# Which long-baseline neutrino experiment?

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# Options for a U.S. long-baseline program

NOvA - I:

- off-axis beam from FNAL, L=810 km to 25 kt TASD
- beam energy is tuned to 1st osc. max.
- neutrino mode only

Sensitive only to $\theta_{13} \Rightarrow$ upgrade required

## Possible upgrades:

### NOvA - II:

- upgrade FNAL proton infrastructure (HINS)
- run in neutrino and antineutrino modes
- 2nd detector (liquid Ar TPC at original site)
- 2nd detector (50 Kt water Cherenkov)

- at same L but different OA angle (2nd osc. max.)
- at same L/E but shorter L (diff. matter effect)

Wide band beam:

- upgrade in FNAL proton infrastructure (HINS)
- run in neutrino and antineutrino modes
- 300 kt water Cherenkov detector at DUSEL
- energy spectrum information

Off-axis studied extensively. Consider WBB

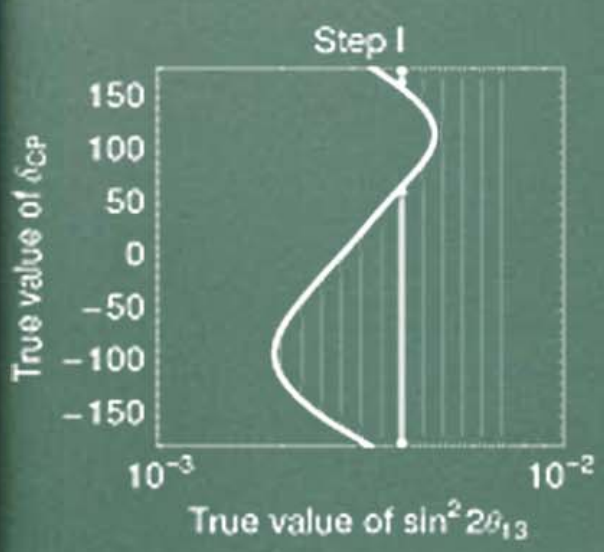
# Performance indicators:

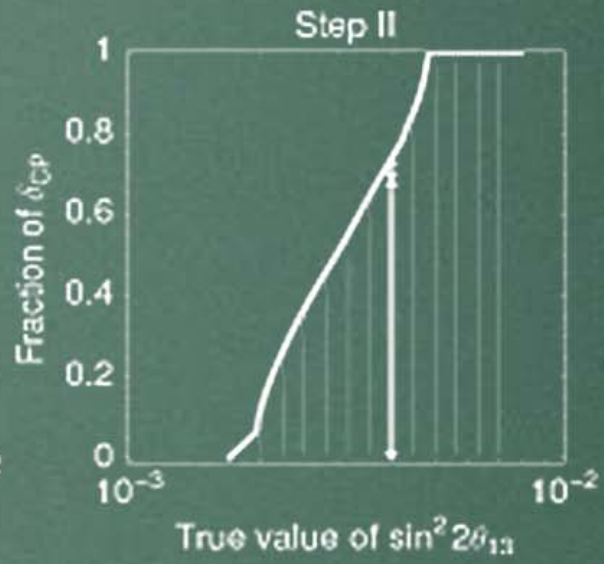
1. $\theta_{13}$ discovery potential – exclusion of $\theta_{13} = 0$

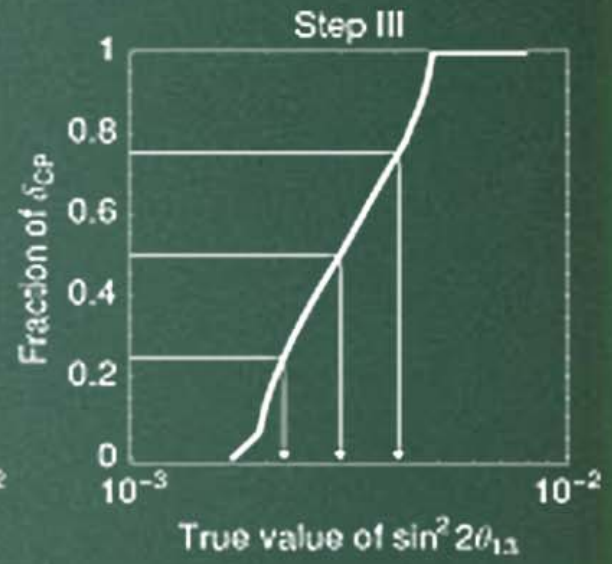
2. discovery of mass hierarchy – suppose $\Delta m^2_{31} > 0$ how well can $\Delta m^2_{31} < 0$ be excluded?

3. CP violation – exclusion of CP conserving values, $\delta = 0, \pi$

# Definition of CP fraction

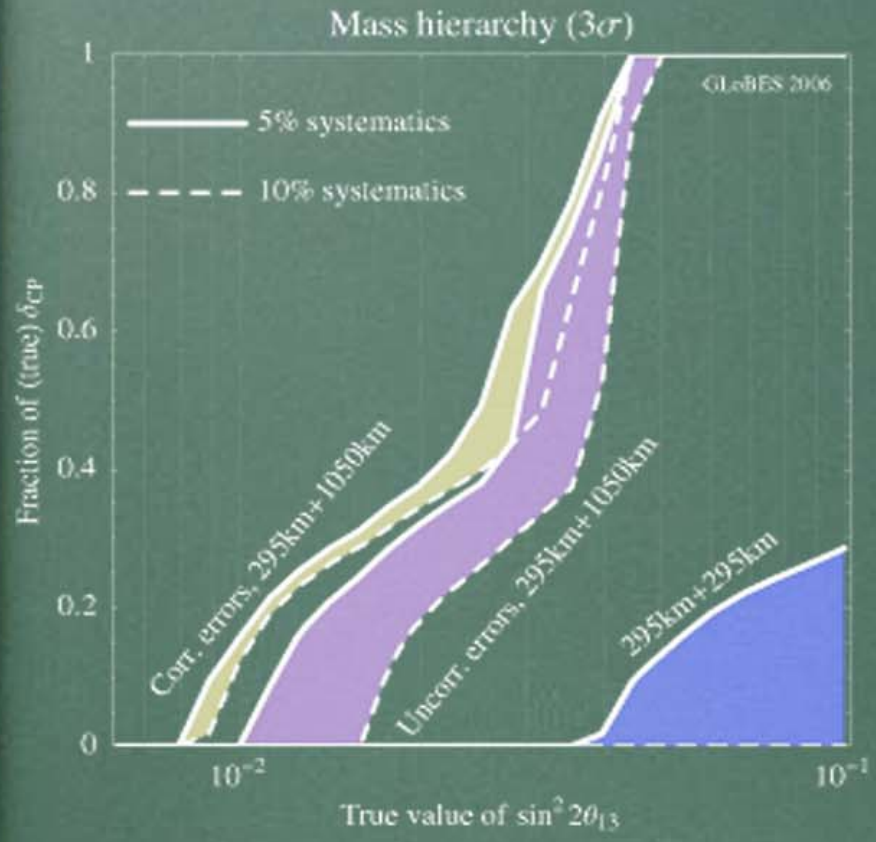


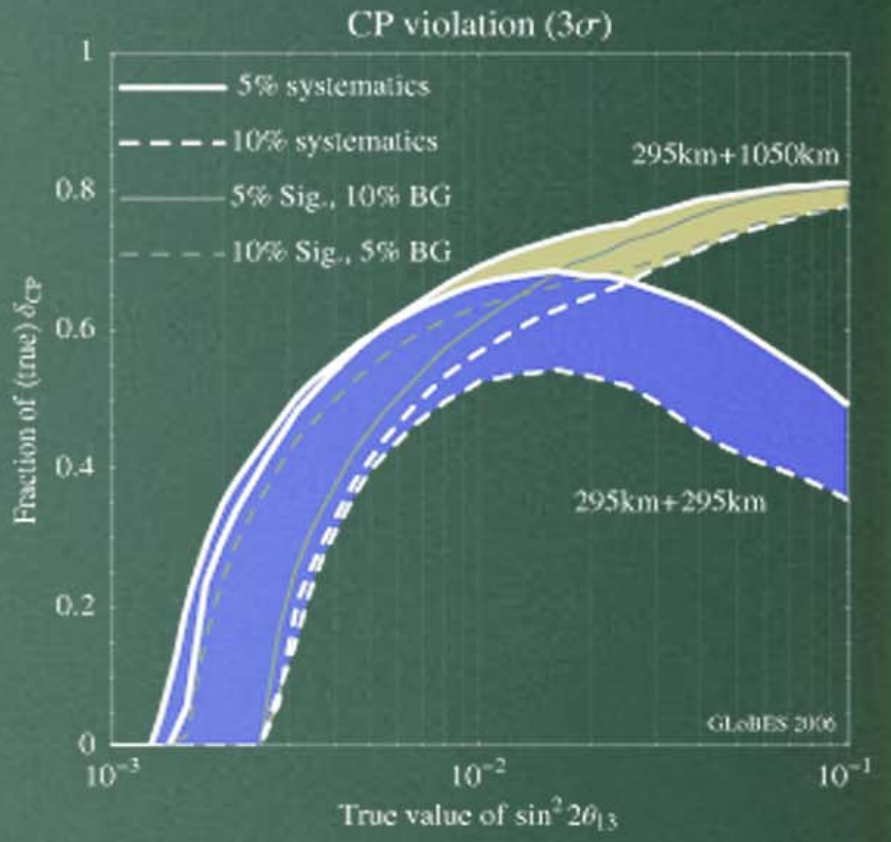



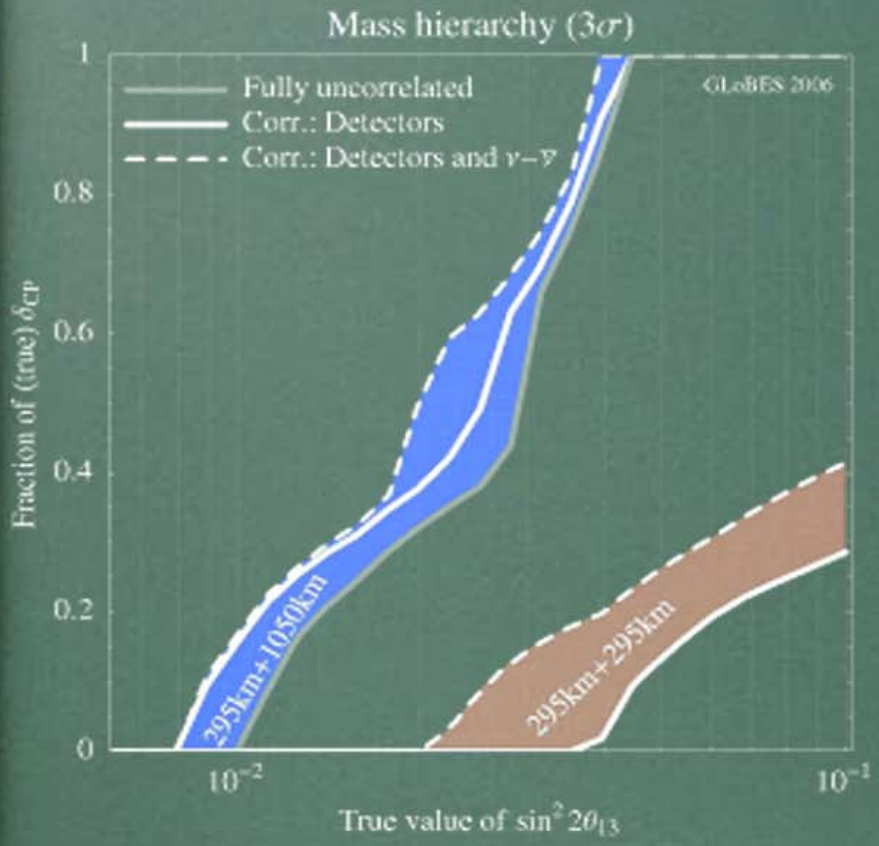



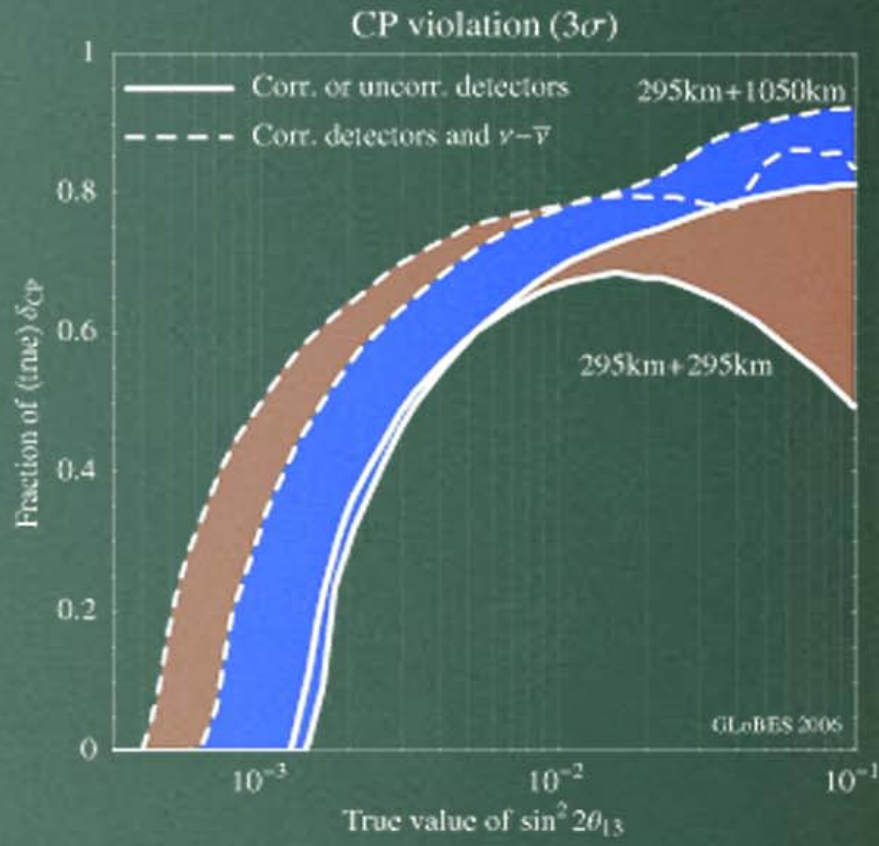
# T2KK

- 4MW protons from Tokai
- same decay tunnel as for T2K
- two 270 kt WC detectors
- two baselines, 295 km and 1050 km
- same off-axis angle
- 4 years neutrinos + 4 years antineutrinos
- $\pi^0$ rejection as in T2K


Mass hierarchy ($3\sigma$)
GLoBES 2006
5% systematics
10% systematics
Corr. errors, 295km+1050km
Uncorr. errors, 295km+1050km
295km+295km
Fraction of (true) $\delta_{CP}$
True value of $\sin^2 2\theta_{13}$
1
0.8
0.6
0.4
0.2
0
$10^{-2}$
$10^{-1}$


CP violation ($3\sigma$)
5% systematics
10% systematics
5% Sig., 10% BG
10% Sig., 5% BG
295km+1050km
295km+295km
GLoBES 2006
Fraction of (true) $\delta_{CP}$
True value of $\sin^2 2\theta_{13}$
1
0.8
0.6
0.4
0.2
0
$10^{-3}$
$10^{-2}$
$10^{-1}$


Mass hierarchy ($3\sigma$)
Fully uncorrelated
Corr.: Detectors
Corr.: Detectors and $\nu-\overline{\nu}$
GLoBES 2006
295km+1050km
295km+295km
Fraction of (true) $\delta_{CP}$
True value of $\sin^2 2\theta_{13}$
1
0.8
0.6
0.4
0.2
0
$10^{-2}$
$10^{-1}$


CP violation ($3\sigma$)
Corr. or uncorr. detectors
Corr. detectors and $\nu-\overline{\nu}$
295km+1050km
295km+295km
GLoBES 2006
Fraction of (true) $\delta_{CP}$
True value of $\sin^2 2\theta_{13}$
1
0.8
0.6
0.4
0.2
0
$10^{-3}$
$10^{-2}$
$10^{-1}$

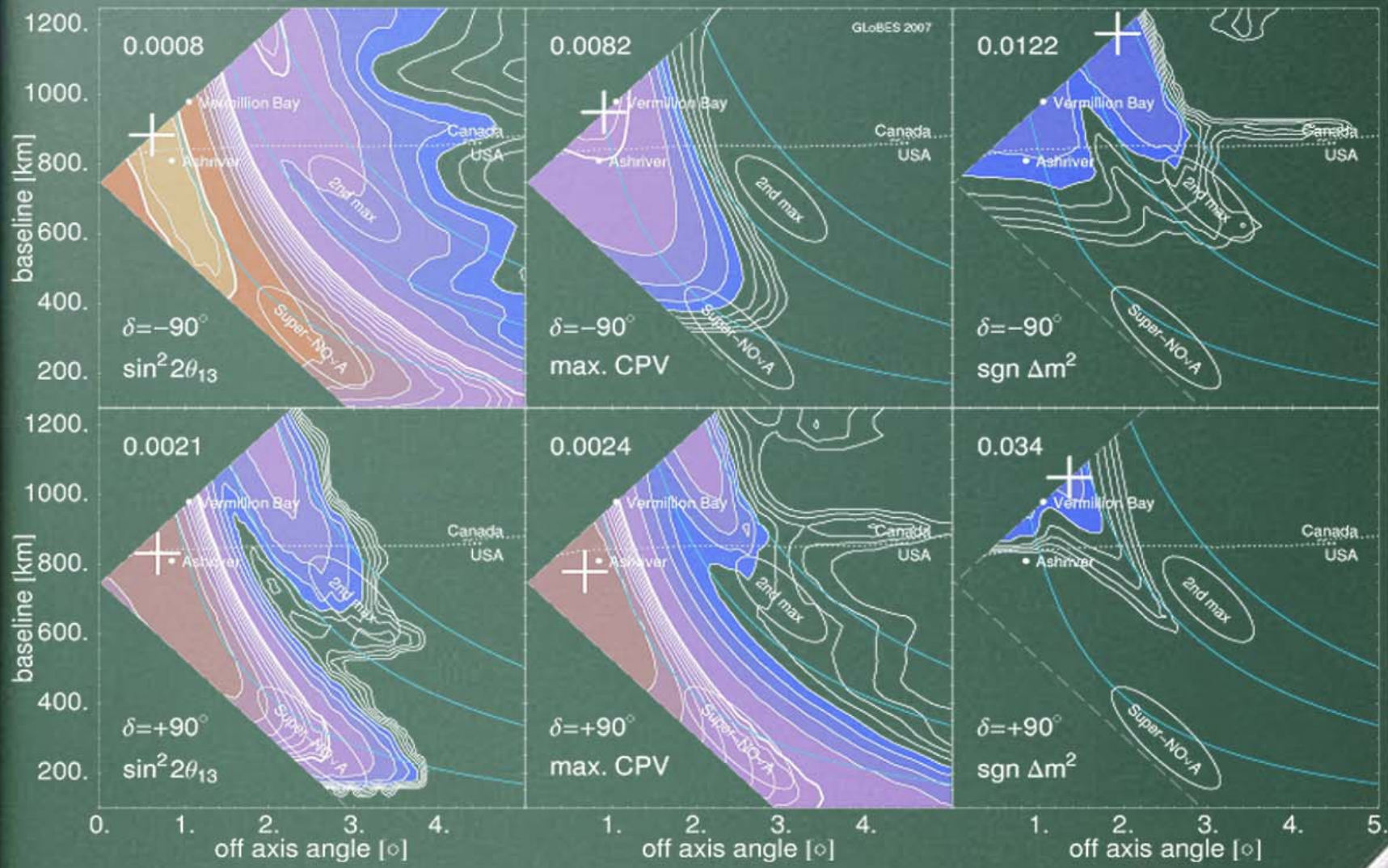
# NOvA*

- 1.13 MW from MI at FNAL
- same decay tunnel as for MINOS and NOvA
- 100 kt LArTPC
- 3 years neutrinos + 3 years antineutrinos of 25kt NOvA at Ash River
- +3 years neutrinos + 3 years antineutrinos of both

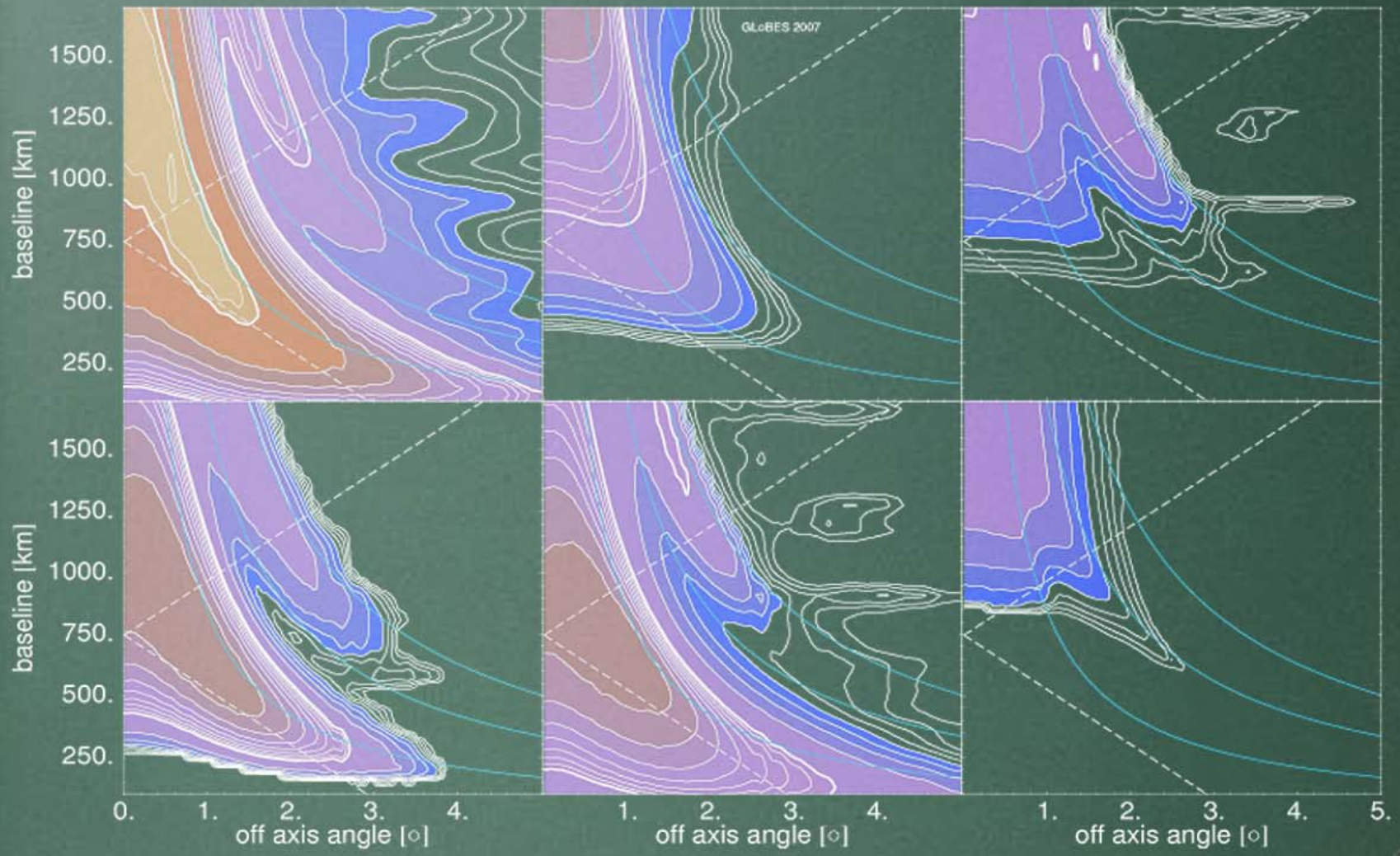
## LArTPC

- 80% efficiency
- no NC background
- 5% energy resolution for QE events
- 20% energy resolution for non-QE events

# Where to put NOvA*?



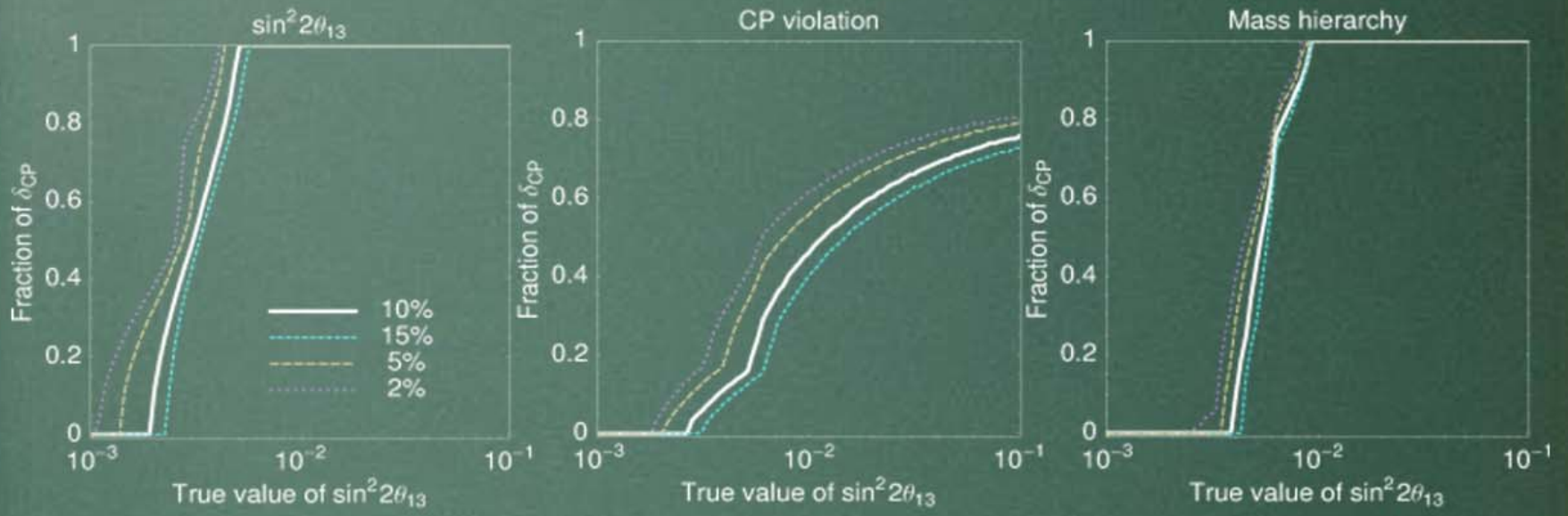
# On-axis or off-axis?



# WBB

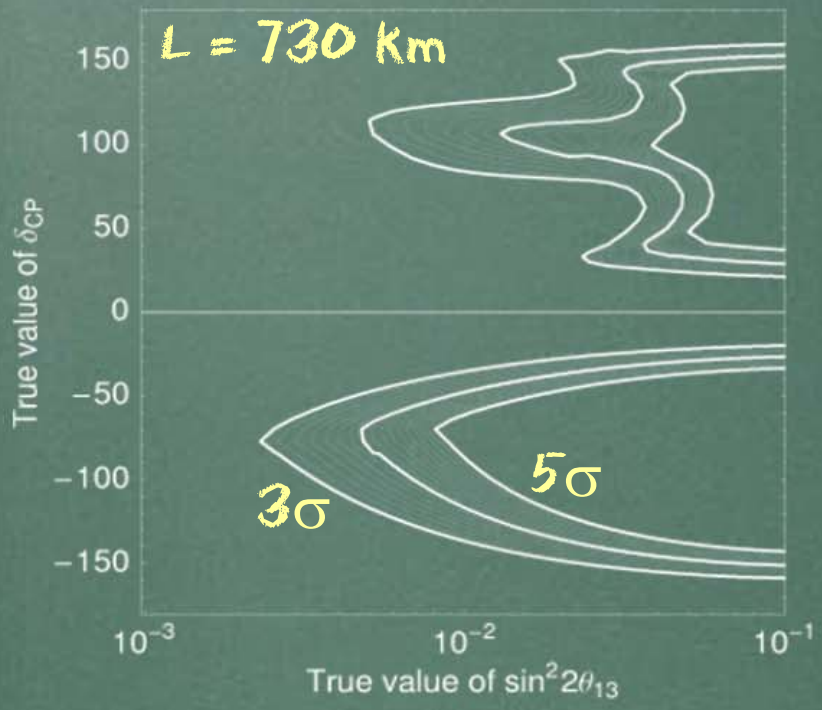
- 1($\nu$) + 2($\overline{\nu}$) MW at 28 GeV
- 300 kt WC detector on axis
- L = 1300 km
- 5 years neutrinos + 5 years antineutrinos
- performance based on full detector MC
- improved $\pi^0$ rejection

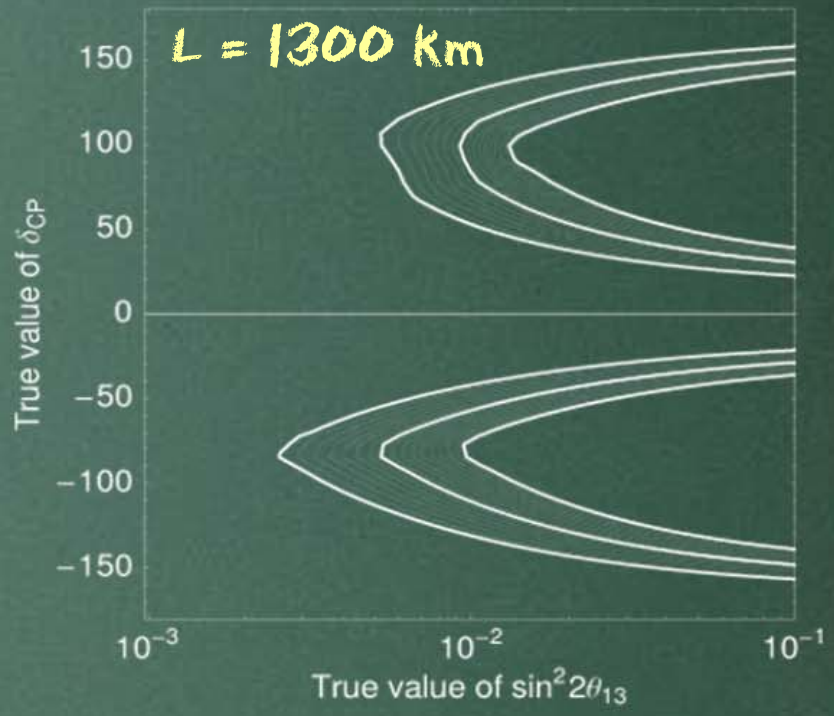
# $3\sigma$ sensitivities

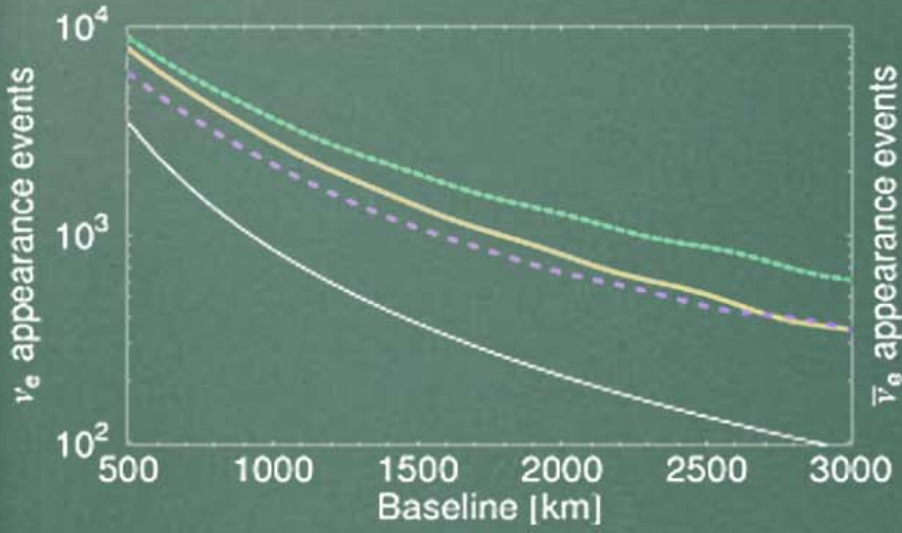


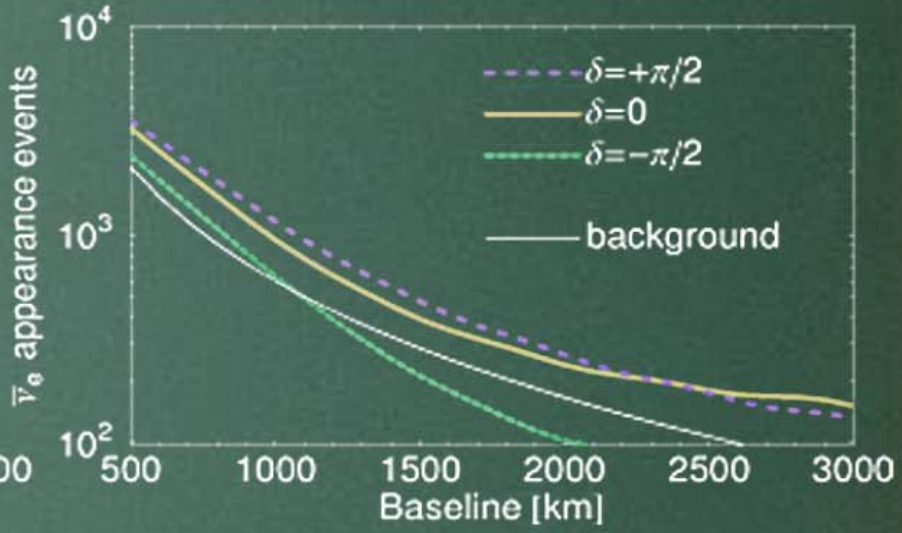

Barger, Dierckxsens, Diwan, Huber, Lewis, Marfatia, Viren (hep-ph/0607177)

# Discovery potential for CP violation



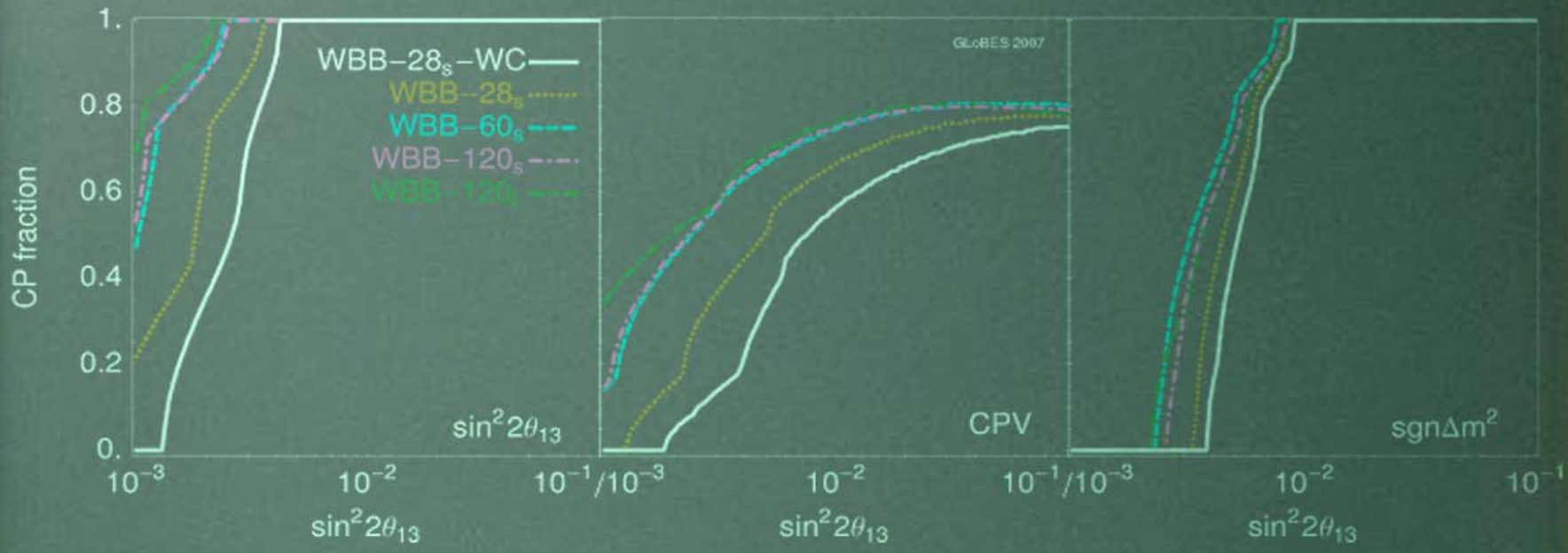






$\sin^2 2\theta_{13} = 0.1$

# Proton energies and decay tunnel length



Different proposals assume different

- uptime/year
- number of years
- detector size
- beam power

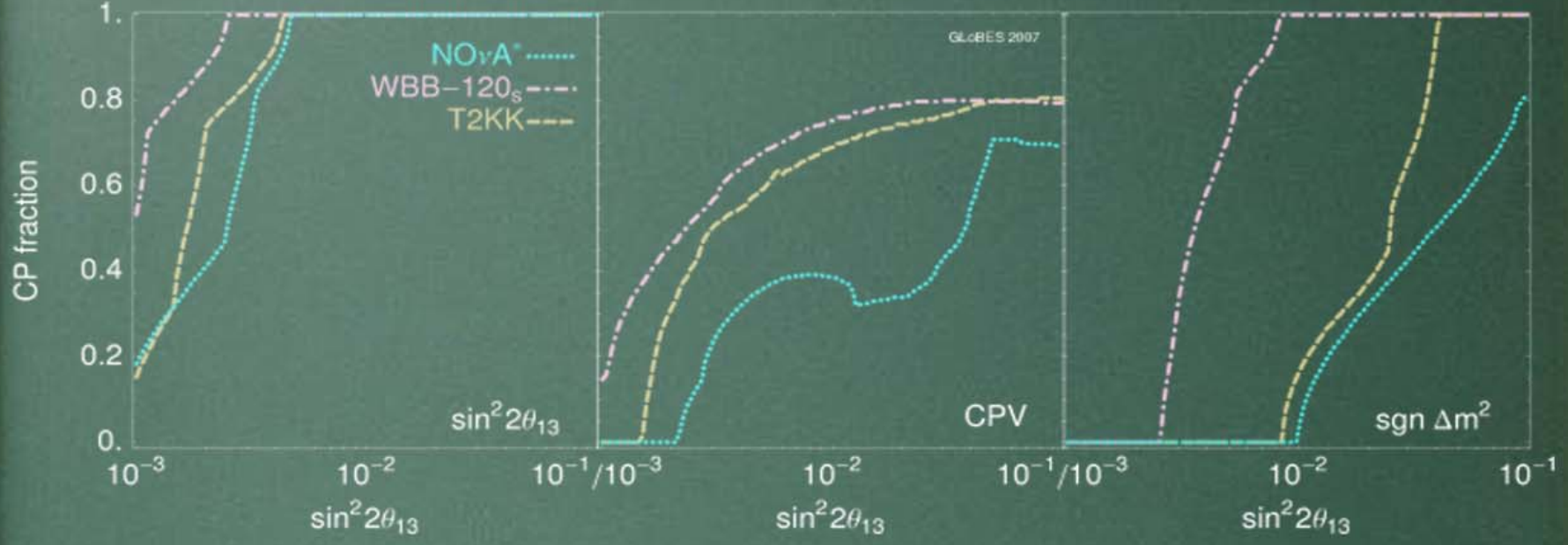
Exposure = detector mass (MMt) x target power (MMW)

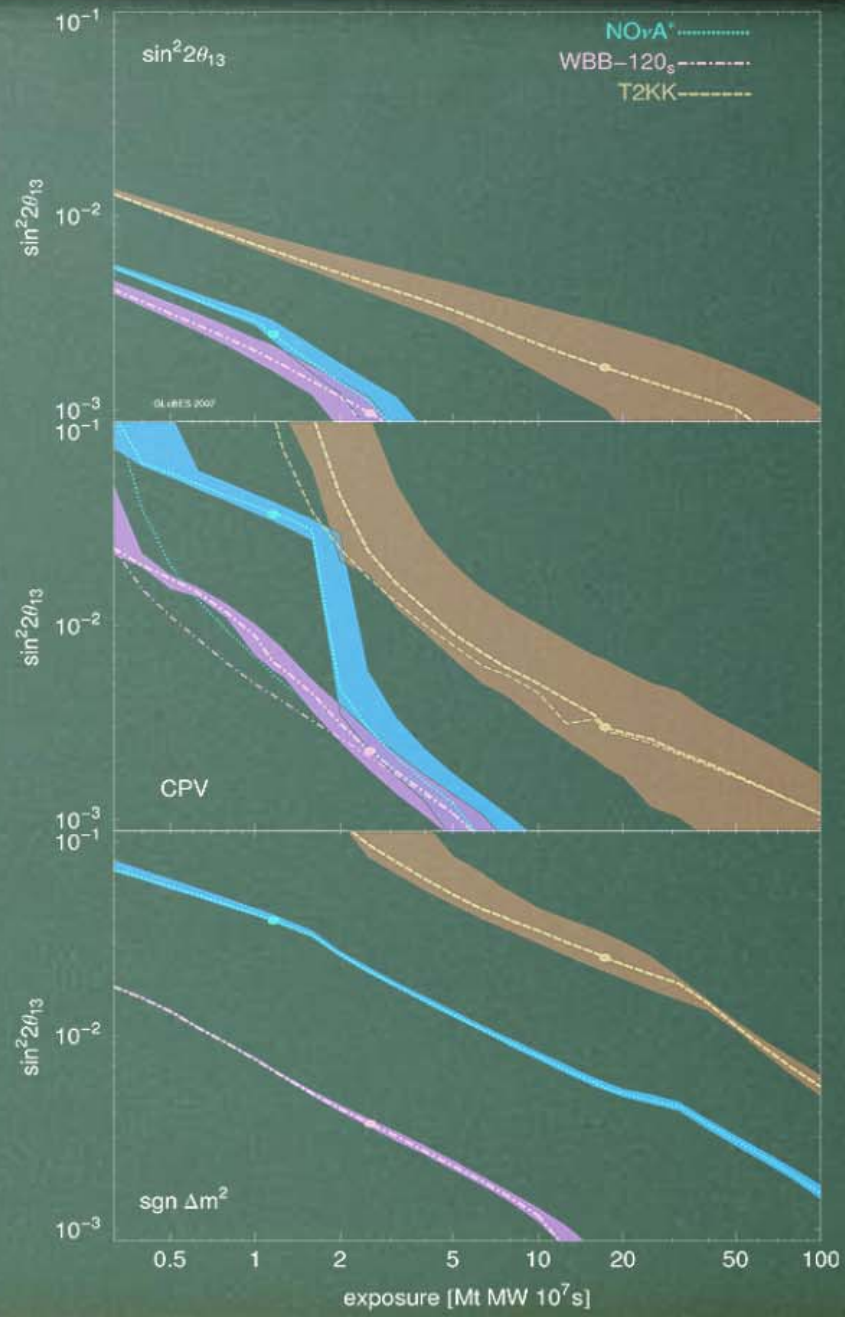
x running time ($10^7$s)

is a measure of integrated luminosity

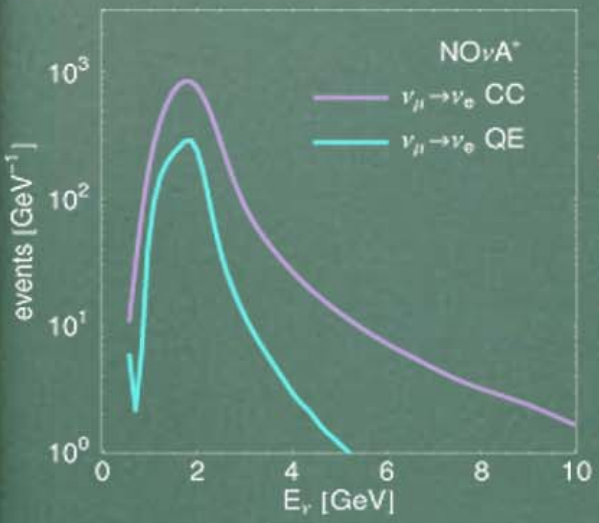
Very approximately, cost $\propto$ exposure

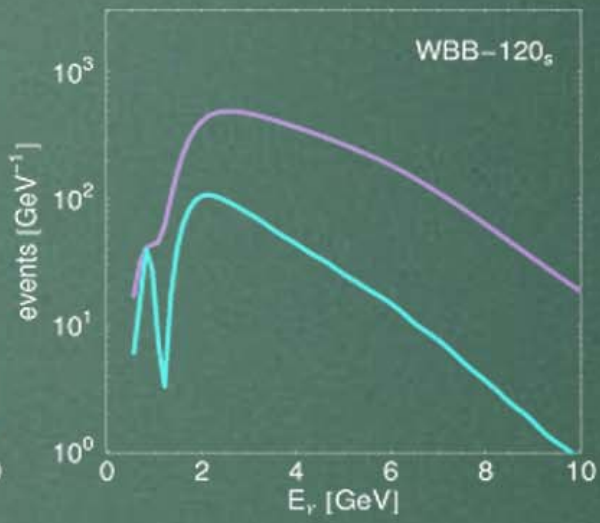
| Setup | $t_\nu$ [yr] | $t_{\bar{\nu}}$ [yr] | $P_{\text{Target}}$ [MW] | $L$ [km] | Detector technology | $m_{\text{Det}}$ [kt] | $\mathcal{L}$ |
|---|---|---|---|---|---|---|---|
| NO$\nu$A* | 3 | 3 | 1.13 ($\nu/\bar{\nu}$) | 810 | LArTPC | 100 | 1.15 |
| WBB-120$_{\text{S}}$ | 5 | 5 | 1 ($\nu$) +2 ($\bar{\nu}$) | 1290 | LArTPC | 100 | 2.55 |
| T2KK | 4 | 4 | 4 ($\nu/\bar{\nu}$) | 295+1050 | Water Cherenkov | 270+270 | 17.28 |
| $\beta$-beam | 4 | 4 | n/a | 730 | Water Cherenkov | 500 | n/a |
| NuFact | 4 | 4 | 4 | 3000+7500 | Magn. iron calor. | 50+50 | n/a |

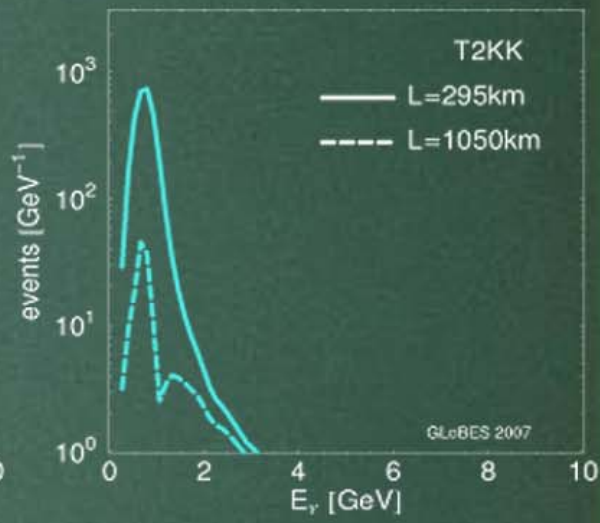

CP fraction
1.
0.8
0.6
0.4
0.2
0.
NOνA
WBB−120s
T2KK
GLoBES 2007
sin²2θ13
CPV
sgn Δm²
10⁻³
10⁻²
10⁻¹/10⁻³
10⁻¹
sin²2θ13


$\sin^2 2\theta_{13}$
NOνA
WBB–120$_s$
T2KK
GLoBES 2007
CPV
sgn $\Delta m^2$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0.5
1
2
5
10
20
50
100
exposure [Mt MW $10^7$s]

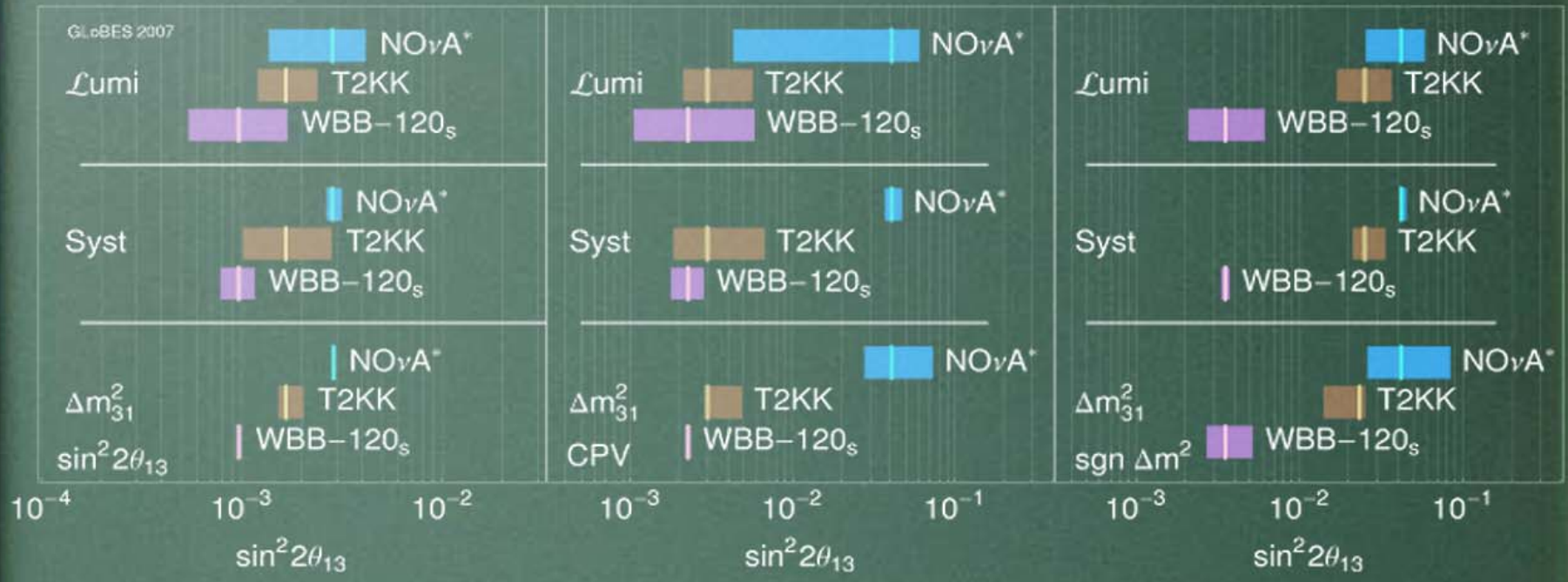
# Event rates for 1 MT MW $10^7$s and $\sin^2 2\theta_{13} = 0.04$



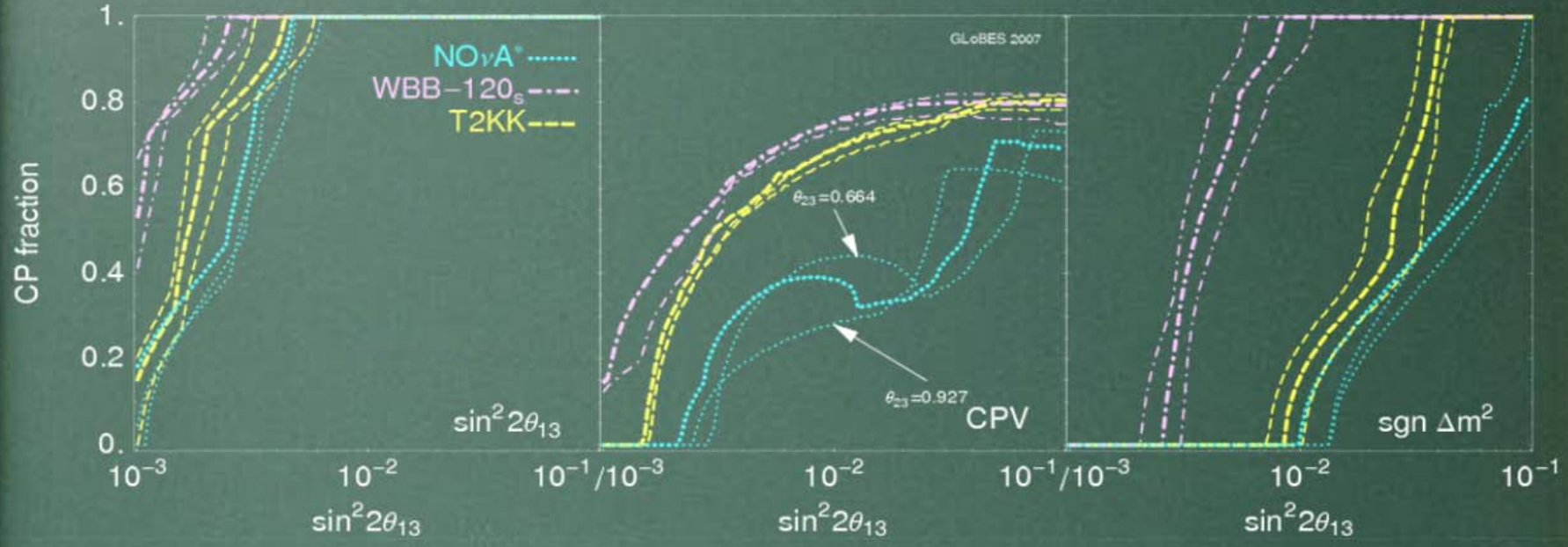



# Robustness

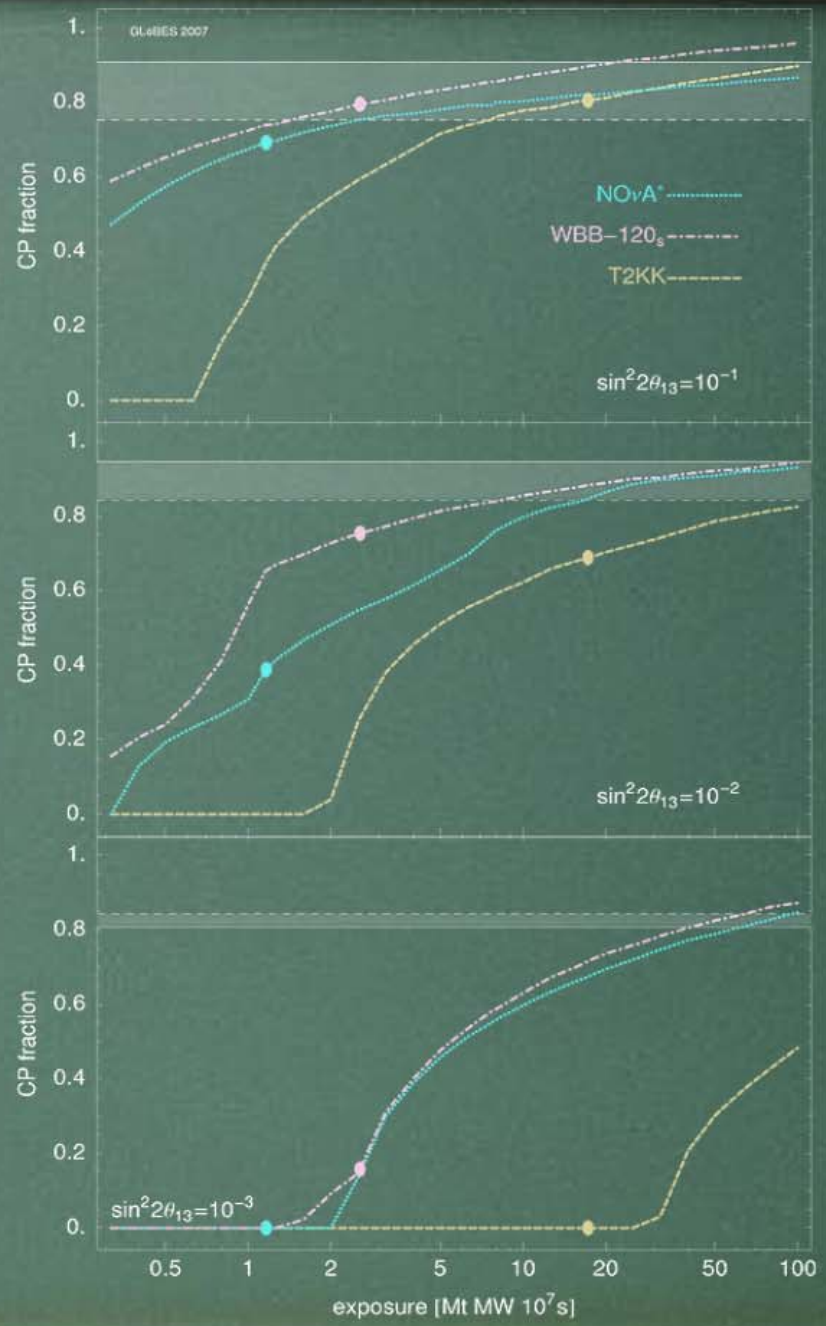



- Exposure from 2 to 0.5 nominal value
- Systematics from 2% to 10%
- $\Delta m^2_{31}$ from 3-2x$10^{-3}$ eV$^2$

# Effect of octant degeneracy



# CPV


GLoBES 2007
CP fraction
NOνA*
WBB–120$_s$
T2KK
$\sin^2 2\theta_{13}=10^{-1}$
$\sin^2 2\theta_{13}=10^{-2}$
$\sin^2 2\theta_{13}=10^{-3}$
0.
0.2
0.4
0.6
0.8
1.
0.5
1
2
5
10
20
50
100
exposure [Mt MW $10^7$s]

## Summary

- Optimal NOvA* location in the U.S. is Ash River
- To be competitive for CPV, it is crucial that NOvA* gets enough exposure ( > 2 Mt MW $10^7$ s)
- WBB experiments can make all 3 measurements and have the most robust performance
- WBB-LAr better than WBB-WC if the cost of LAr is less than 4 times that of water
- Every strategy requires MW beams, 0.1 Mt detectors and a decade of running (0.5 billion $)
- For $\sin^2 2\theta_{13} > 0.01$ no need for a NuFact or $-beam