Neutrino Mixing Parameters: Long-Term Projects

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Outline

1. **Neutrino properties: questions for the future**

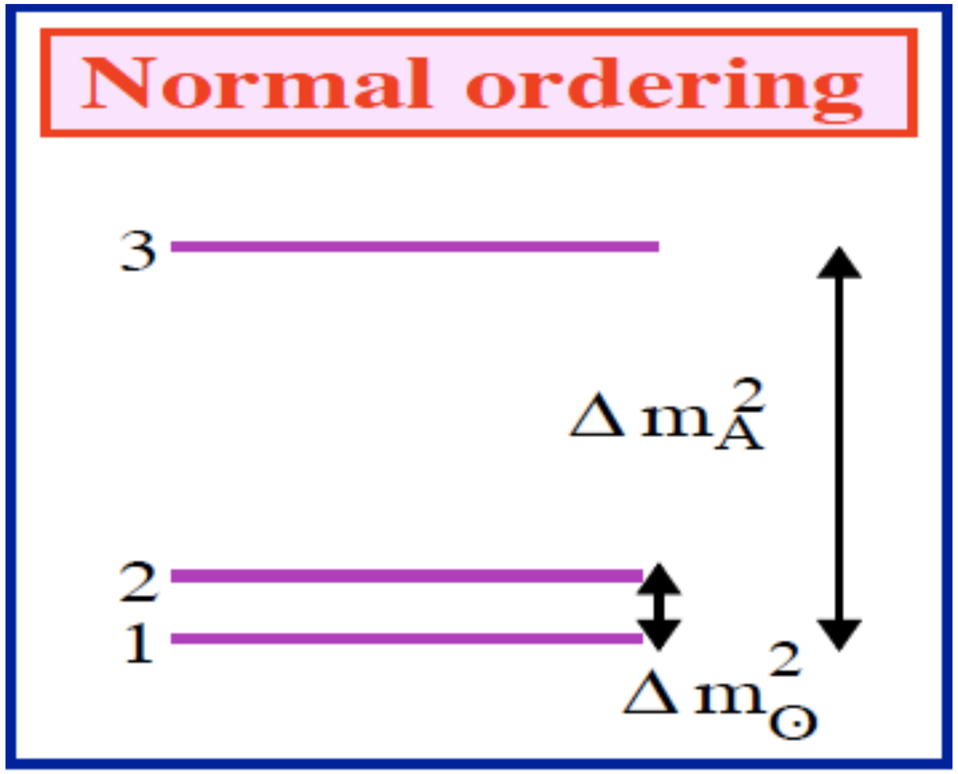
2. **Neutrinoless double beta decay**

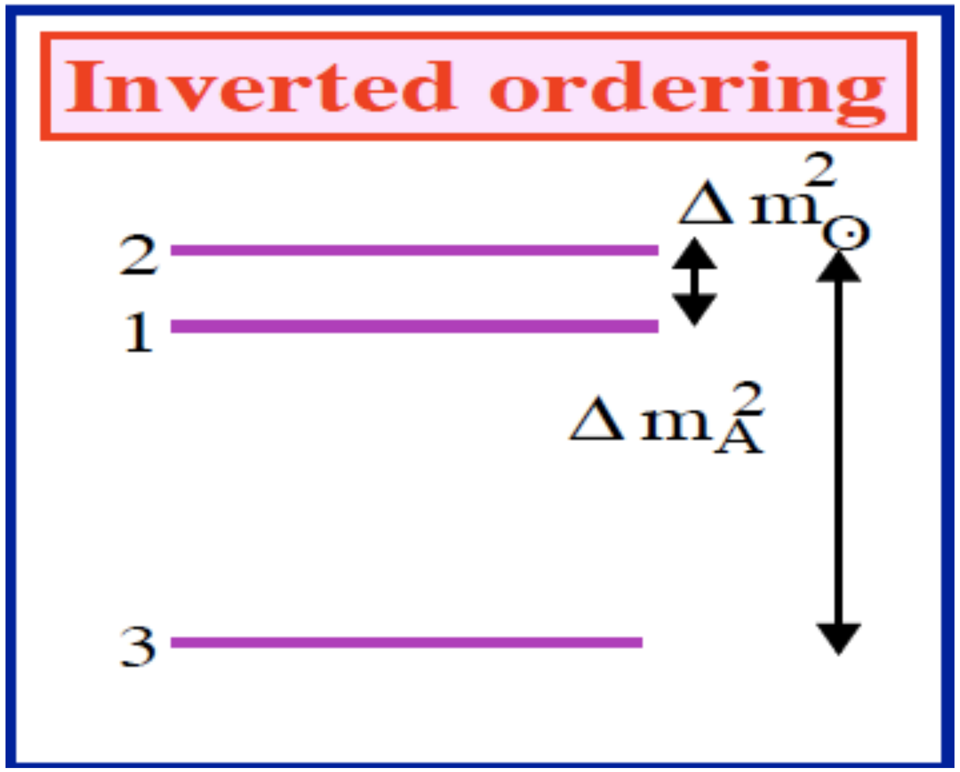
3. **Longbaseline neutrino oscillation experiments**
    - Superbeams
    - Beta beams
    - Neutrino factory

4. **Conclusions and outlook**

Present status of (standard) neutrino physics

$\Delta m_s^2 \ll \Delta m_A^2$ implies at least 3 massive neutrinos.





$$
\begin{aligned}
m_1 &= m_{\min} \\
m_2 &= \sqrt{m_{\min}^2 + \Delta m_{\mathrm{sol}}^2} \\
m_3 &= \sqrt{m_{\min}^2 + \Delta m_{\mathrm{A}}^2}
\end{aligned}
$$

$$
\begin{aligned}
m_3 &= m_{\min} \\
m_1 &= \sqrt{m_{\min}^2 + \Delta m_{\mathrm{A}}^2 - \Delta m_{\mathrm{sol}}^2} \\
m_2 &= \sqrt{m_{\min}^2 + \Delta m_{\mathrm{A}}^2}
\end{aligned}
$$

Measuring the masses requires: $m_{\min}$ and the ordering.

Mixing is described by a unitary mixing matrix.

$$U = \underset{\text{Solar, reactor } \theta_\odot \sim 30^o}{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \underset{\text{Atm, Acc. } \theta_A \sim 45^o}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}$$

$$\underset{\text{CPV phase}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}} \underset{\text{Reactor, Acc. } \theta < 12^o}{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}} \underset{\text{CPV Majorana phases}}{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}}$$

(Lisi's talk)

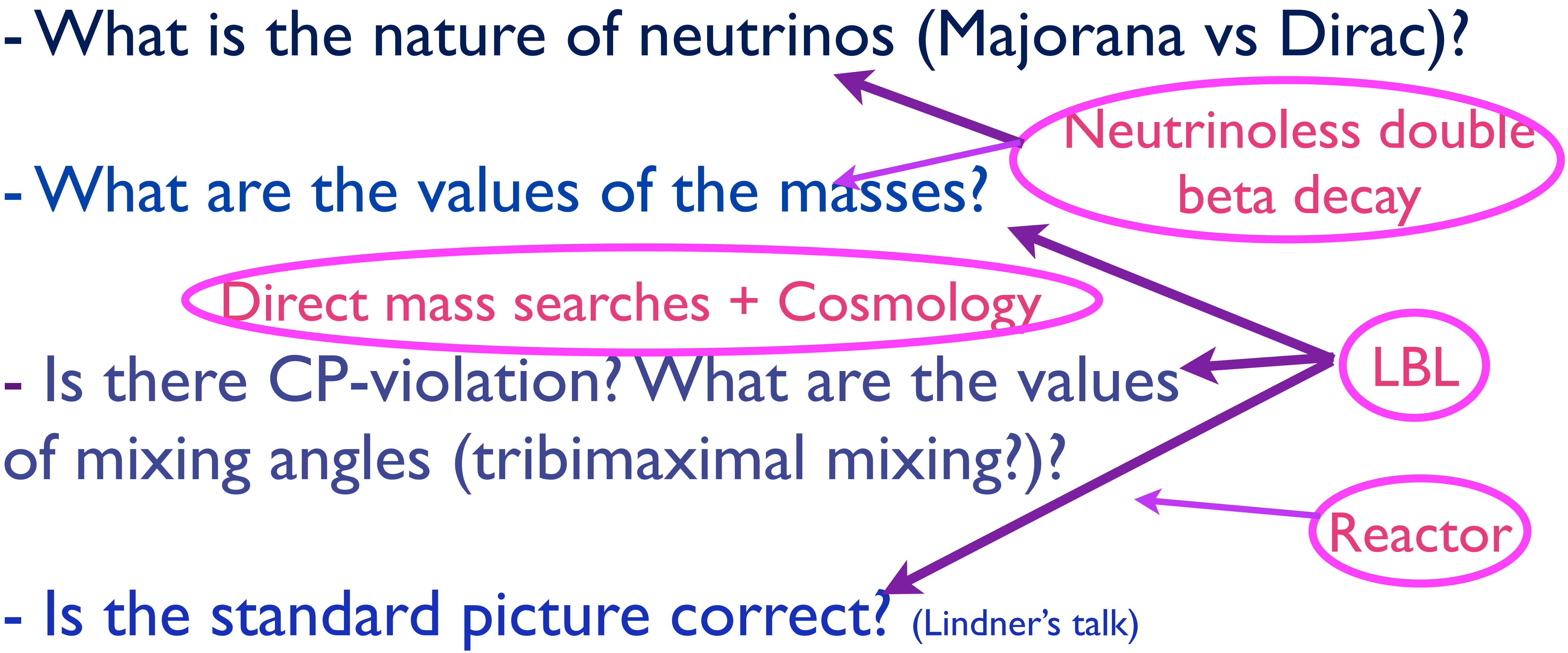
If $U \neq U^*$, there is leptonic CP-violation

$$P(\nu_l \to \nu_{l'}) \neq P(\bar{\nu}_l \to \bar{\nu}_{l'})$$

This is a fundamental question to answer and is related to leptogenesis and the possible origin of the baryon asymmetry of the Universe.

Phenomenology questions for the future

(Lindner's talk)



- What is the nature of neutrinos (Majorana vs Dirac)?

Neutrinoless double beta decay

- What are the values of the masses?

Direct mass searches + Cosmology

- Is there CP-violation? What are the values of mixing angles (tribimaximal mixing?)?

LBL

Reactor

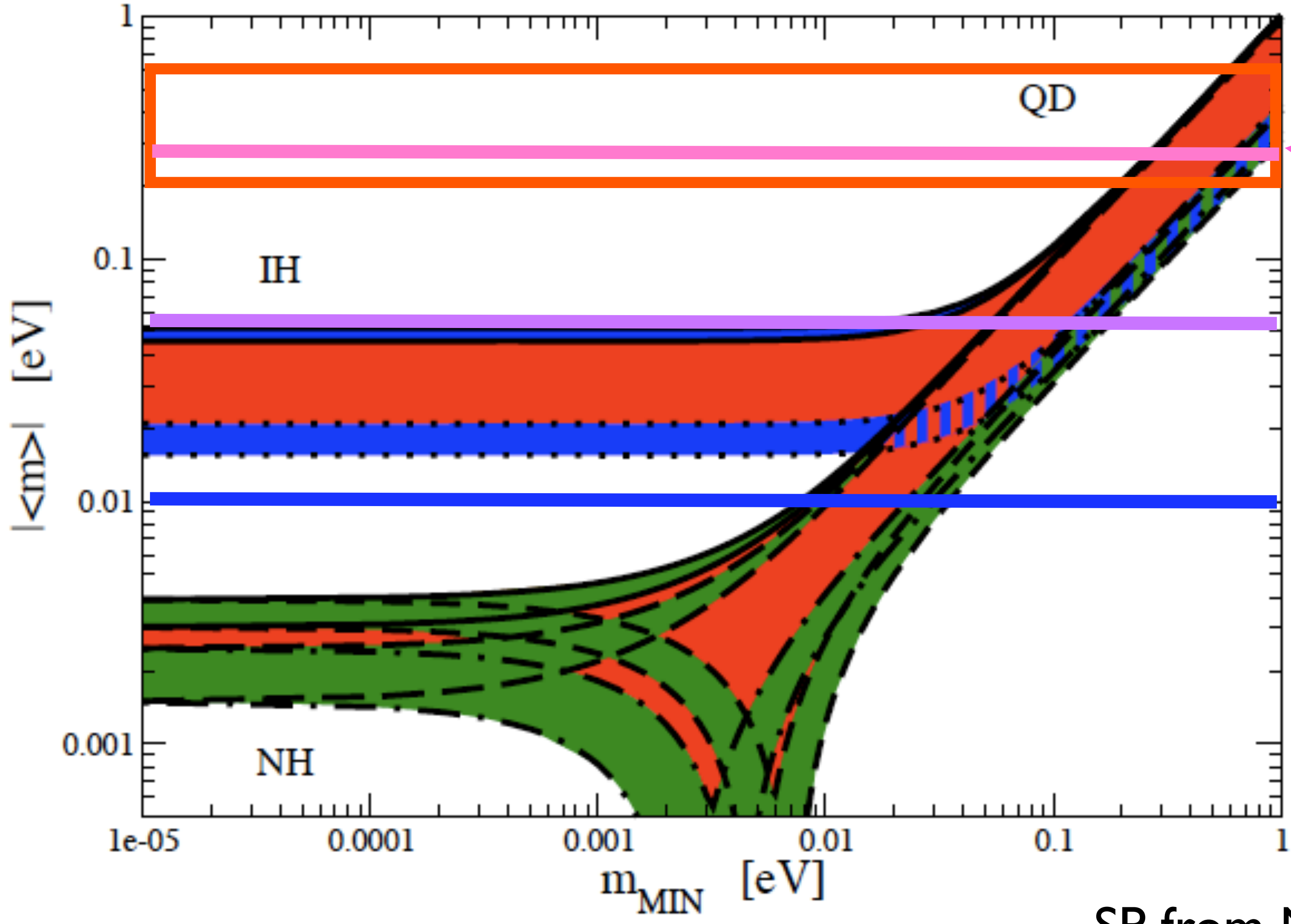
- Is the standard picture correct? (Lindner's talk)

A wide experimental programme is under way or at the proposal stage. Other relevant searches are: solar (Borexino), atmospheric (megaton-scale detector, INO), supernova neutrinos (Lunardini's talk), SBL exp for sterile neutrino searches.

Neutrinoless double beta decay

The half-life depends on neutrino properties through

$$|\langle m\rangle| \sim |m_1 \cos^2\theta_{12} + m_2 \sin^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}}|$$



Klapdor-Kleingrothaus claim 2002 and 2006

Present bounds: Heidelberg-Moscow, IGEX, Cuoricino and NEMO3

Next generation: GERDA, EXO, CUORE, SuperNEMO, SNO+, Majorana, COBRA...

Future experiments: ~1 ton

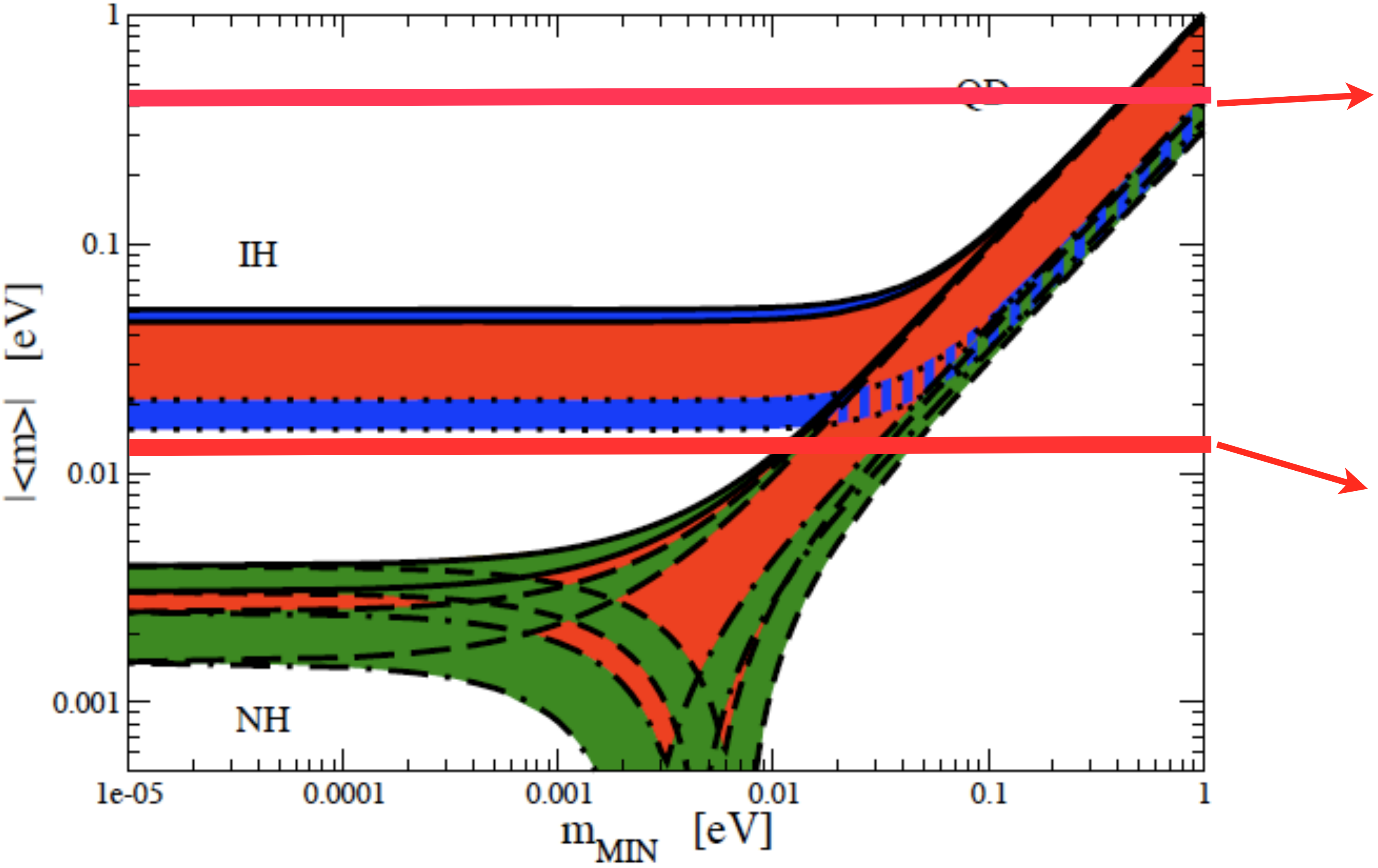
SP from Nakamura, Petcov review in PDG

See also parallel talks by Janicsko and Garrido

Wide experimental program for the future:

a positive signal would indicate that L is violated!

It might give information on neutrino masses (and CPV).



It would imply QD spectrum for neutrinos.

It would imply that inverted ordering is excluded.

It will be critical to establish the origin of the signal (light or heavy Majorana neutrinos, RV SUSY,...). (Lindner's talk).

Long baseline neutrino oscillations

Long baseline neutrino oscillation experiments (T2K, LBNE, EU superbeams, neutrino factories and beta beams) will aim at studying the subdominant channels

$$\nu_{\mu,e} \longrightarrow \nu_{e,\mu} \quad \bar{\nu}_{\mu,e} \longrightarrow \bar{\nu}_{e,\mu}$$

$$P(\nu_\mu \to \nu_e) \sim \sin^2\theta_{23} \boxed{\sin^2 2\theta_{13}} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

for negligible matter and CPV effects.

in order to establish

1. **the mixing angles (θ_{13})**
2. **the mass hierarchy**
3. **Leptonic CPV**
4. **Non-standard effects.**

Matter effects

These oscillations take place in the Earth (e, p, n). A potential V in the Hamiltonian describes matter effects: $V = \sqrt{2} G_F (N_e - N_n/2)$

$$P_{\nu_\mu \to \nu_e} = \sin^2 \theta_{23} \sin^2 2\theta_{13}^m \sin^2 \frac{\Delta_{13}^m L}{2}$$

The mixing angle changes wrt vacuum

$$\sin 2\theta_m = \frac{(\Delta m^2/2E) \sin 2\theta}{\sqrt{\left(\frac{\Delta m^2}{2E} \sin 2\theta\right)^2 + \left(\frac{\Delta m^2}{2E} \cos 2\theta - V\right)^2}}$$

and the probability gets enhanced for neutrinos (antineutrinos) depending on the mass ordering.

CP-violation

A measure of CPV effects is given by

$$A_{CP} = \frac{P(\nu_l \to \nu_{l'}) - P(\bar\nu_l \to \bar\nu_{l'})}{P(\nu_l \to \nu_{l'}) + P(\bar\nu_l \to \bar\nu_{l'})} \propto J_{CP} \propto \sin\theta_{13}\sin\delta$$

The full probability can be approximated as

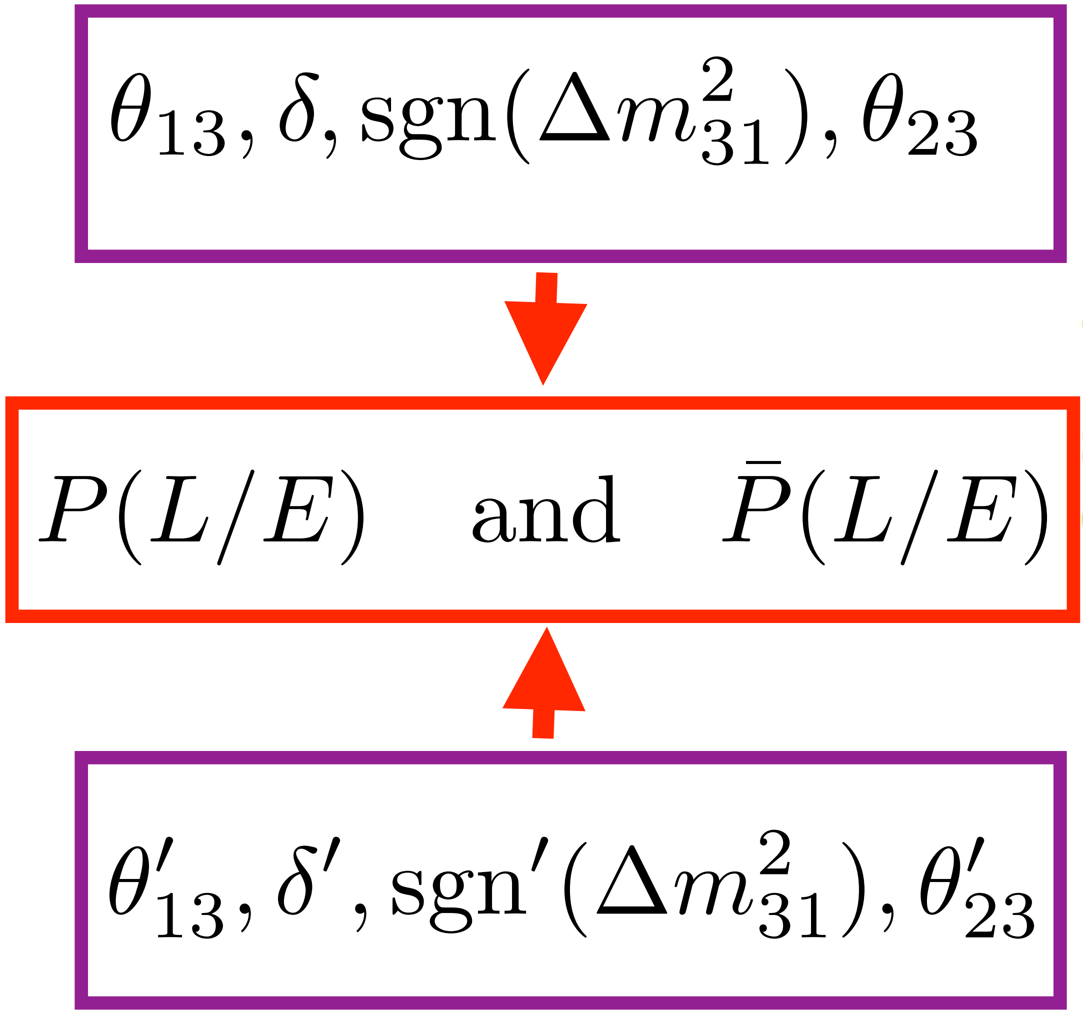
$$\begin{aligned} P(\bar P) \simeq\ & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A\mp\Delta_{13}}\right)^2 \sin^2\frac{(A\mp\Delta_{13})L}{2} \\ & + \tilde J \frac{\Delta_{12}}{A}\frac{\Delta_{13}}{A\mp\Delta_{13}} \sin\frac{AL}{2}\sin\frac{(A\mp\Delta_{13})L}{2}\cos\left(\mp\delta+\frac{\Delta_{13}L}{2}\right) \\ & + c_{23}^2 \sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2\sin^2\frac{AL}{2} \end{aligned}$$

Matter effects

CP violation

Degeneracies

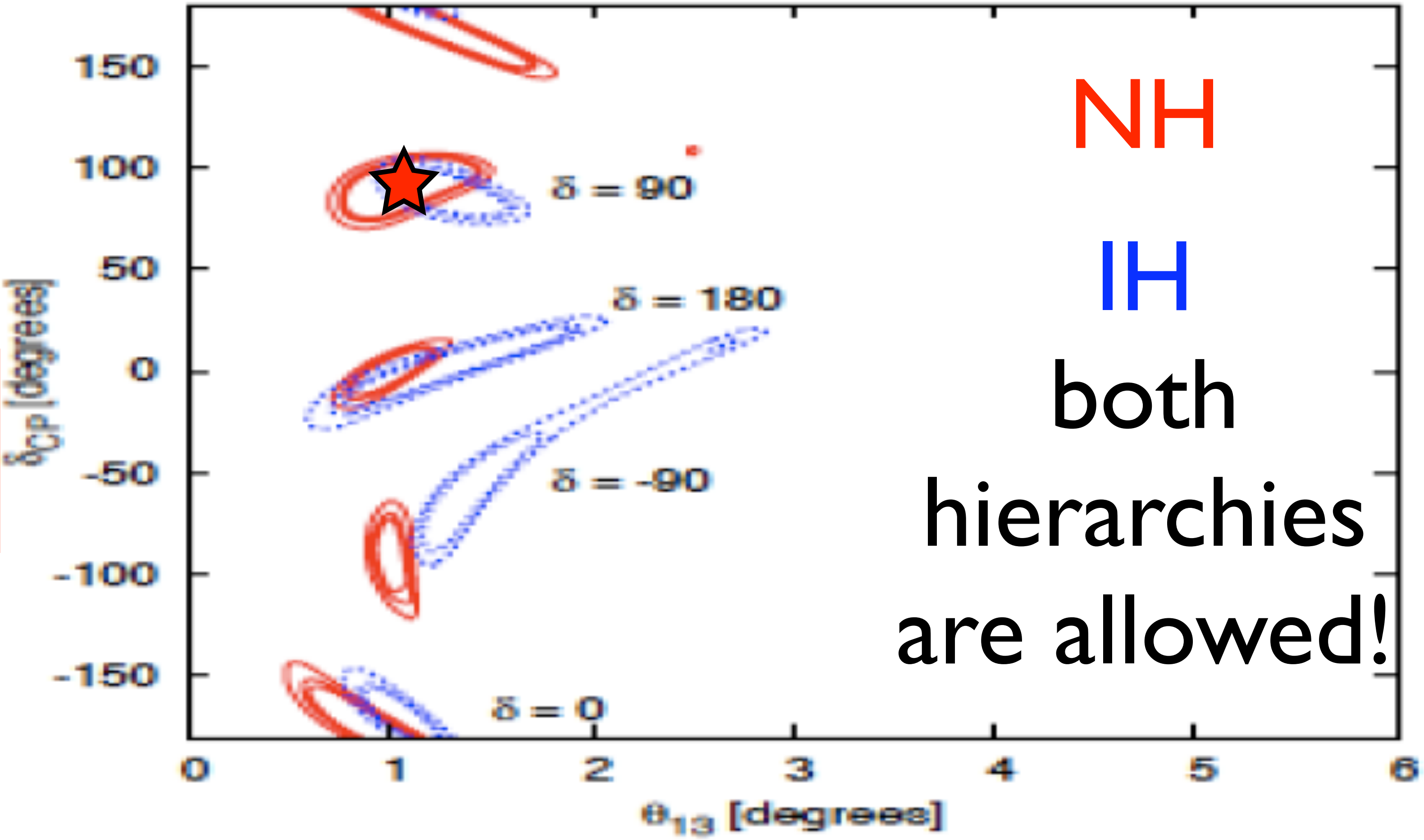
The determination of CPV and the mass ordering is complicated by the issue of **degeneracies**: different sets of parameters which provide an equally good fit to the data (eight-fold degeneracies).



$\theta_{13}, \delta, \mathrm{sgn}(\Delta m^2_{31}), \theta_{23}$

$P(L/E) \quad \text{and} \quad \bar{P}(L/E)$

$\theta'_{13}, \delta', \mathrm{sgn}'(\Delta m^2_{31}), \theta'_{23}$



NH

IH

both hierarchies are allowed!

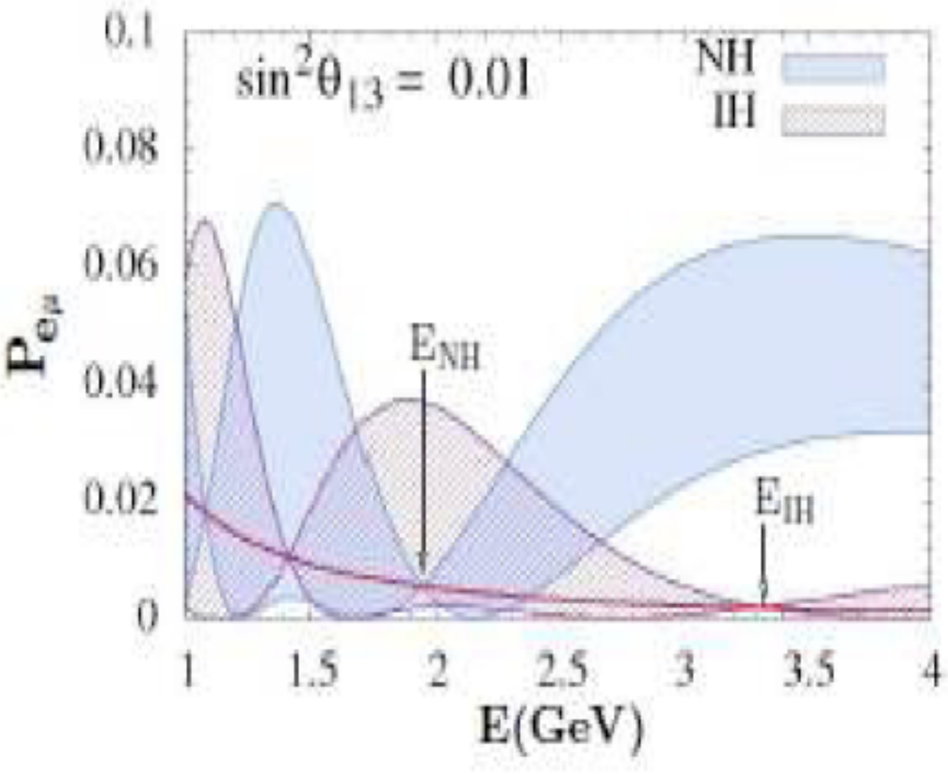
- (θ_{13}, δ) degeneracy (Koike, Ota, Sato; Burguet-Castell et al.)

$$\begin{aligned} \delta' &= \pi - \delta \\ \theta'_{13} &= \theta_{13} + \cos\delta \sin 2\theta_{12} \frac{\Delta m^2_{12} L}{4E} \cot\theta_{23} \cot \frac{\Delta m^2_{13} L}{4E} \end{aligned}$$

Having information at different L/E can resolve this.

- sign(Δm^2_{31}) vs CPV (matter effects). In vacuum:

$$\delta' \to \pi - \delta \qquad \mathrm{sign}'(\Delta m^2_{13}) \to -\mathrm{sign}(\Delta m^2_{13})$$



This degeneracy is broken by matter effects.

For ex. Bimagic baseline at L=2540 km
Excellent sensitivity to the hierarchy
A. Dighe et al., 1009.1093; Raut et al. 0908.3741; Joglekar et al. 1011.1146

- the octant of θ_{23} (low E data) (Fogli, Lisi)

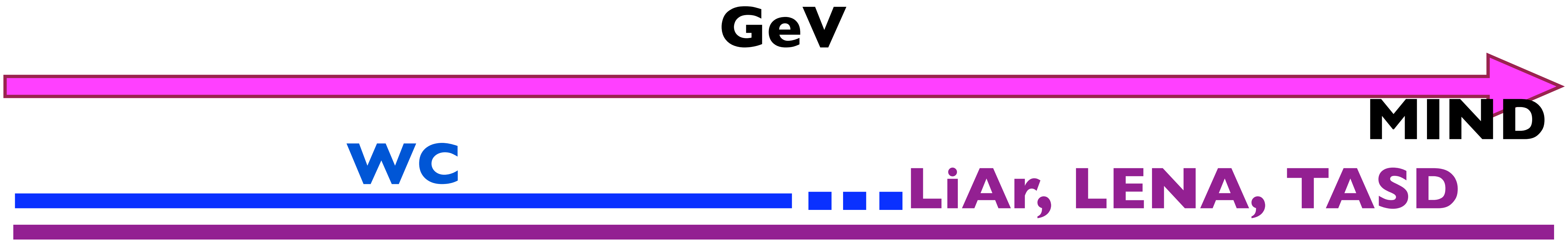
Future long baseline experiments

Different options are considered, depending of the neutrino production technique:

- **superbeams**
- **beta beams**
- **neutrino factory**

The baseline determines the energy of the beam and viceversa: exploit first oscillation maximum for best sensitivity. The energy and the oscillation channels impact on the type of detector used.

See also Raselli's parallel talk



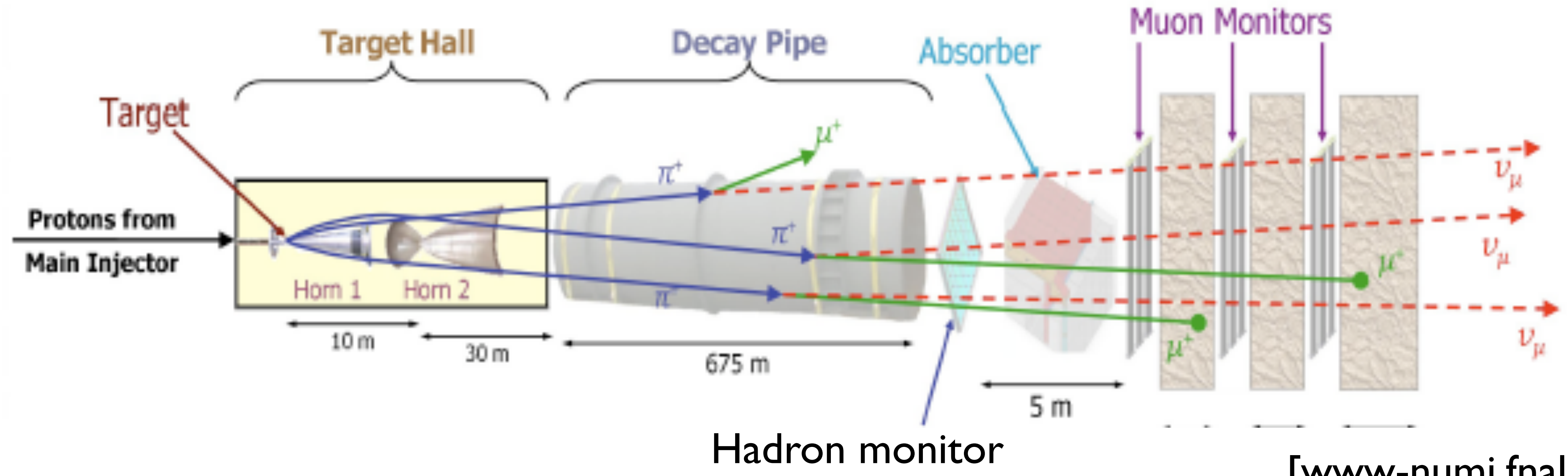
GeV

MIND

WC

LiAr, LENA, TASD

Superbeams

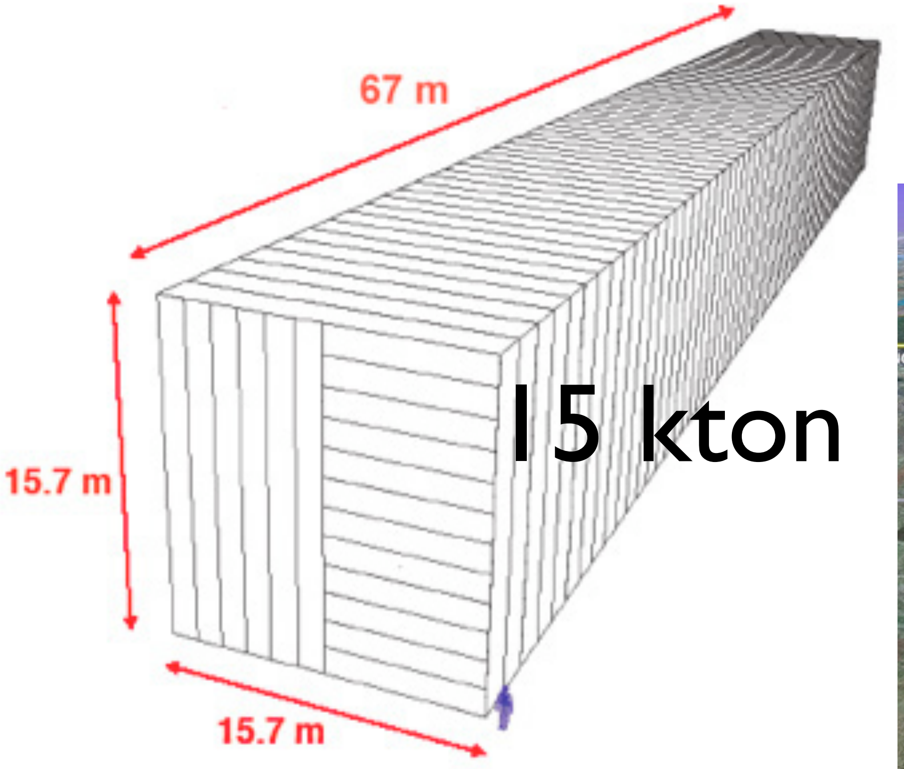


[www-numi.fnal.gov]

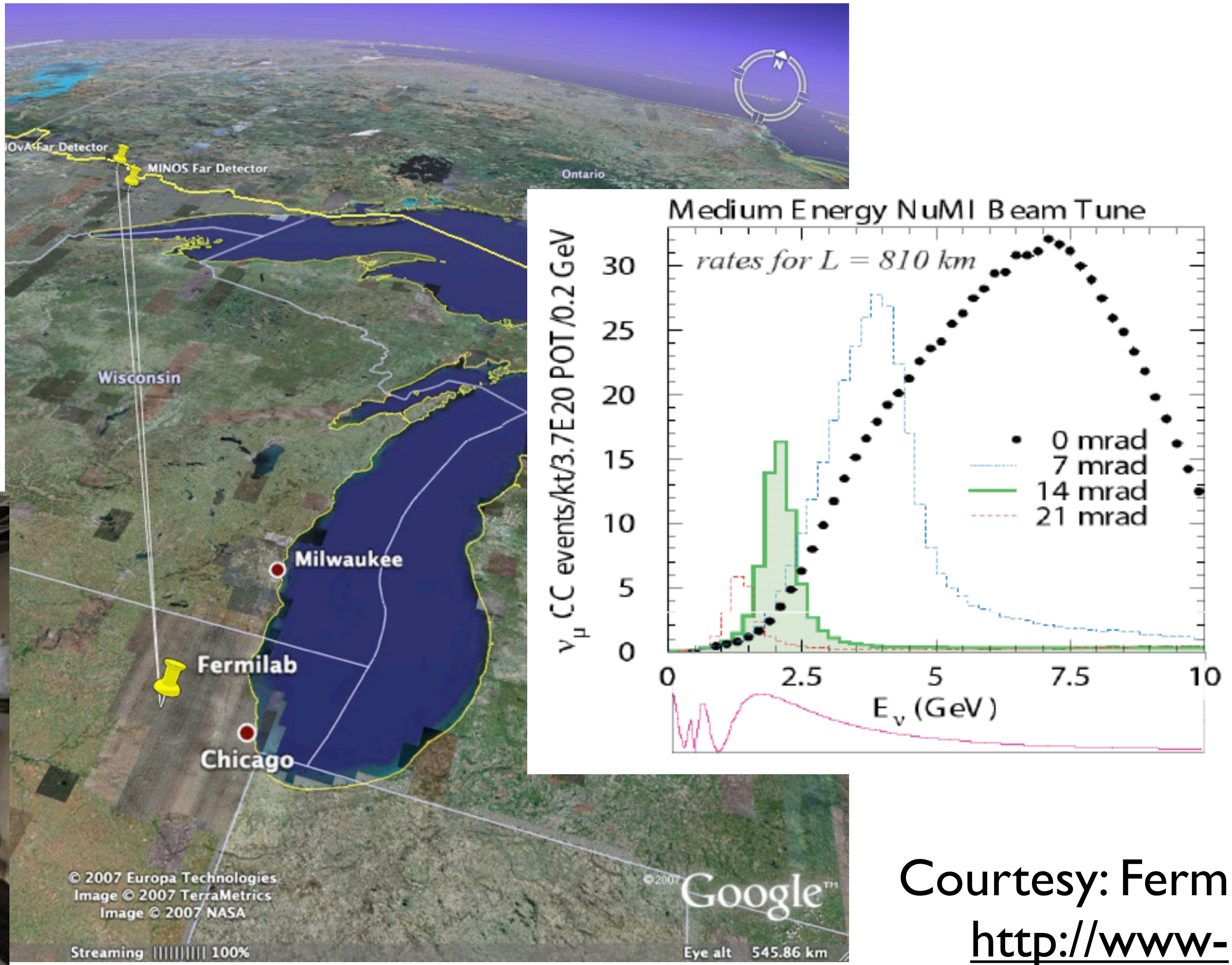
Muon neutrinos come from pion decays with high fluxes and large detectors (T2K, NOvA, T2K-II, LBNE, SPL in EUROnu, LAGUNA-LBNO) at L~100-2000 km.

- Detectors for electron neutrinos: WC, LiAr, TASD.
- Intrinsic contamination of the beam.
- For L>800-1000 km, strong matter effects.

NOvA

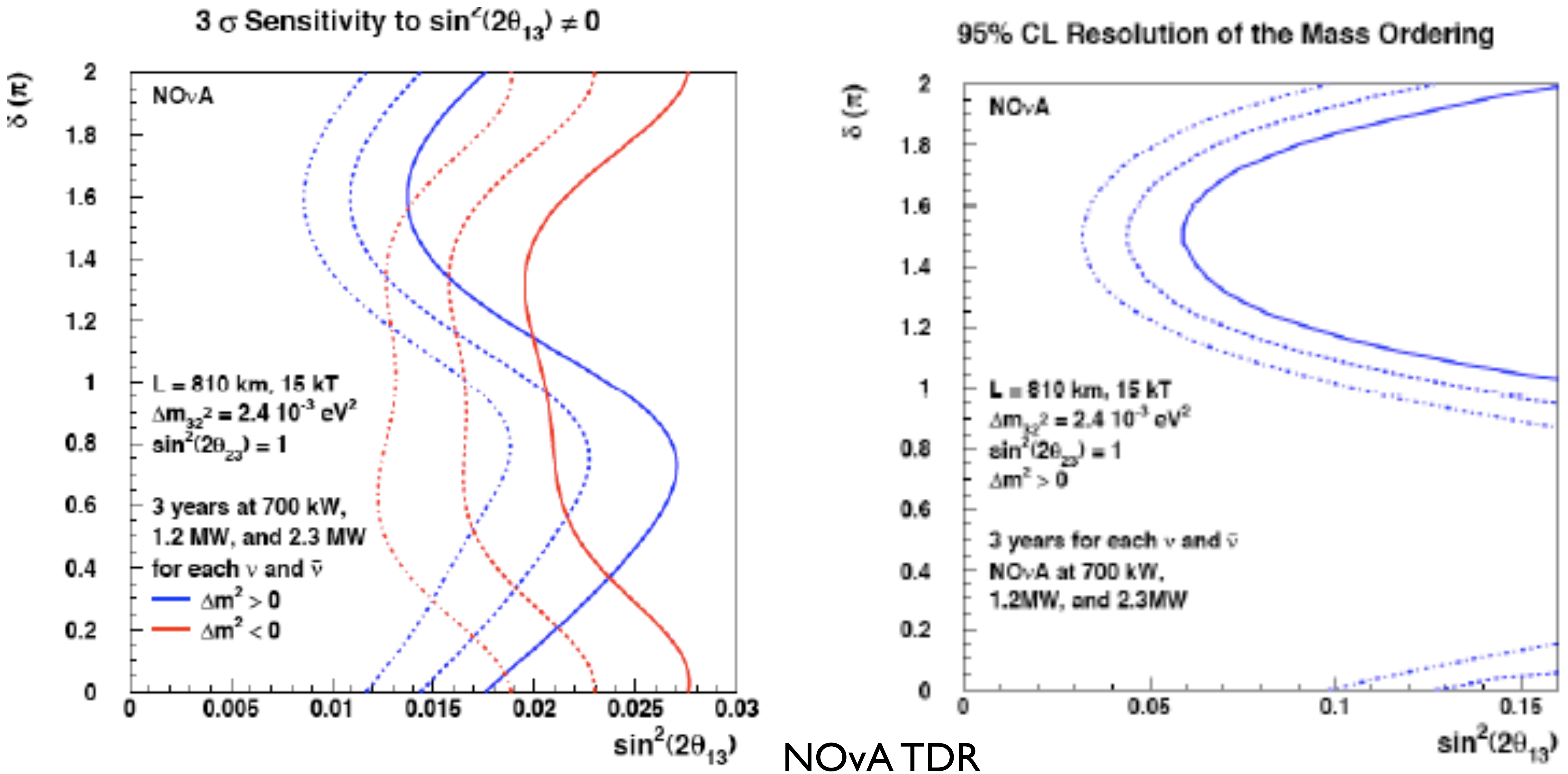



FD enclosure
7.Oct.2010



Courtesy: Fermilab
http://www-nova.fnal.gov/

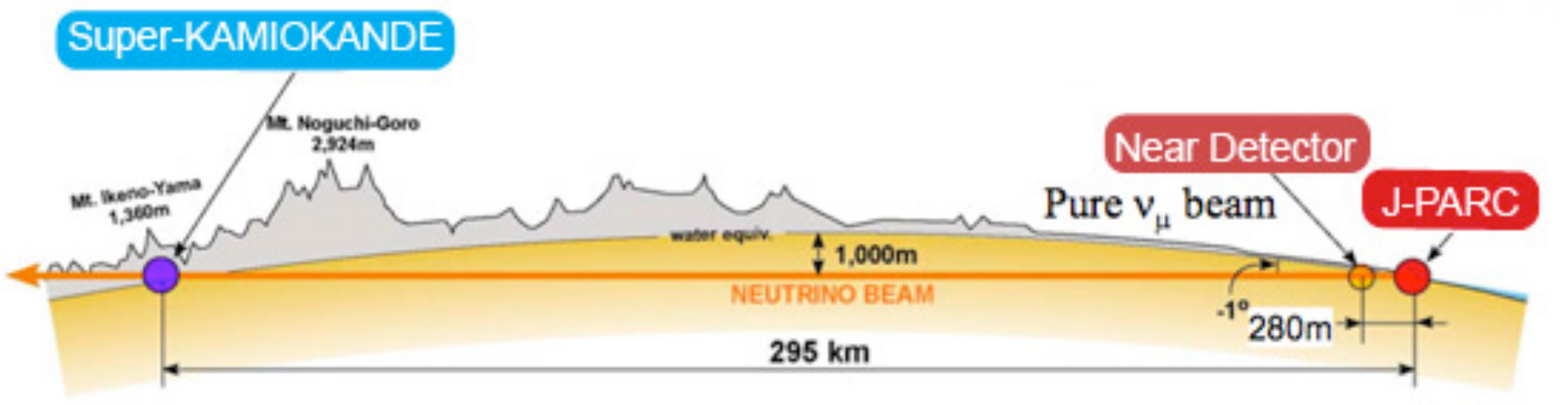
NuMi beam at 700 kW with a far scintillator detector at 800 km off-axis searching for muon to electron neutrino oscillations. Start data taking in 2013.



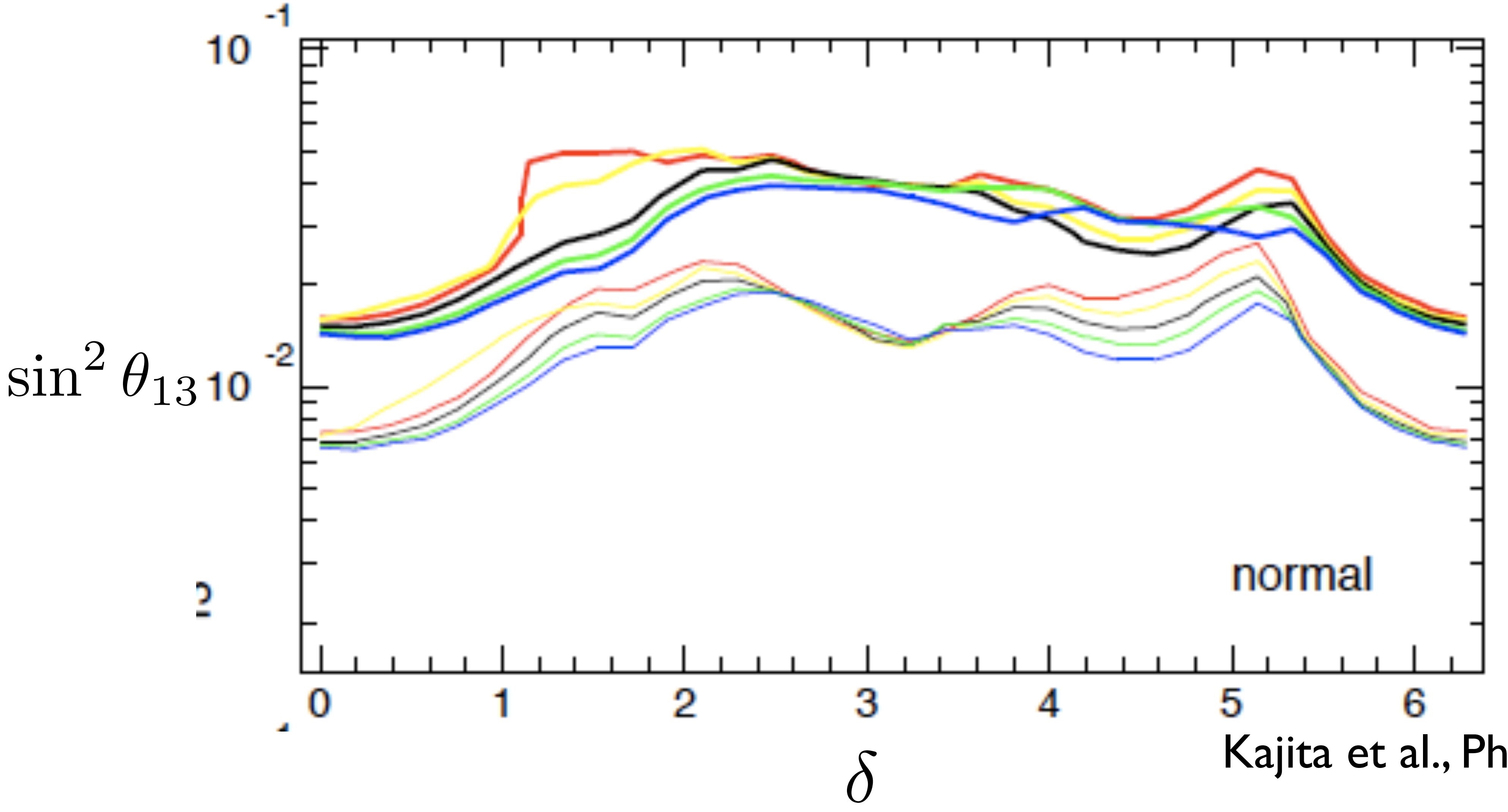
NOvA TDR

NOvA will have a reach in θ_{13} similar to T2K. Due to the longer distance, it has some sensitivity to the mass hierarchy. Combining T2K and NOvA would improve the results (see Huber, Lindner, Winter; also, Mena, Nunokawa, Parke).

T2HK, T2O and T2KK



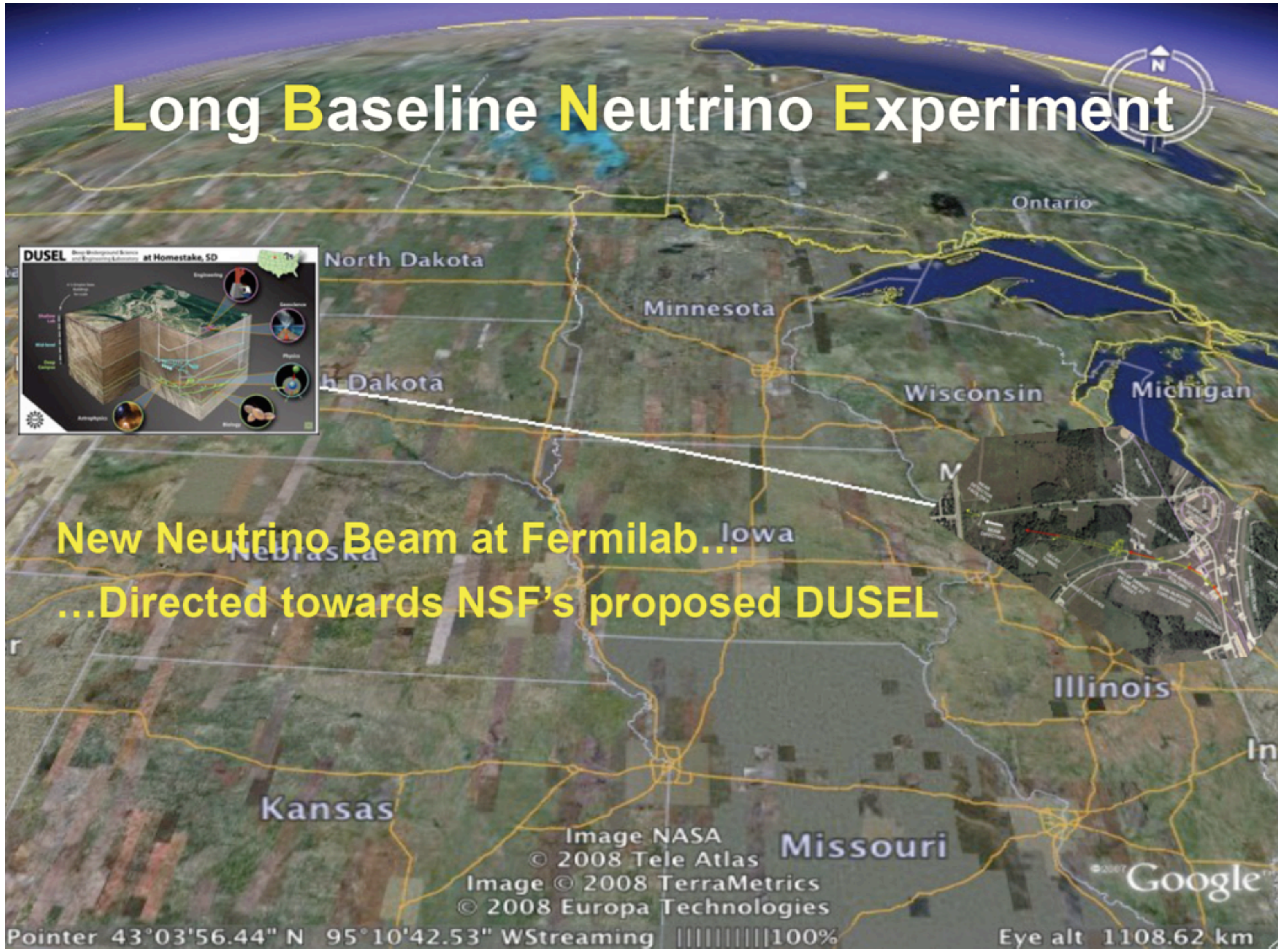
http://www.interactions.org/imagebank/images/KE0123M.jpg



Sensitivity to mass hierarchy. 4 MW (now 1.66 MW) and 0.54+0.27 Mton WC detectors at Kamioka and Korea.

Kajita et al., Phys. Rev. D 72(2005)033003

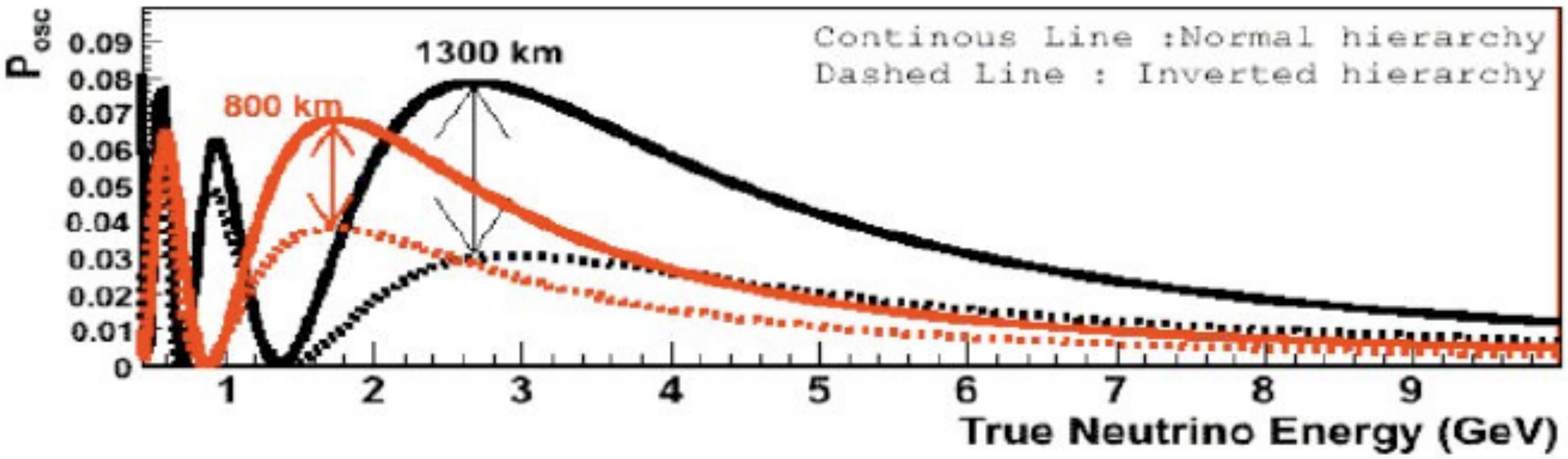
LBNE



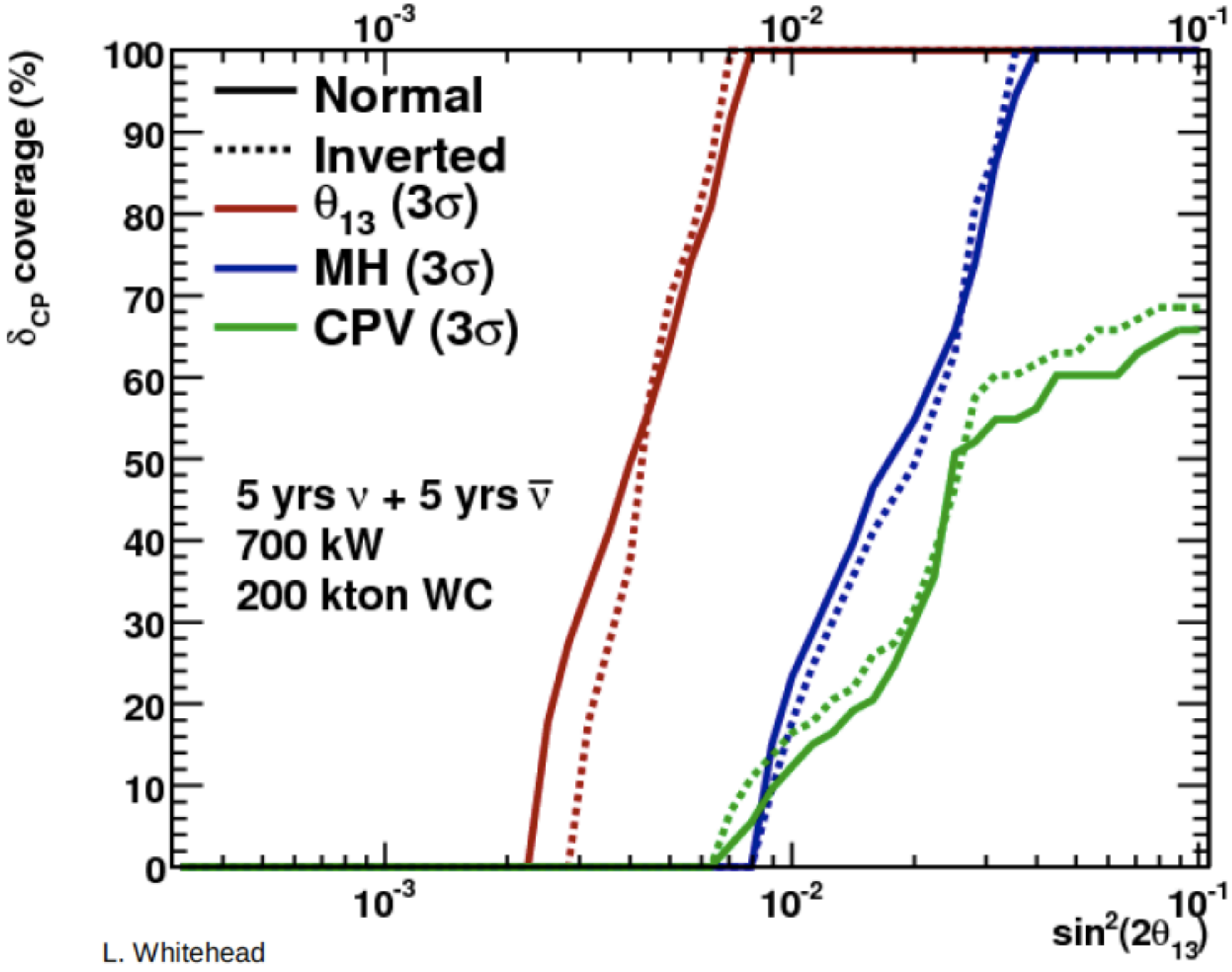
Wideband beam which exploits the rich oscillatory pattern.

With Project X (from 700 kW to 2 MW), even better sensitivities could be obtained.

Presented by S. Parke at NeuTel 2011

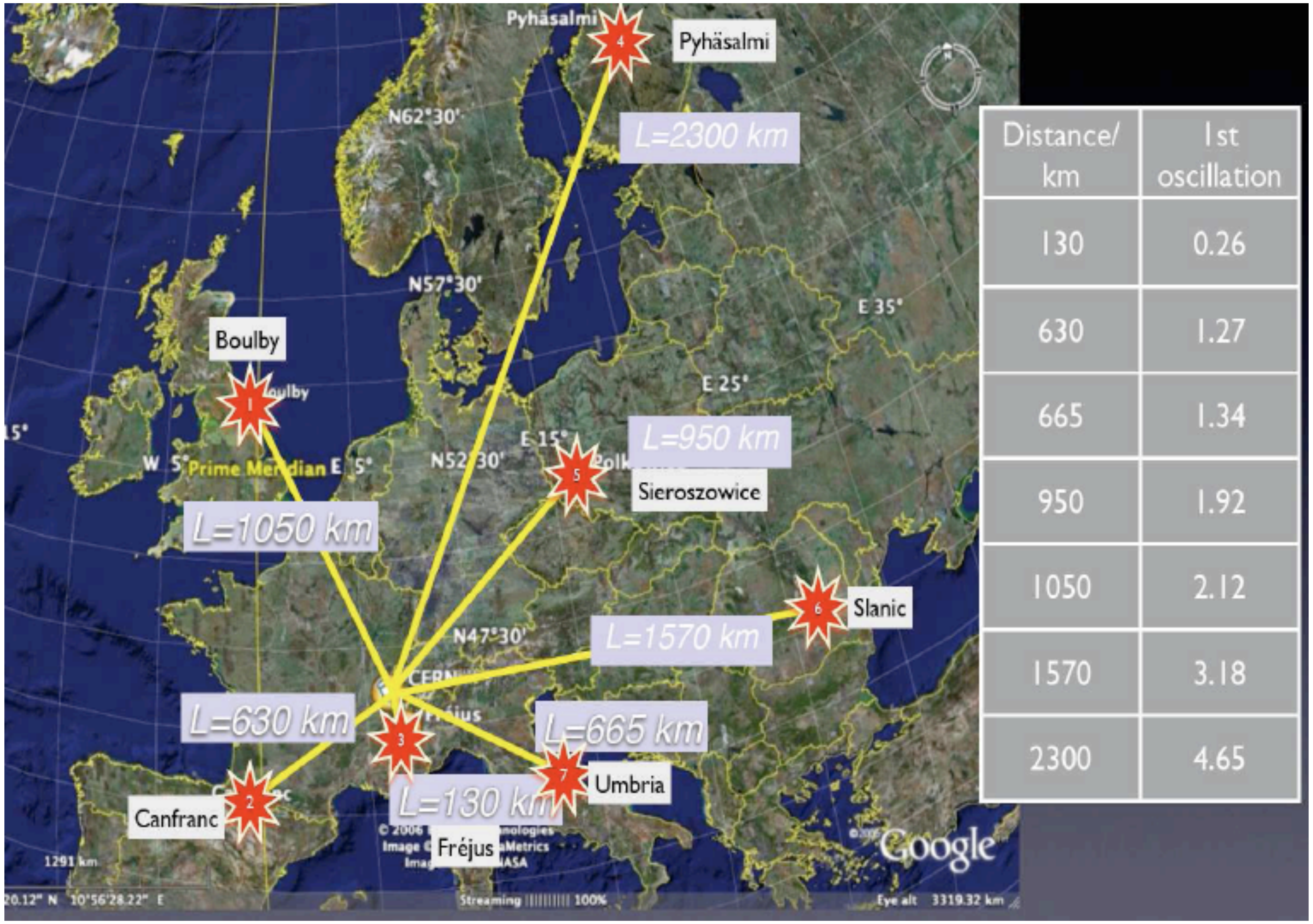


Two detector options: 200 kton WC, 34 kton LiAr. At these energies they have very similar physics reach.



Alternative sites are also considered:
Yucca Mountain (2300 km), Henderson Mine (1500 km), WIPP (1700 km).

LAGUNA-LBNO

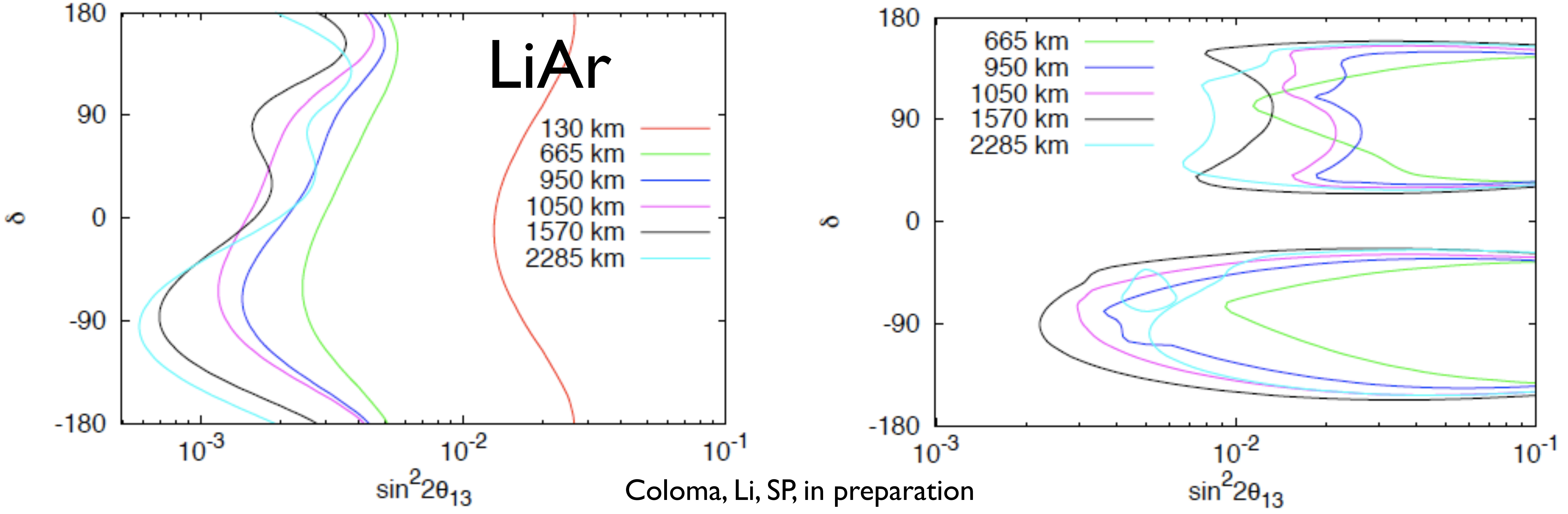


Distance/ km	1st oscillation
130	0.26
630	1.27
665	1.34
950	1.92
1050	2.12
1570	3.18
2300	4.65

European options as part of LAGUNA and LAGUNA-LBNO.

(Li's parallel talk)

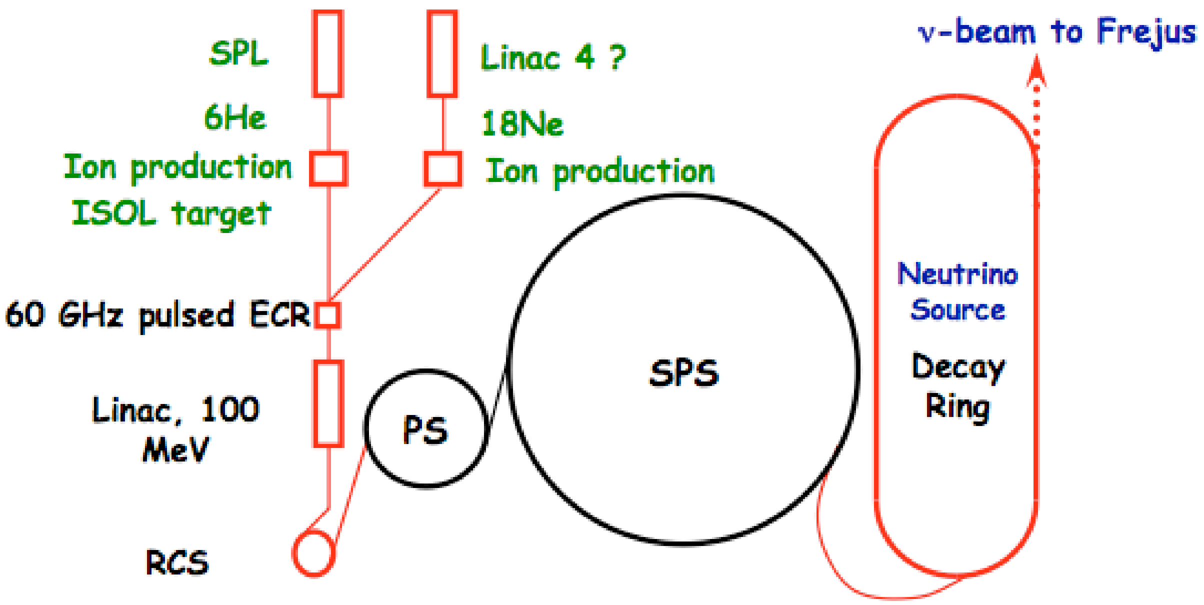
SPL-Frejus studied within EUROnu.



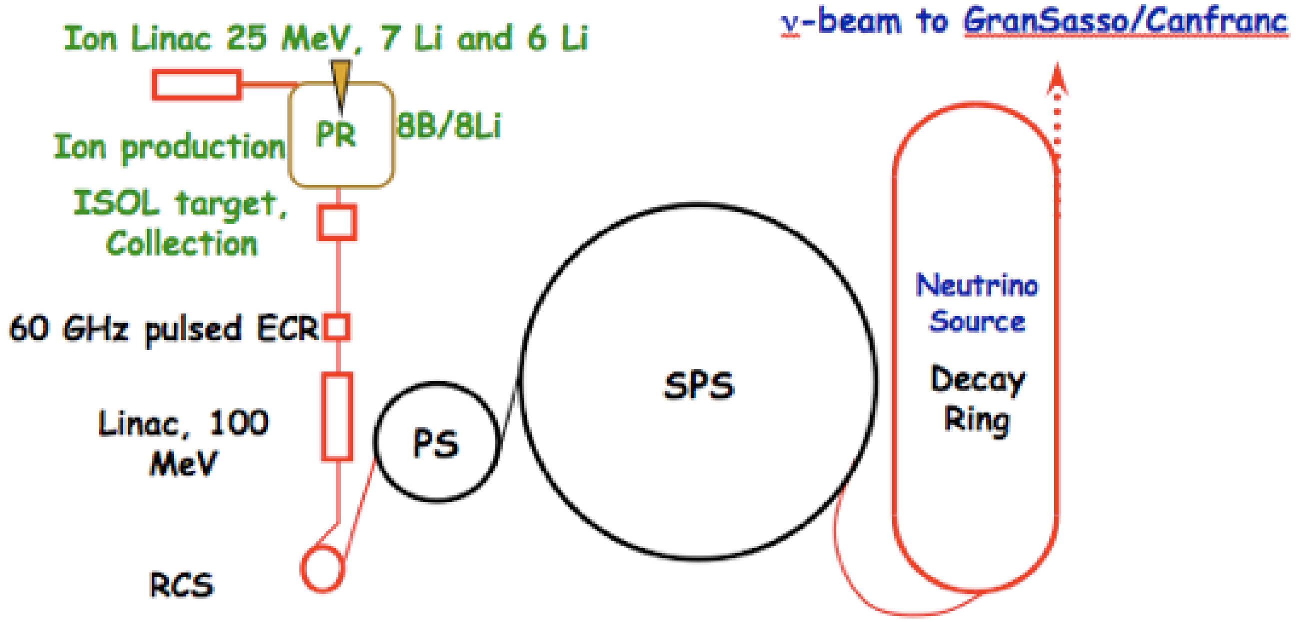
Coloma, Li, SP, in preparation

Betabeams

Electron neutrinos from beta decays of highly accelerated ions. Pure beam but difficult to achieve high neutrino fluxes. Studied in detail within EUROnu.



Scenario 6He/18Ne



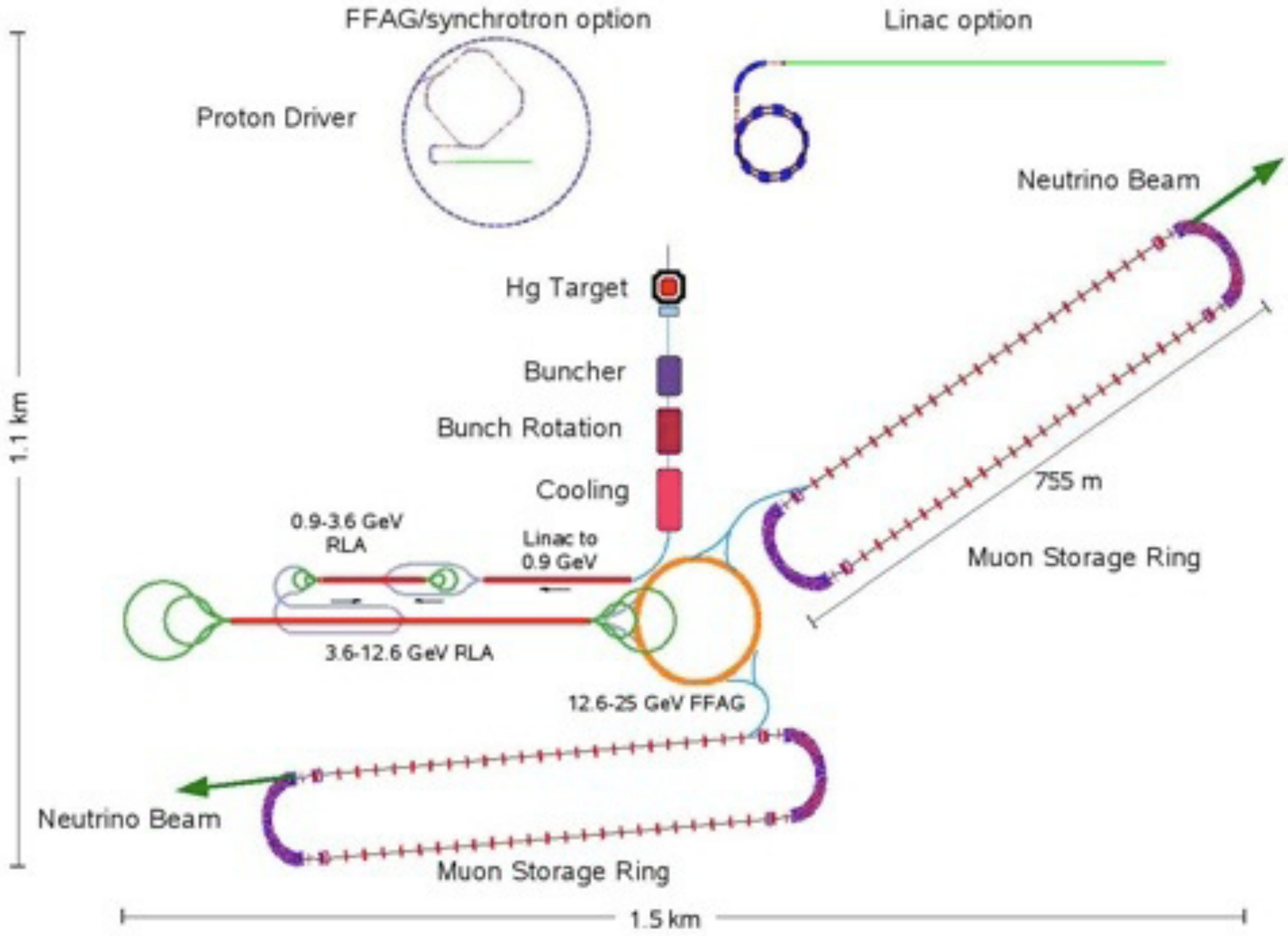
Scenario 8Li/8B

Various options have been considered for high gamma beta beams. They require an upgraded SPS or the LHC.

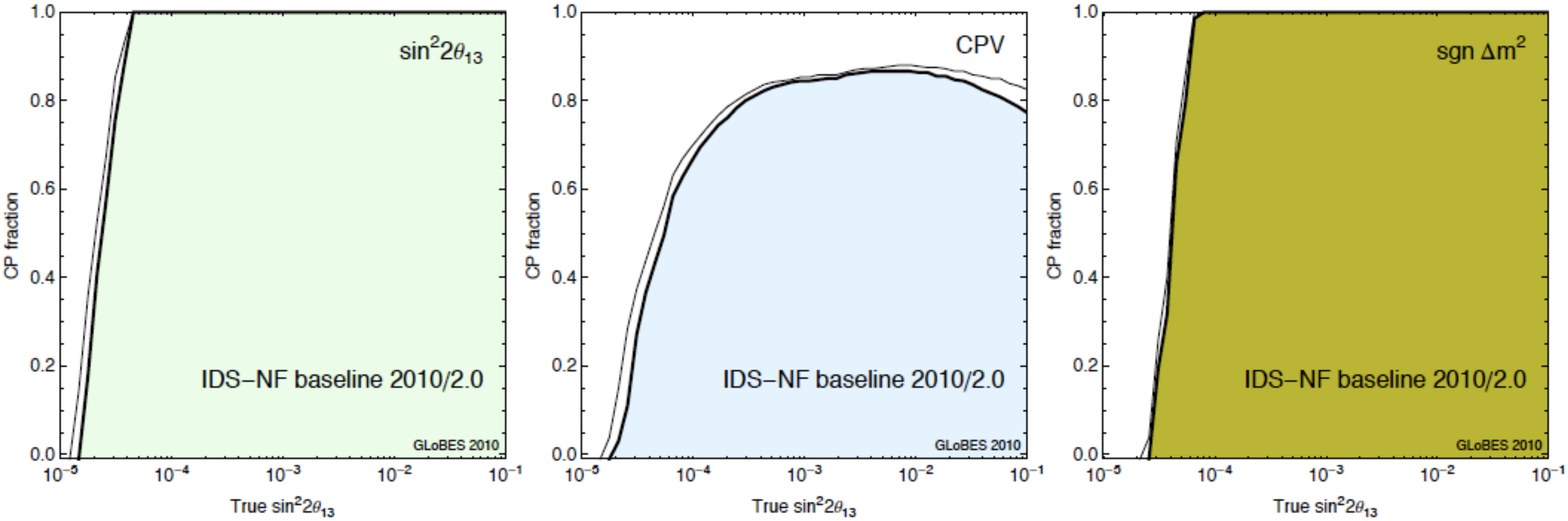
Neutrino factory

Neutrinos from muon decays at L~1500-7000 km. Pure beam and multiple oscillation channels but requires magnetised detector (MIND, LiAr).

See e.g. de Rujula, Gavela, Hernandez; Cervera et al.; Freund, Huber, Lindner; Rubbia ....

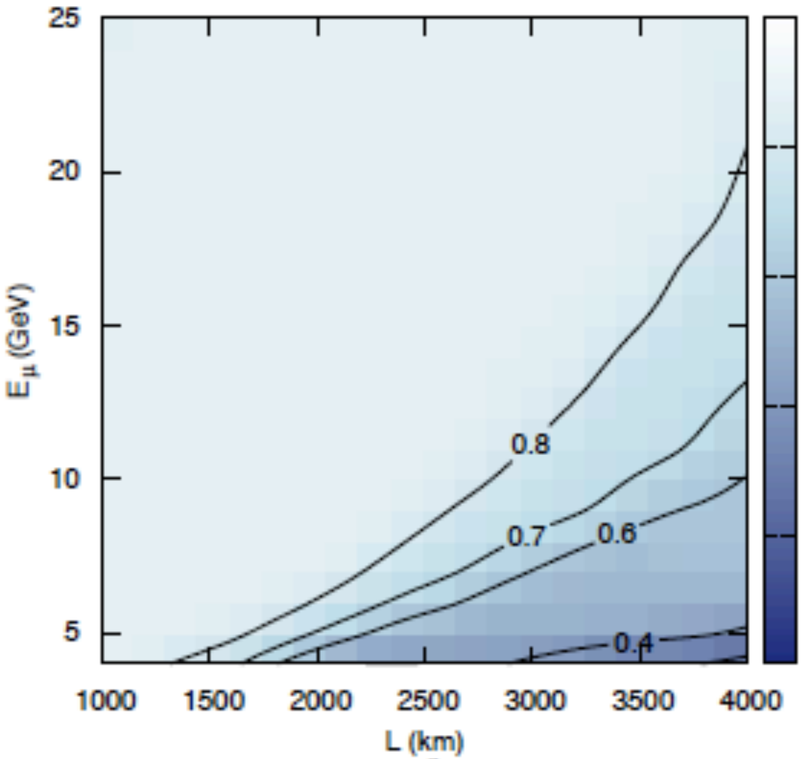


IDS-NF

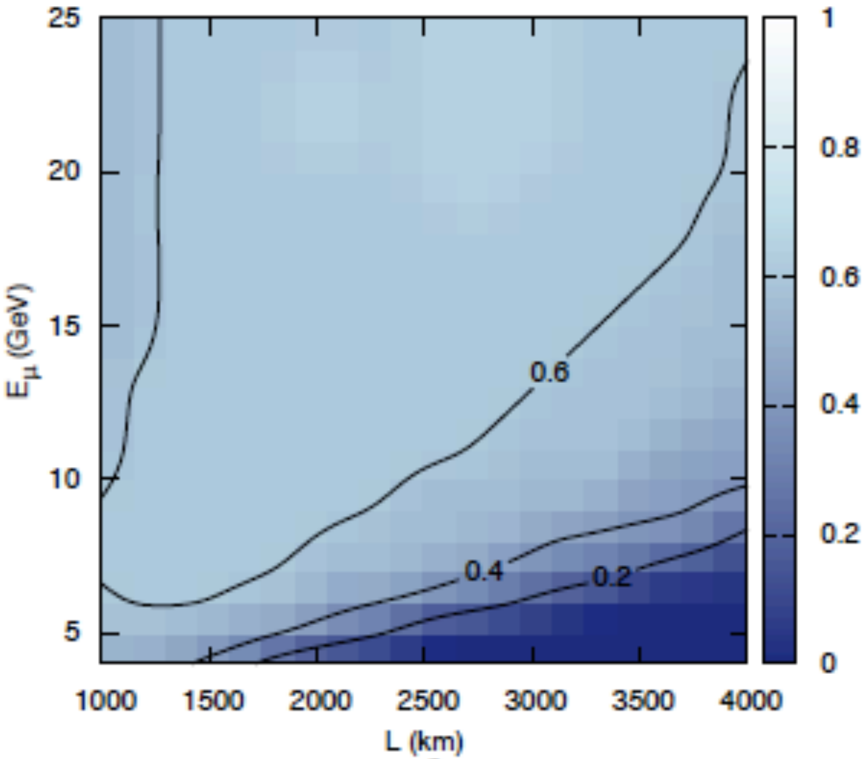


GLOBeS, Huber, Lindner, Winter and Huber, Kopp, Lindner, Rolinec, Winter; see IDS-NF

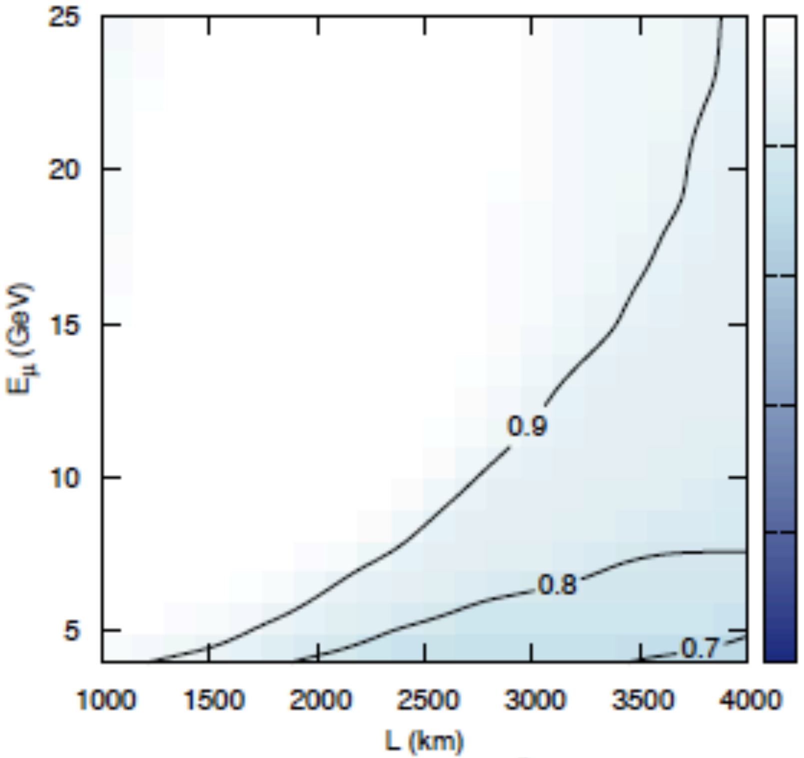
Neutrino factories (HENF, LENF) have excellent reach thanks to very intense fluxes, very small backgrounds and wide beams (IDS study and EUROnu).



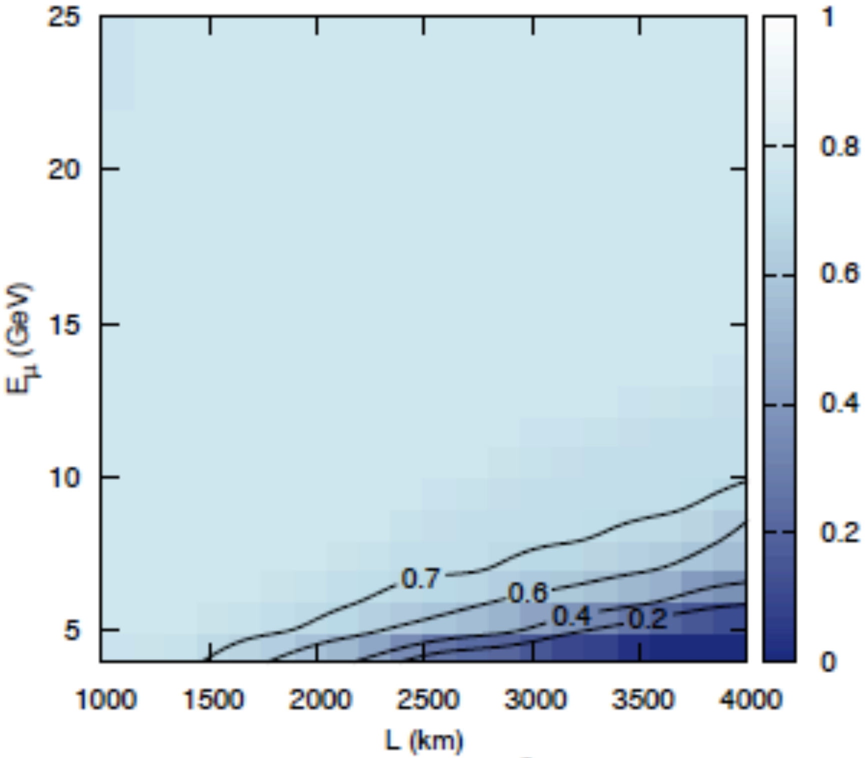
(a)TASD: $\sin^2 2\theta_{13} = 10^{-2}$



(b)TASD: $\sin^2 2\theta_{13} = 10^{-3}$



(c)LAr (optimistic): $\sin^2 2\theta_{13} = 10^{-2}$



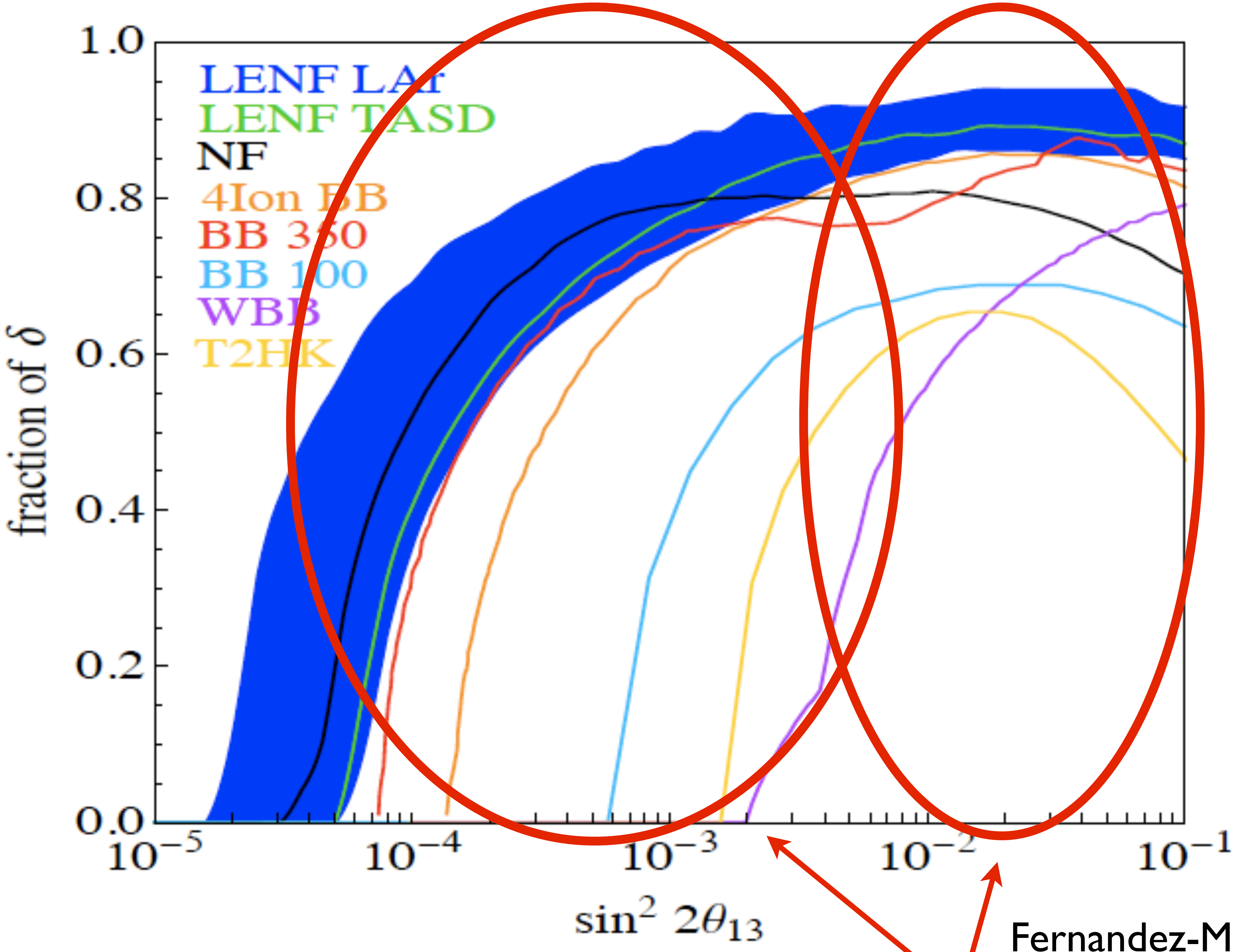
(d)LAr (optimistic): $\sin^2 2\theta_{13} = 10^{-3}$

Sensitivity to CP-violation.

Lines show the fraction of delta for which CPV can be determined.

Excellent sensitivity for large θ_{13} rather independent from L and E and increase in sensitivity with energy for small θ_{13}.

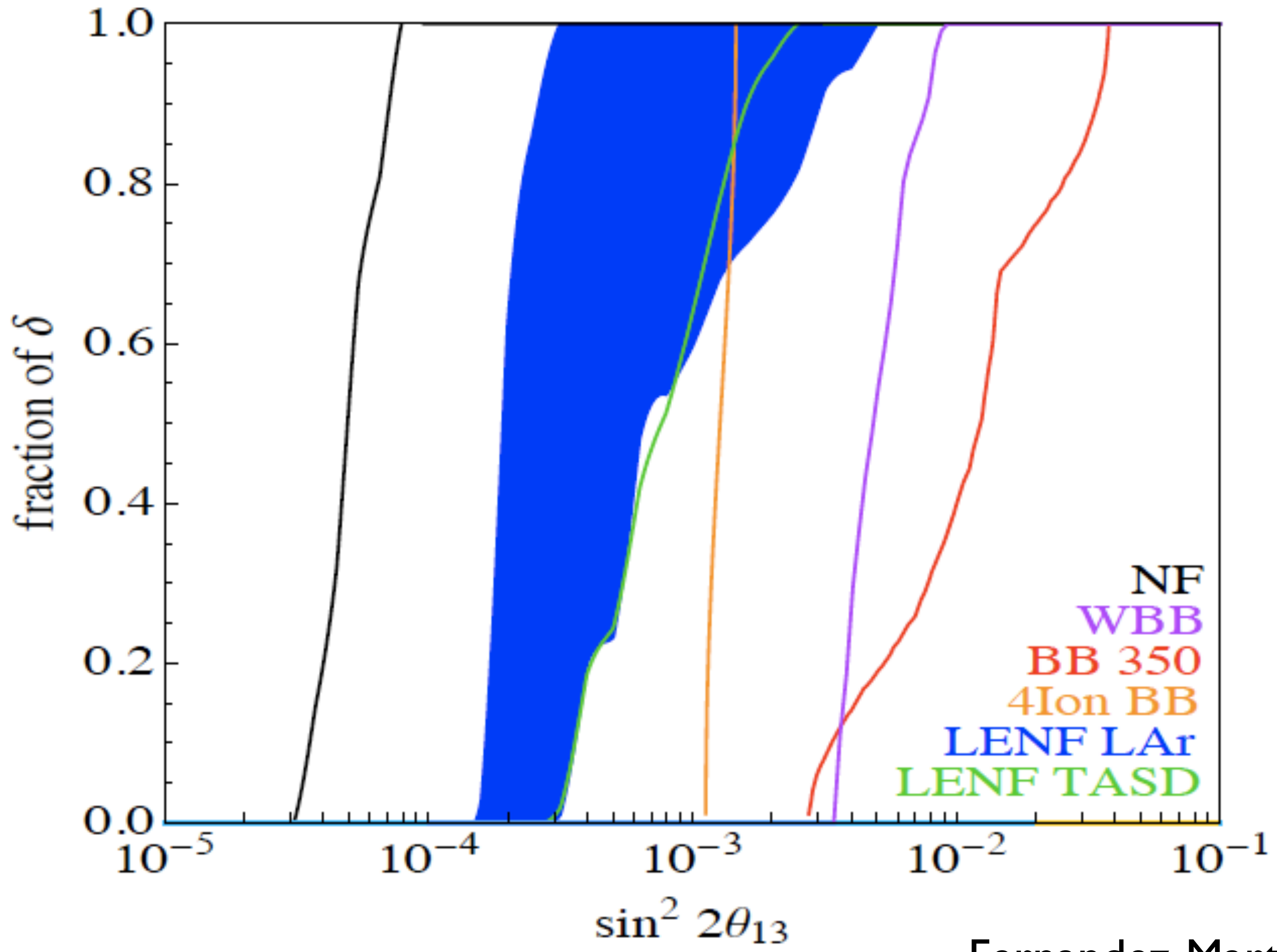
Ballett, Huber, SP



CPV

Fernandez-Martinez et al., 0911.3776

Depending on the values of θ_{13} and on the precision required, **different experimental setups and optimisations are required.**



Fernandez-Martinez et al., 0911.3776

Similar considerations hold also for the type of mass ordering, with long baselines (and consequently high energies) preferred for small θ_{13}.

Going beyond the standard 3 neutrino mixing scenario

A plethora of hints of physics beyond 3 neutrino mixing and SM interactions is present.

Lisi's talk

MINOS antineutrino disappearance data

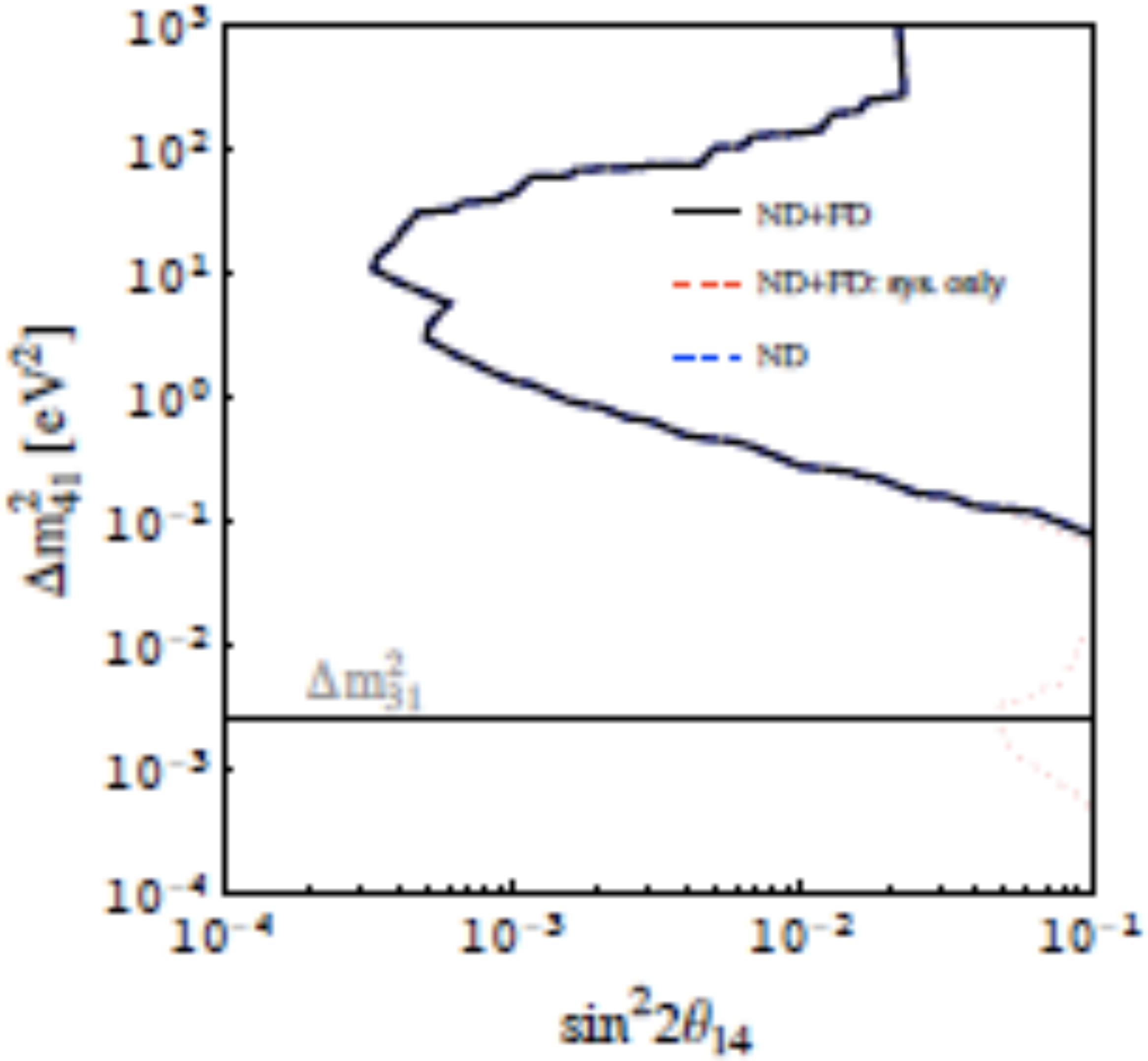
LSND appearance experiment

MiniBooNE neutrino and antineutrino results

Reactor anomaly

If confirmed, it would lead to a radical shift in our understanding of neutrino and physics BSM and would require a reanalysis of the reach of future neutrino oscillation experiments.

Lindner's talk



If sterile neutrinos exist, LBL experiments could use the near detectors to test their existence.

See e.g. Meloni, Tang, Winter, 1007.2419. Also, Donini et al., Antusch et al., Tang and Winter...

LBL experiments are also sensitive to NSI (a possible explanation for MINOS data, Mann et al., Kopp, Machado, Parke). The longer baseline (higher energy), the better physics reach.

Conclusions

- In the past few years, the neutrino oscillation parameters have been measured with precision. The (near) present experiments are going to improve the precision and possibly discover θ_{13} .

- A wide future neutrino programme is planned: neutrinoless double beta decay and long baseline neutrino oscillation experiments.

- They will give crucial information on neutrino properties. Their combination, and also together with direct searches, SBL, supernova, cosmology, can significantly improve the physics reach and test the standard picture (search for inconsistencies).