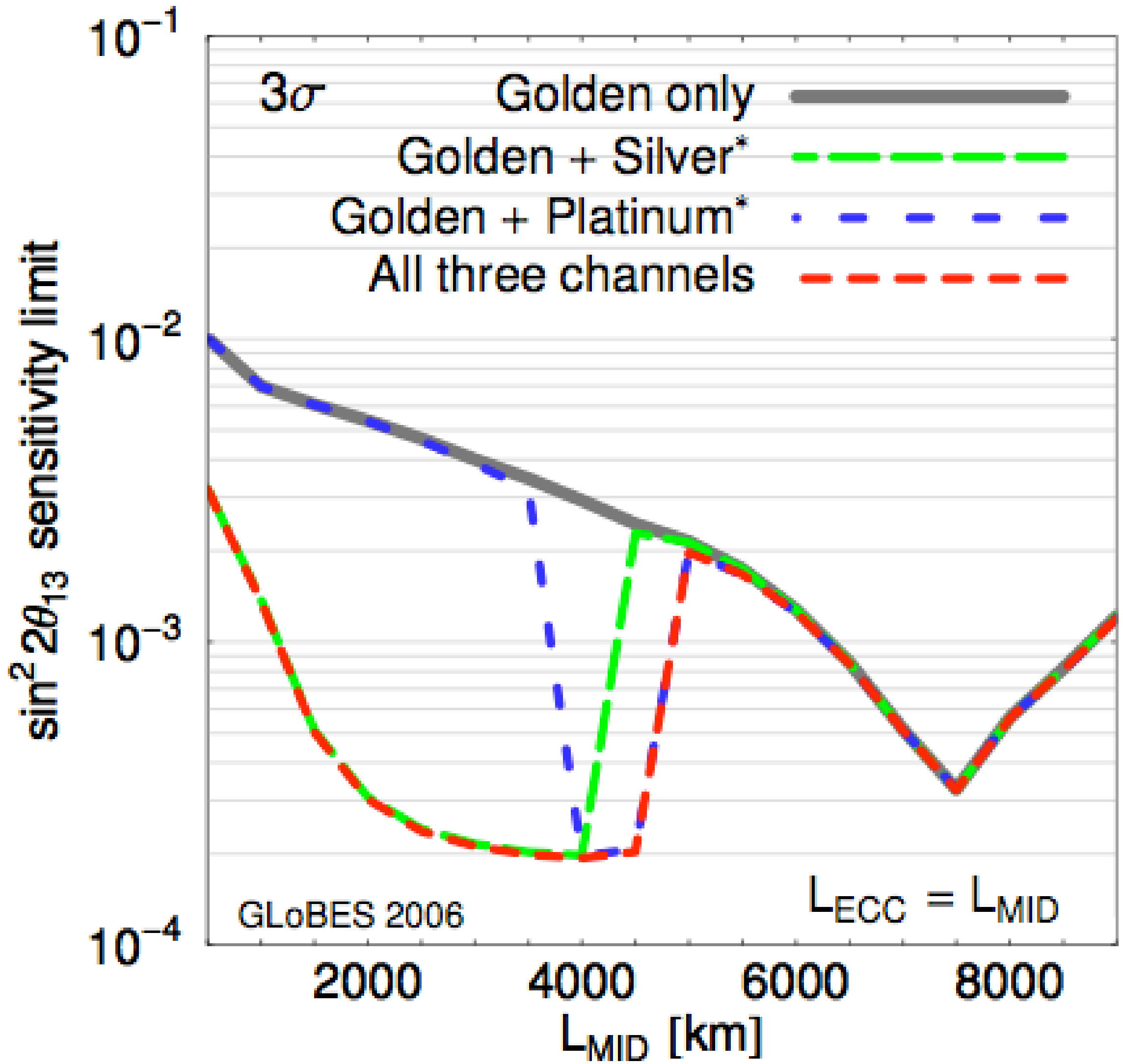


golden **50 Kton MIND**

silver **5 Kton emulsions**

platinum **15 Kton Liquid Argon**

Ideally one would like to build a very massive hybrid detector able to measure all oscillation channels at a reasonable cost



Energy analysis

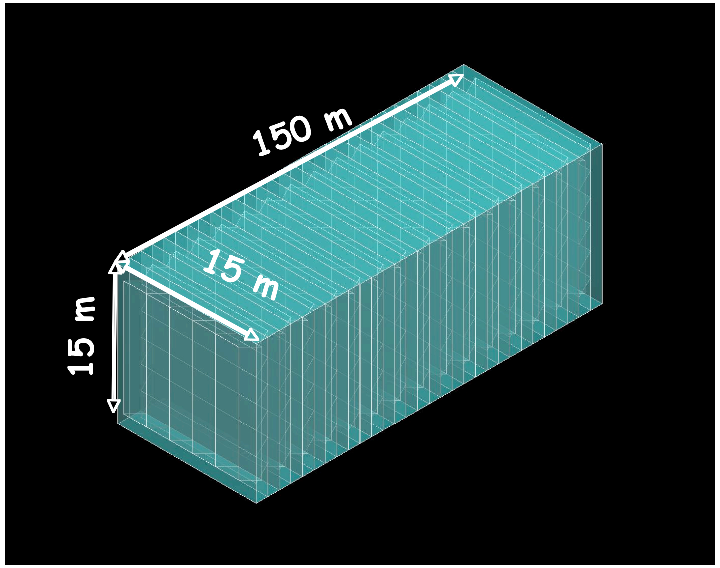
degeneracy solvers

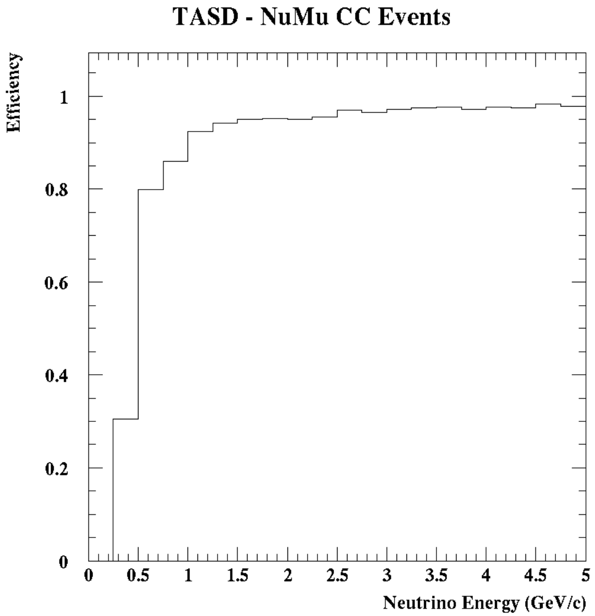
- several channels
- **several energies**
- several baselines

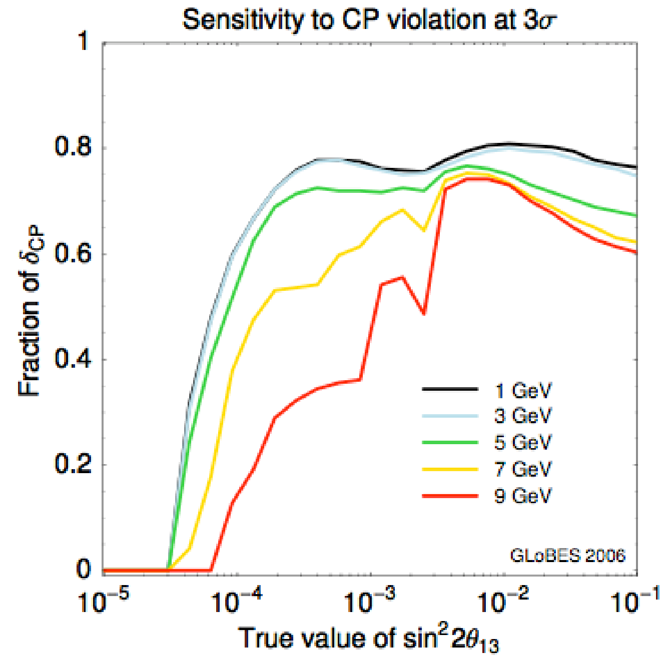
Options

- Improve energy resolution
- Reduce threshold to detect second maximum

Totally Active Scintillating Detector



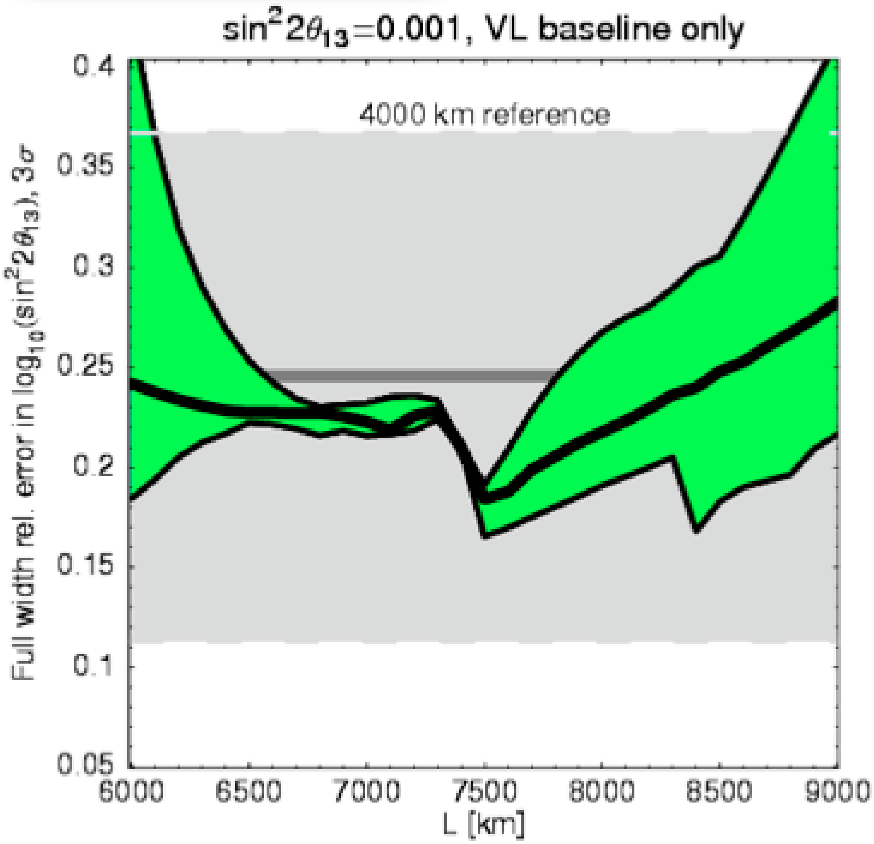




The magic baseline

degeneracy solvers

- several channels
- several energies
- **several baselines**



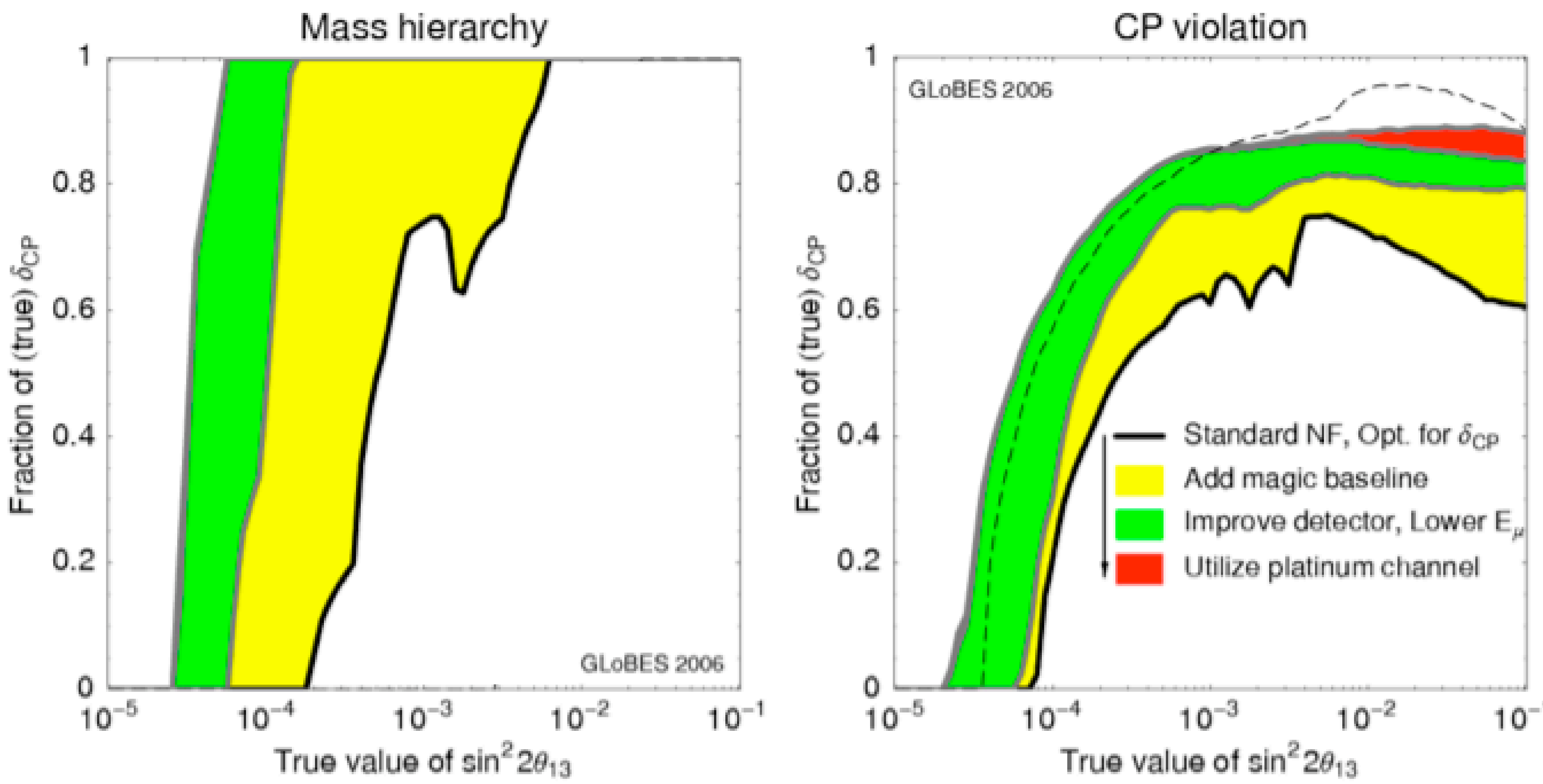
At ~7500 Km the oscillation probability is independent of δ_{CP}

Good to measure θ_{13} and solve the intrinsic degeneracy

In combination with the intermediate baseline (4000 Km) constitutes a good option

Two MIND-like detectors: feasible and “cheap”

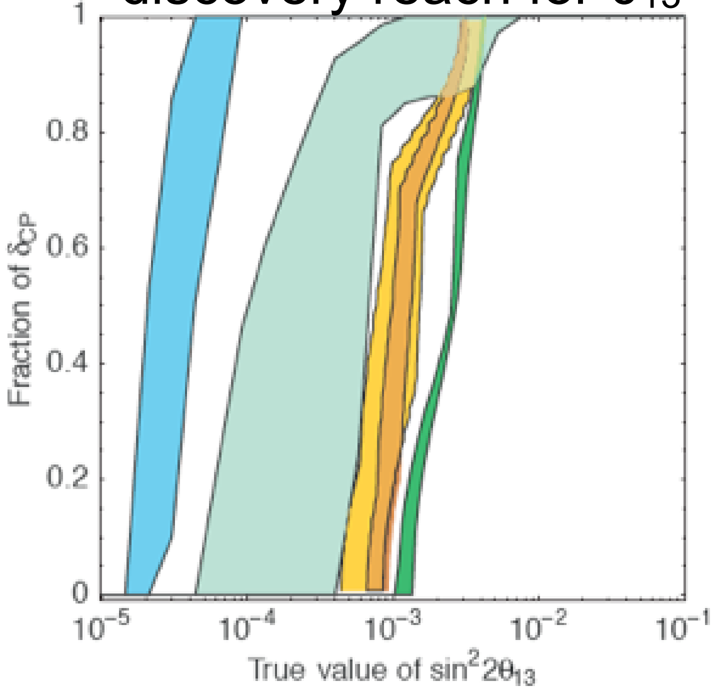
Which neutrino factory ?



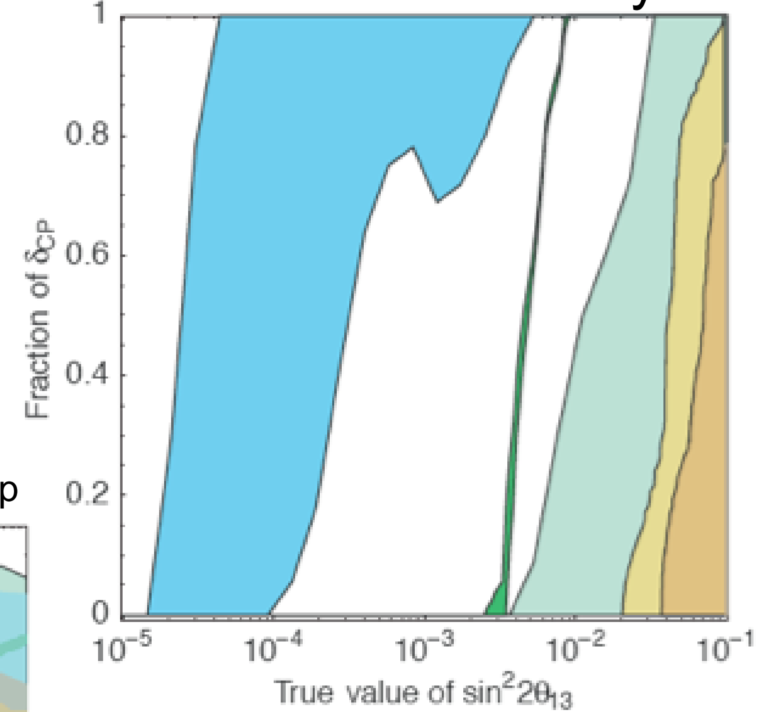
And the winner is ...

Comparison of facilities

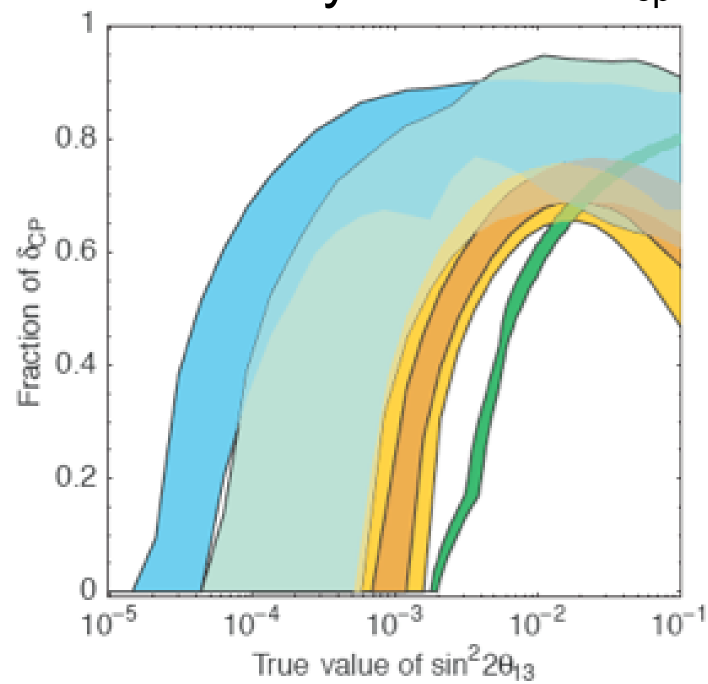
discovery reach for θ_{13}



discovery reach for mass hierarchy



discovery reach for δ_{cp}



Which road to take

... but the Neutrino Factory is very challenging, requires lots of R&D and it is expensive

Do we need such a powerful facility ?

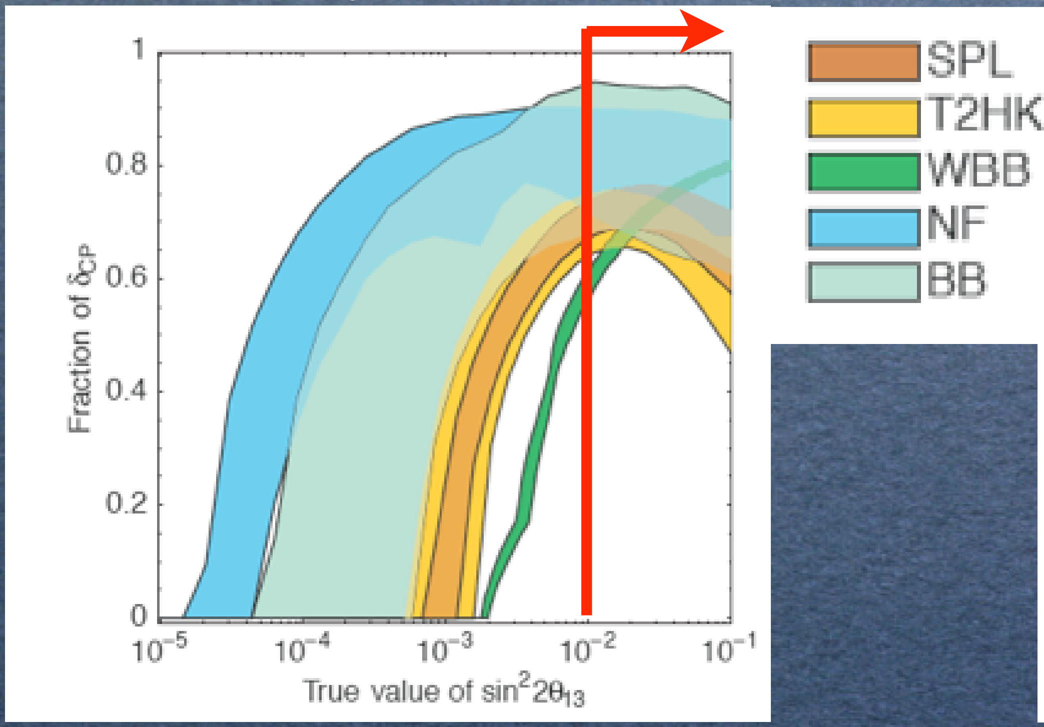
Beta-Beam is also challenging,
but probably less.
It is also very expensive,
but may be less.

However it has much lower
sensitivity to mass hierarchy.

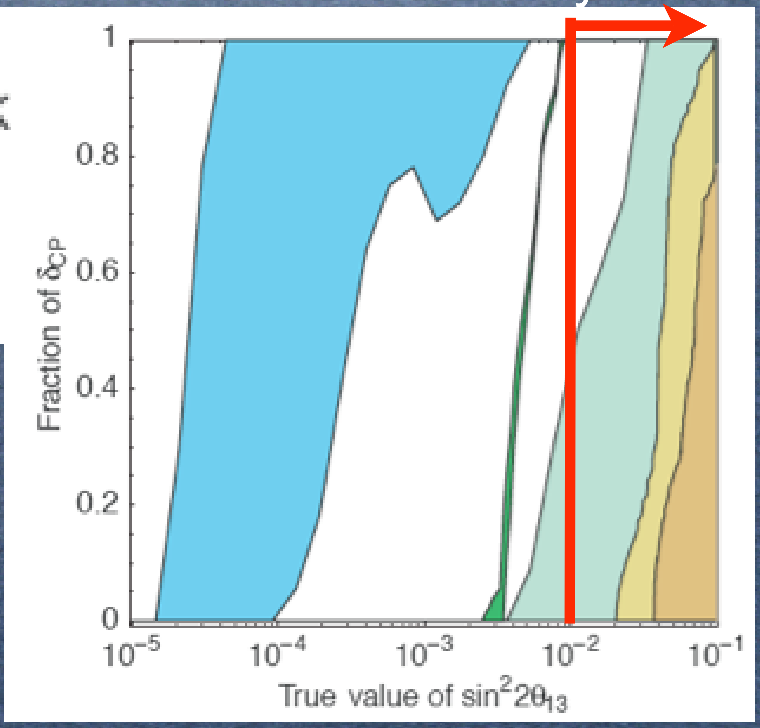
everything depends on the value of θ_{13}

Hypothesis I: we measure θ_{13} by 2012

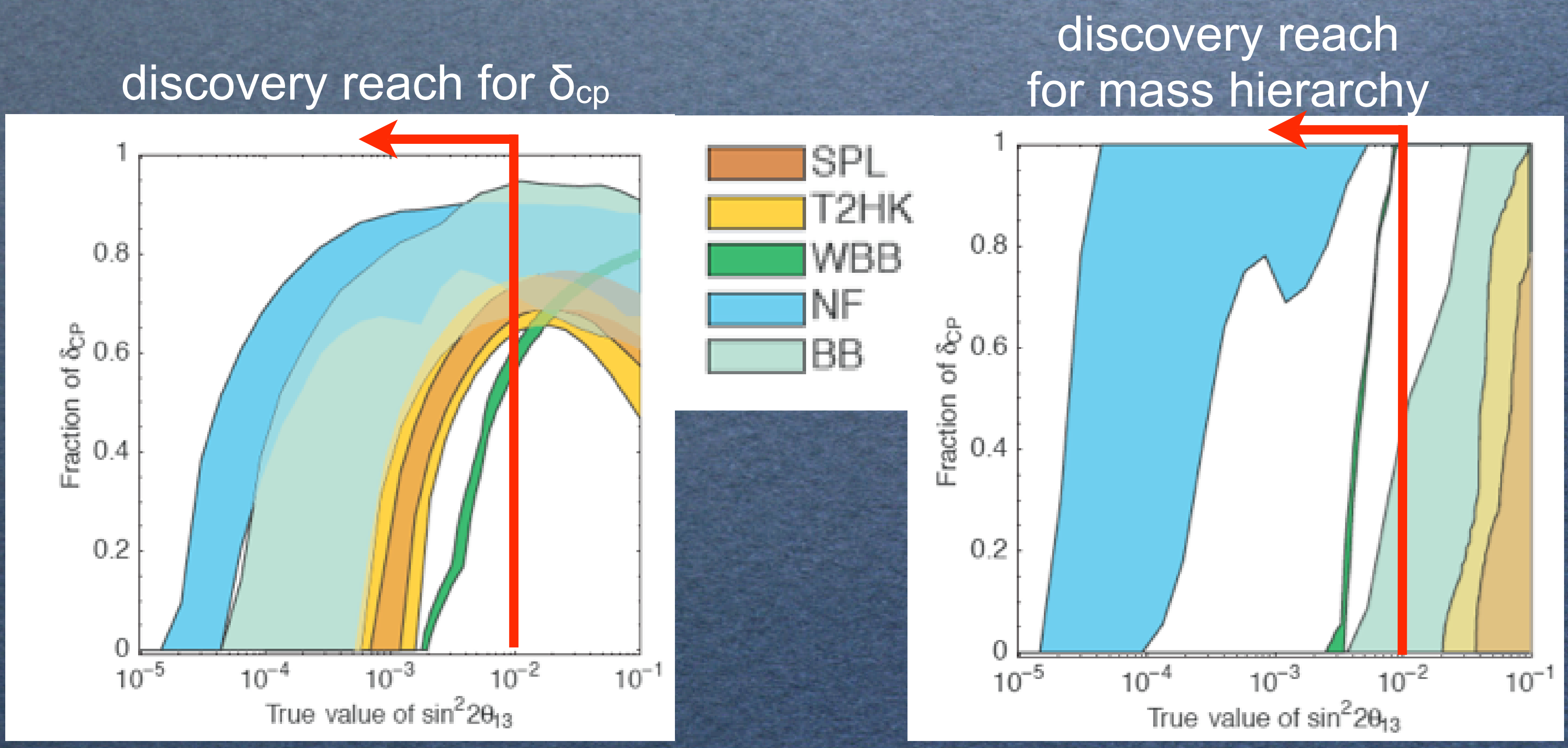
discovery reach for δ_{cp}



discovery reach for mass hierarchy



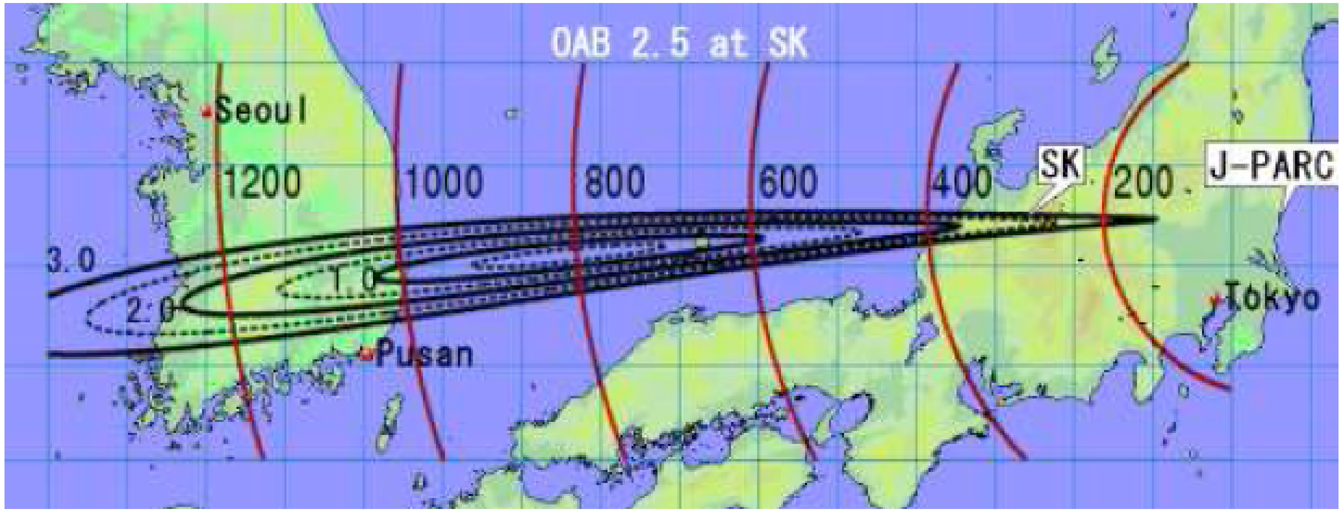
Hypothesis II:
θ_{13} unknown by 2012



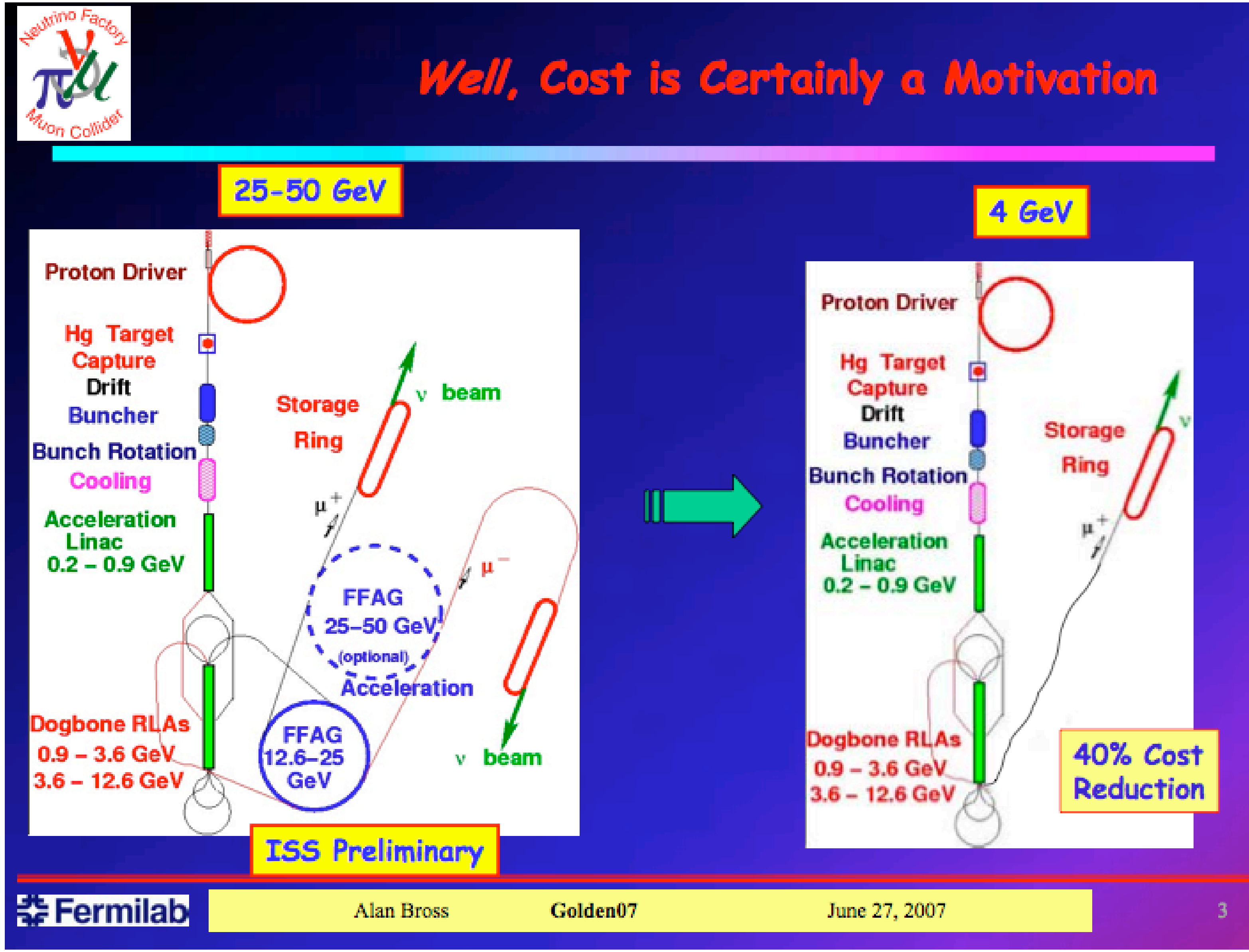
Is there any other solution ?

A variety of ideas

- Electron capture beta beam (monoenergetic)
- Beta-beam with two ions and two baselines
- Beta-beam with two ions at a single baseline
- Beta-beam combined with a super-beam (CPT conjugates)
- Beta-beam or super-beam combined with atmospheric data
- Super-beam with two detectors at different baselines and off-axis angles (T2KK)

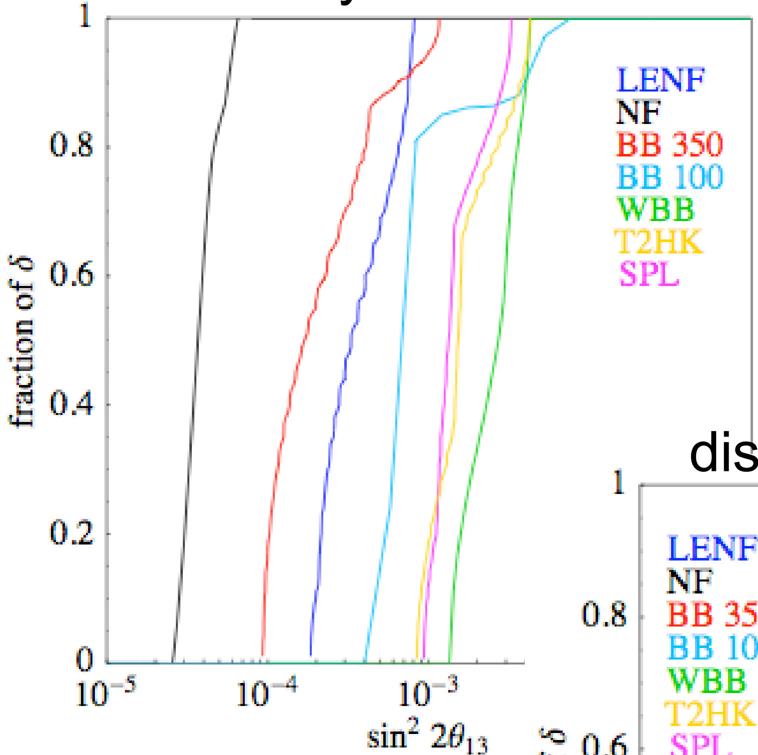


Low Energy Neutrino Factory

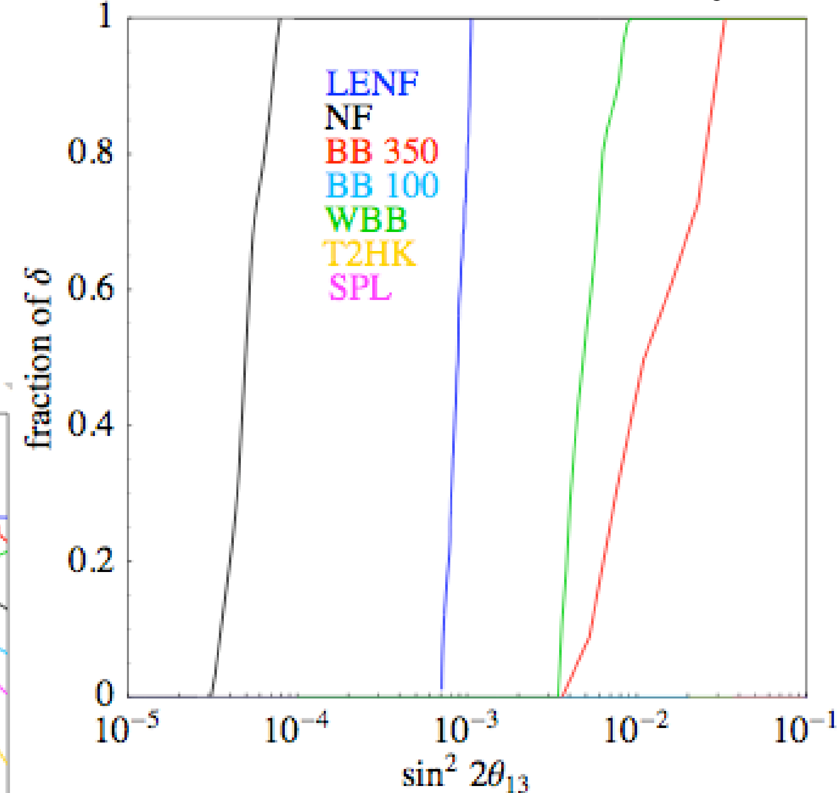


Expected sensitivity for LENF

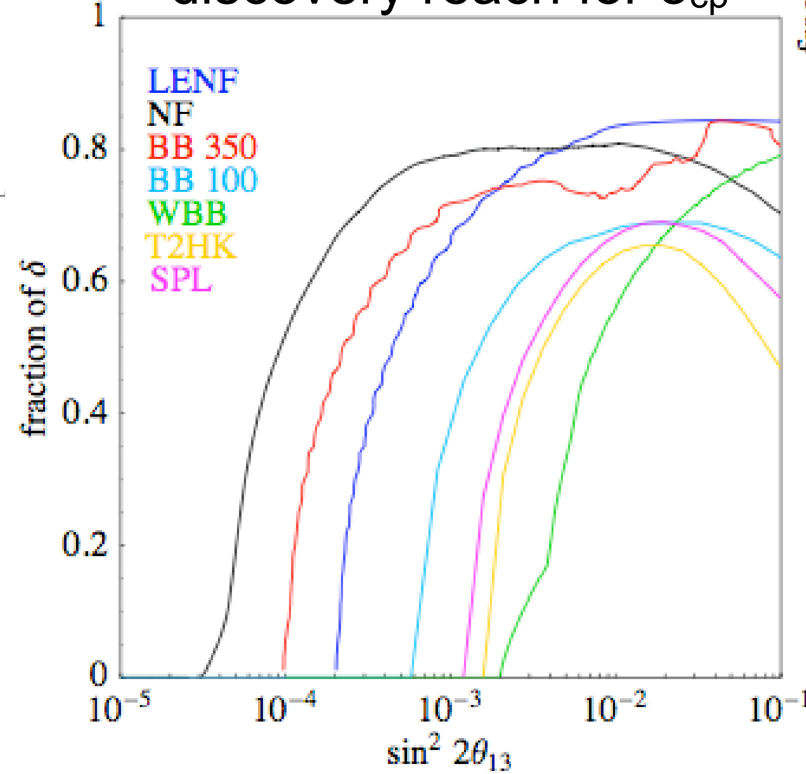
discovery reach for θ_{13}



discovery reach for mass hierarchy



discovery reach for δ_{cp}



There is no final strategy yet and several options are still opened

We should do our home work in order to be prepared to take a decision by 2012

$$decision = f(\theta_{13}, €, \ldots)$$

thanks