A picture book of neutrino physics with superbeams

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Options for a U.S. long-baseline program

NOvA - I:

- off-axis beam from FNAL, L=810 km to 20 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:

- minor upgrade in FNAL proton infrastructure (without 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. θ_{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, $\delta = 0, \pi$

Assumptions:

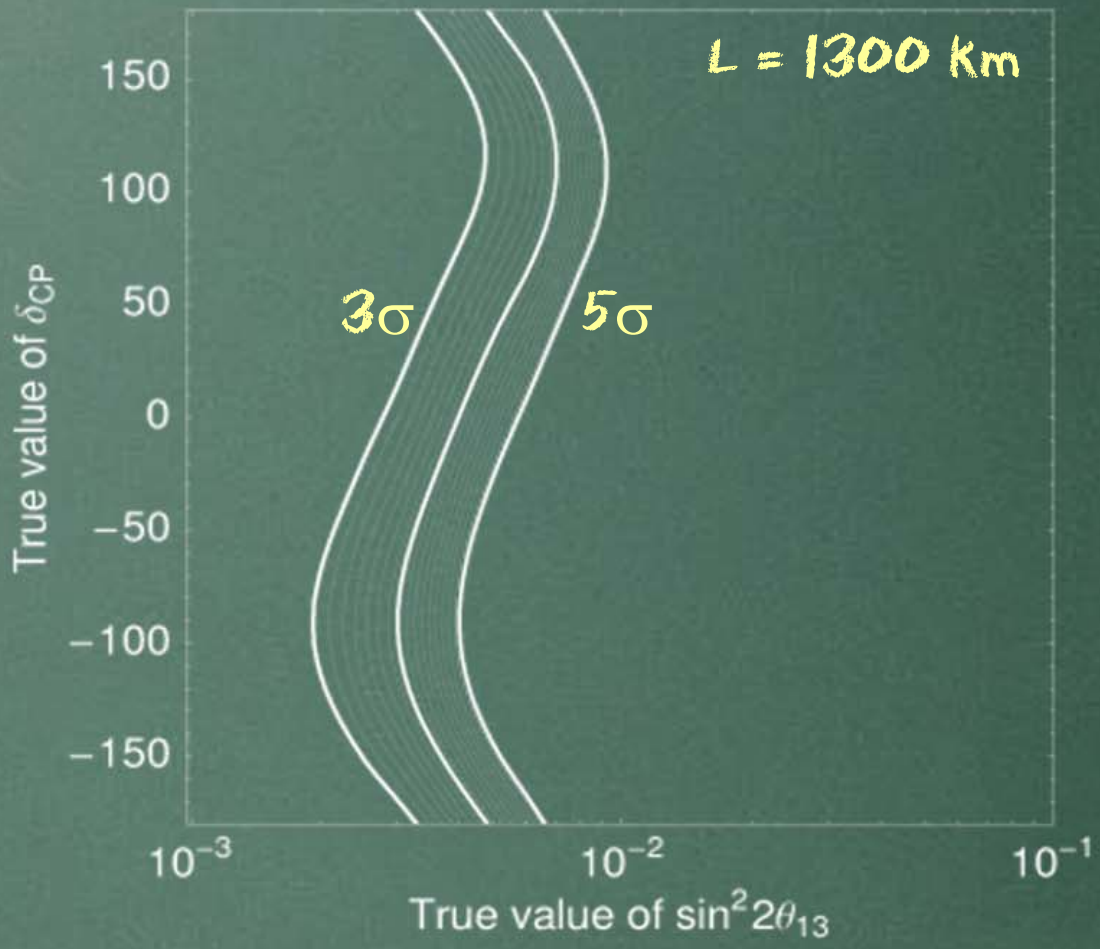
- protons with E = 28 GeV
- 300 kt (fiducial mass) water Cherenkov detector
- π^0 suppression (factor of 15 below 2 GeV
  2 above 2 GeV)
- 1% uncertainty for each type of signal
- 10% uncertainty in background
- 1 MW for 5 years in neutrino mode
- 2 MW for 5 years in antineutrino mode

$\theta_{12} = 0.55 \pm 10\%$ $\quad \Delta m^2_{21} = (8 \pm 0.8) \times 10^{-5}$ eV^2

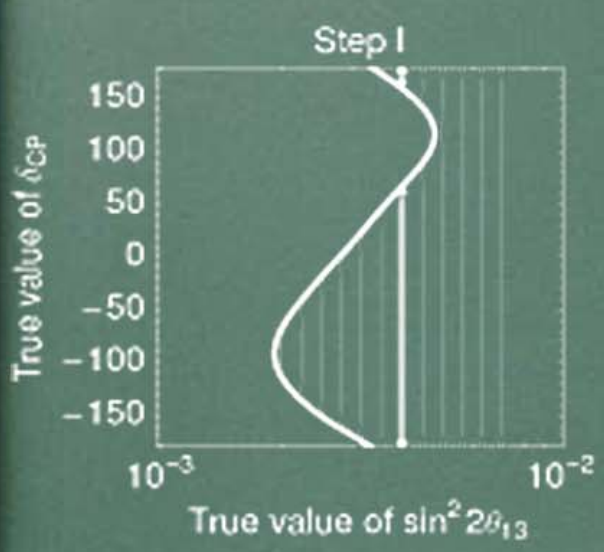
$\theta_{23} = \pi/4 \pm 5\%$ $\quad \Delta m^2_{31} = (2.5 \pm 0.125) \times 10^{-3}$ eV^2

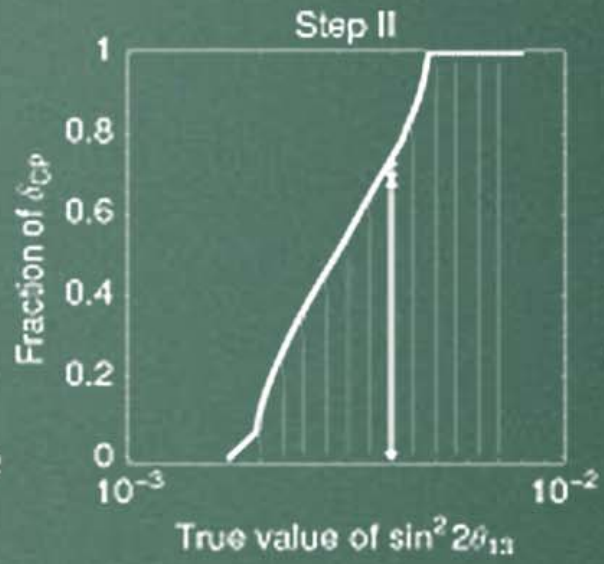
5% uncertainty in the matter density

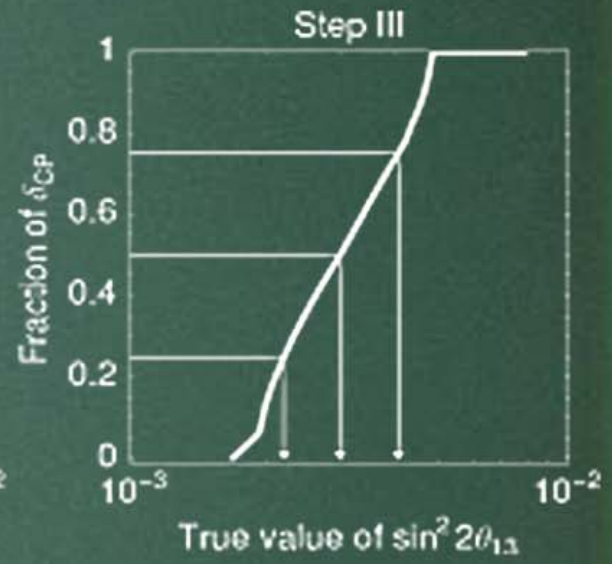
Discovery potential for $\sin^2 2\theta_{13} \neq 0$

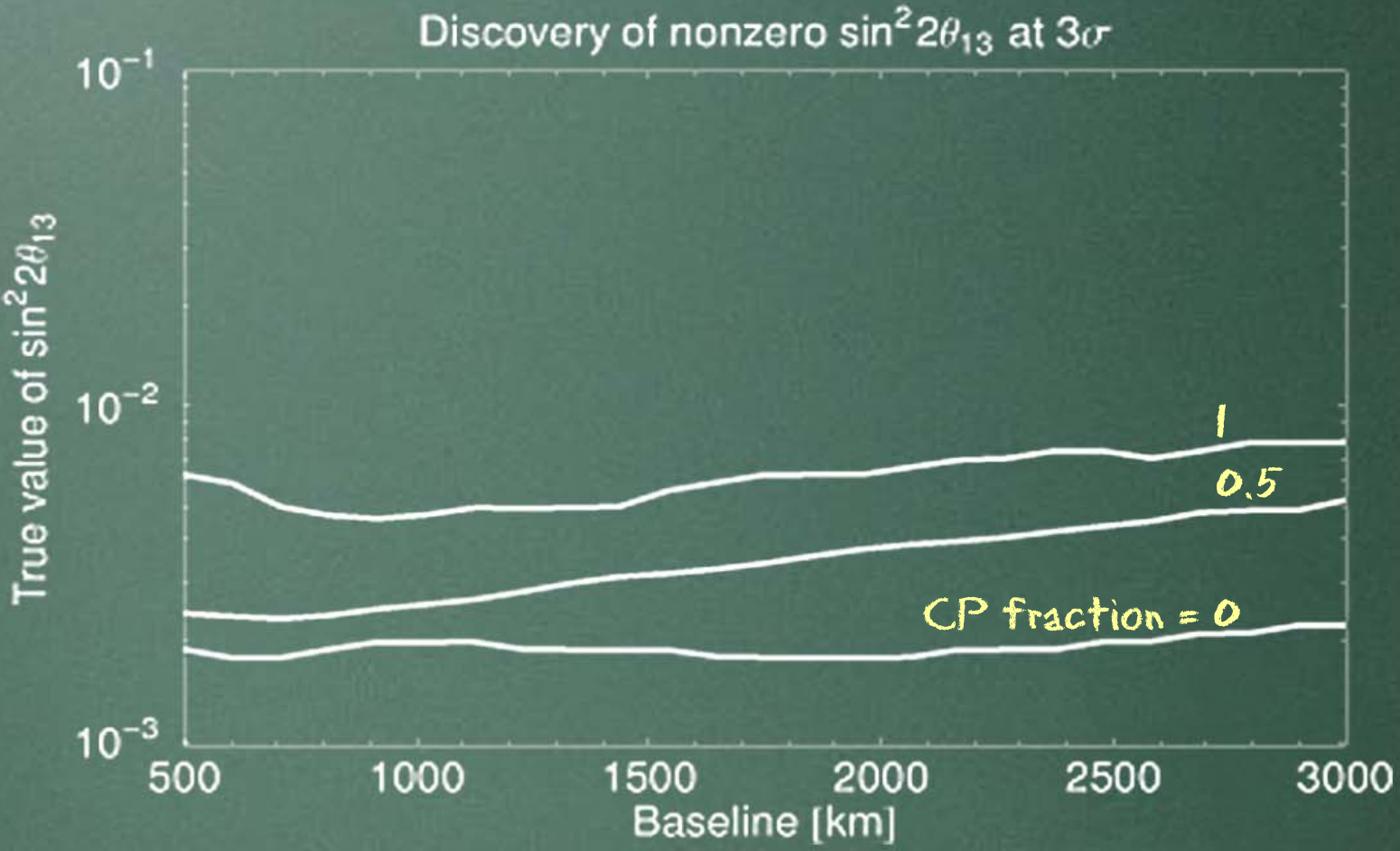


Definition of CP fraction

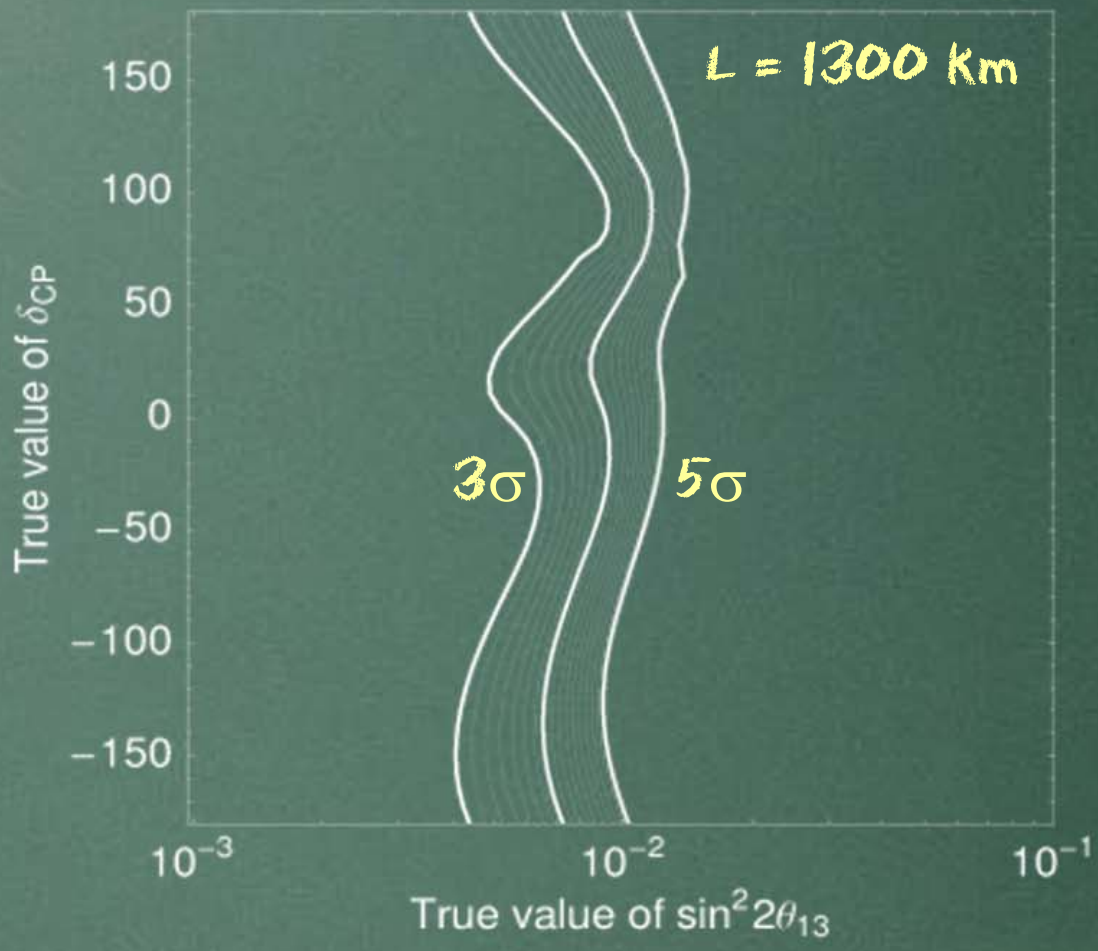


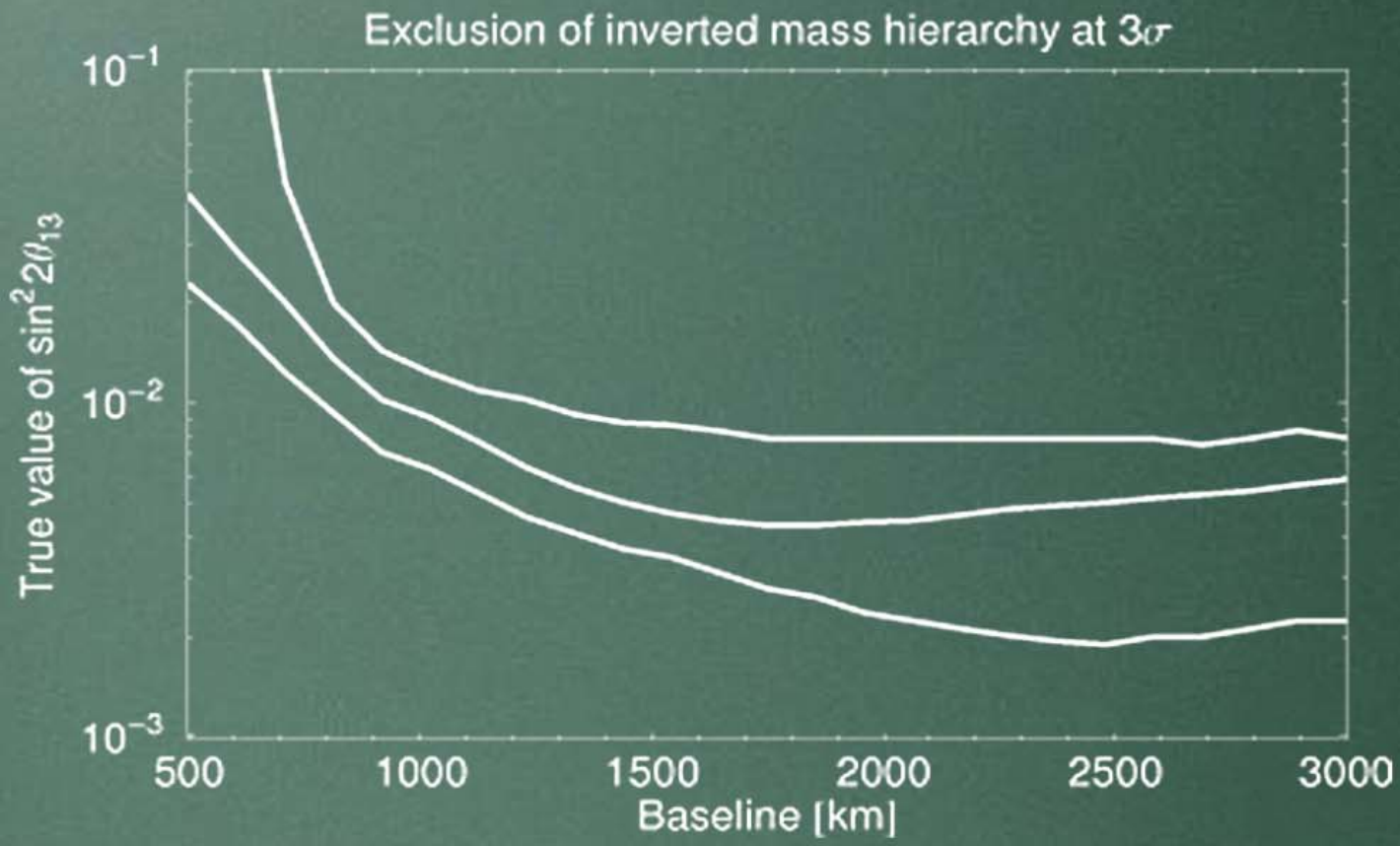




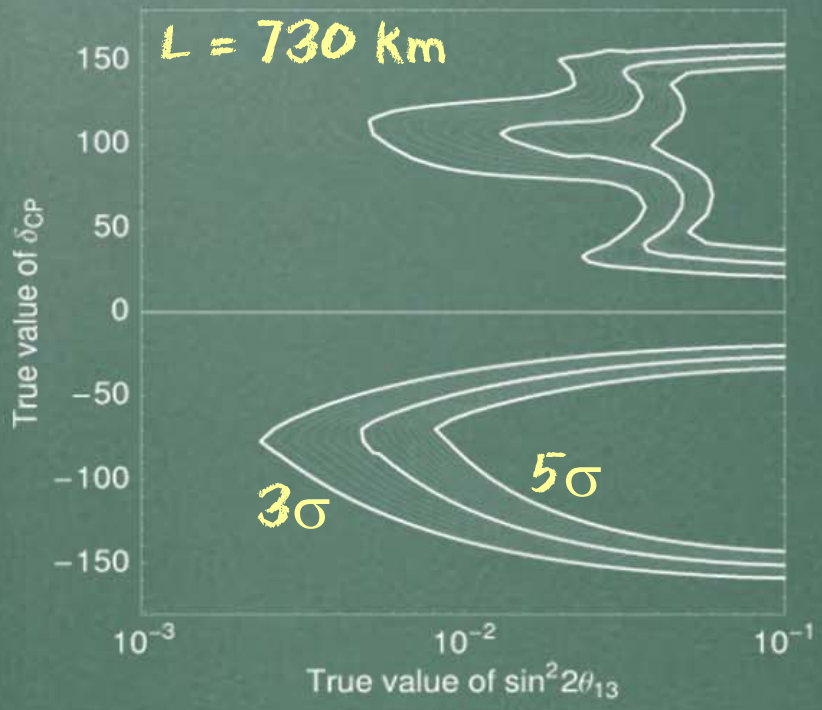

Discovery of nonzero $\sin^2 2\theta_{13}$ at 3σ
True value of $\sin^2 2\theta_{13}$
10^{-1}
10^{-2}
10^{-3}
500
1000
1500
2000
2500
3000
Baseline [km]
1
0.5
CP fraction = 0

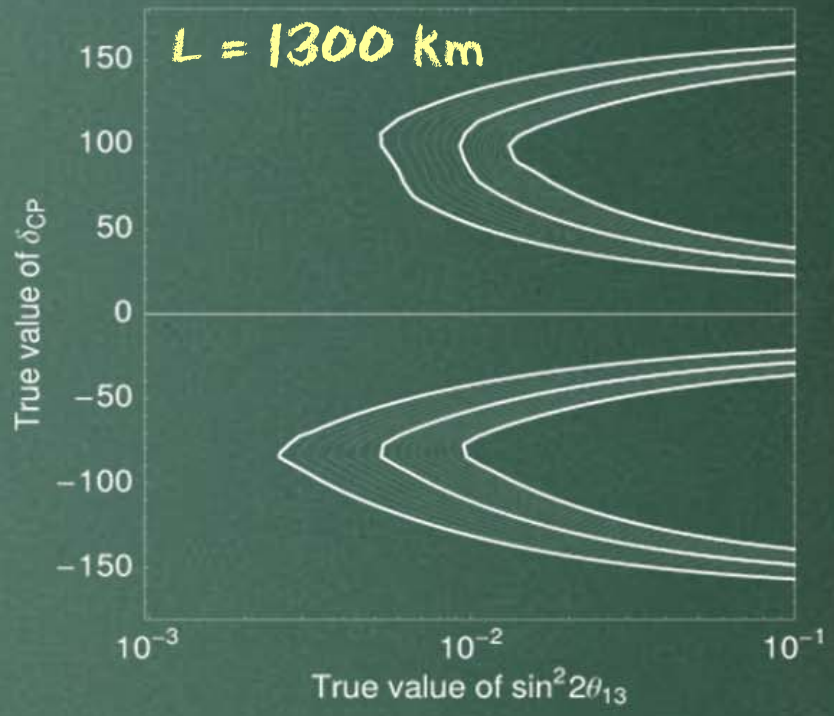
Discovery potential for a normal hierarchy

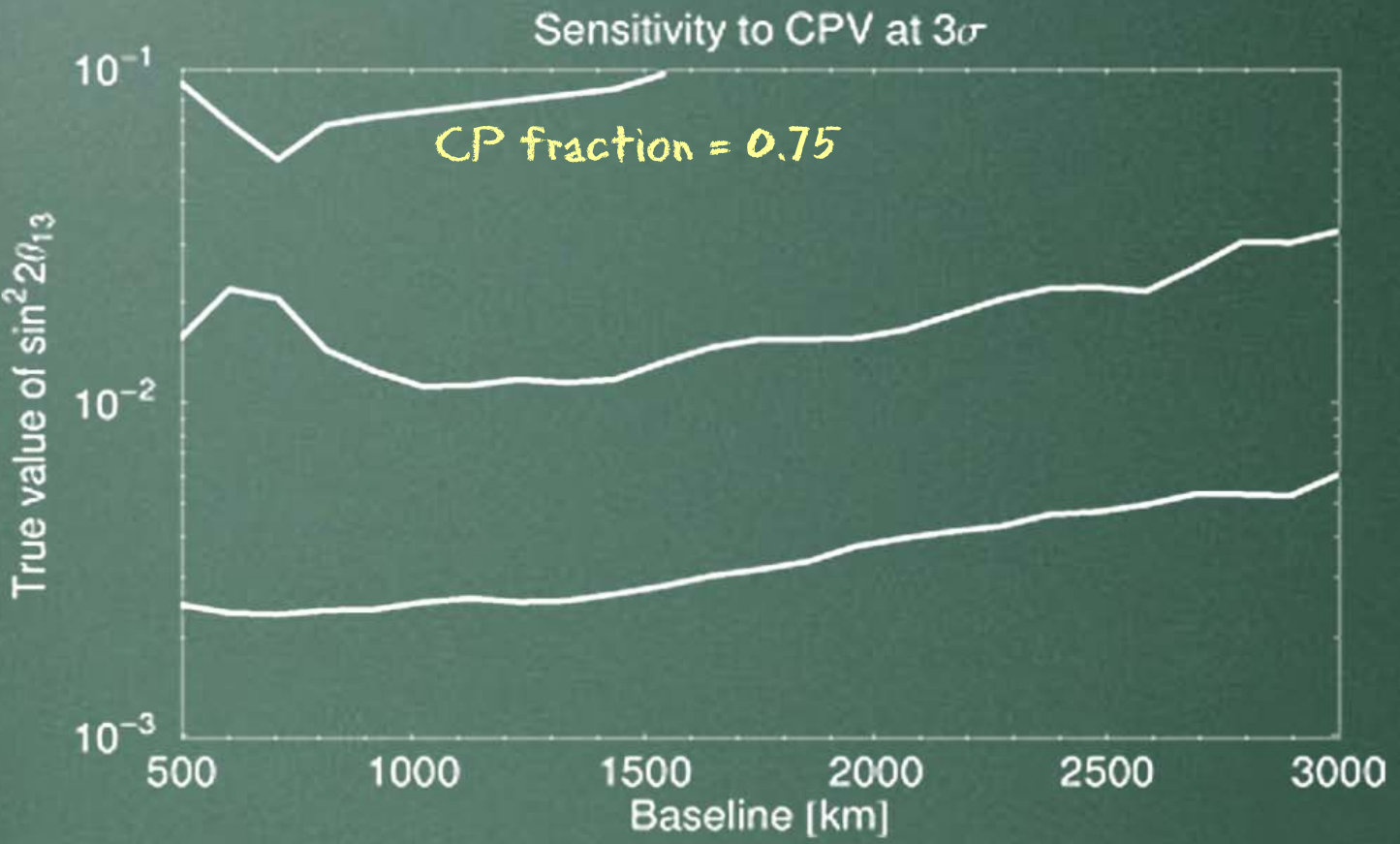



Exclusion of inverted mass hierarchy at 3σ
10^{-1}
10^{-2}
10^{-3}
True value of $\sin^2 2\theta_{13}$
500
1000
1500
2000
2500
3000
Baseline [km]

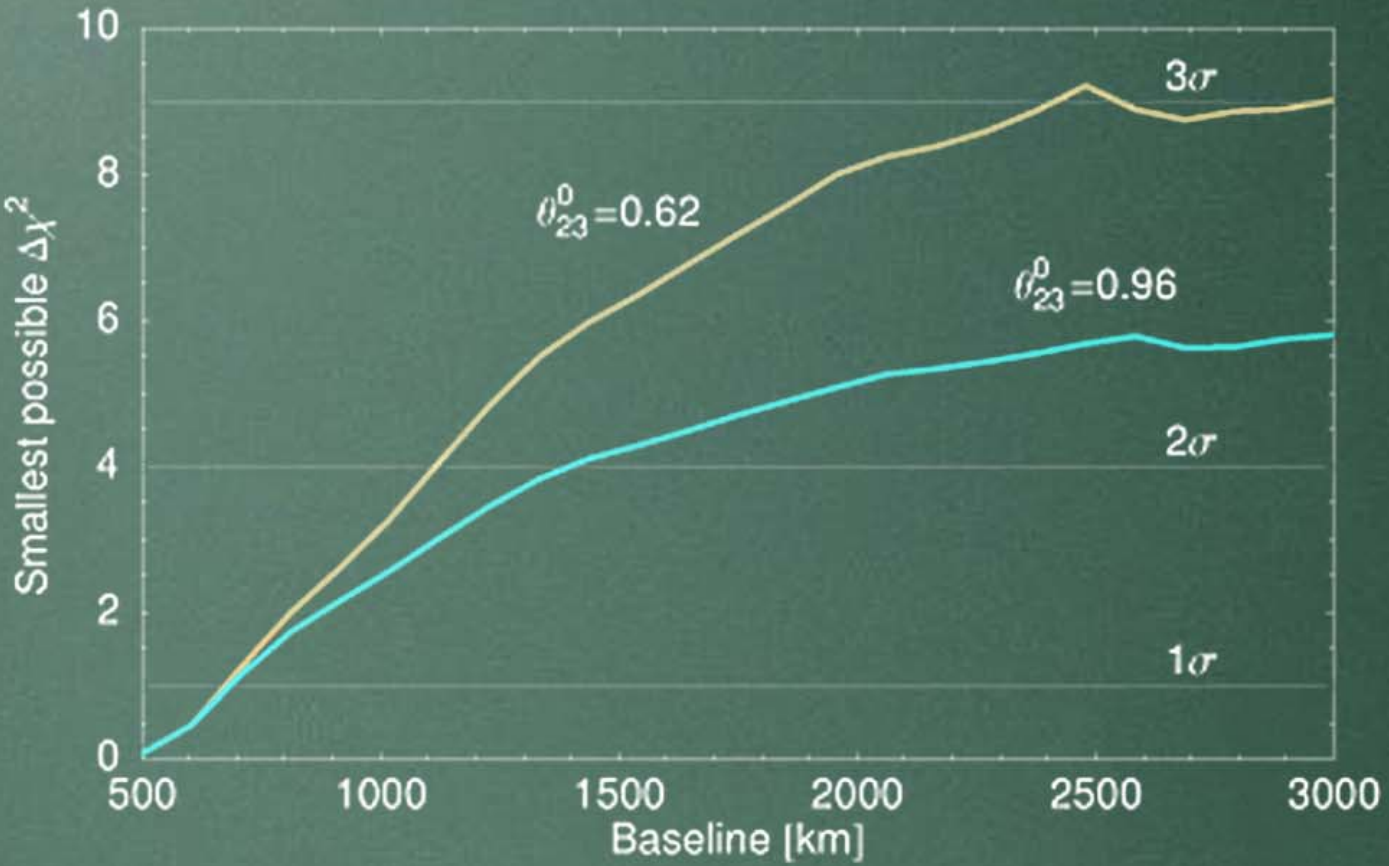
Discovery potential for CP violation



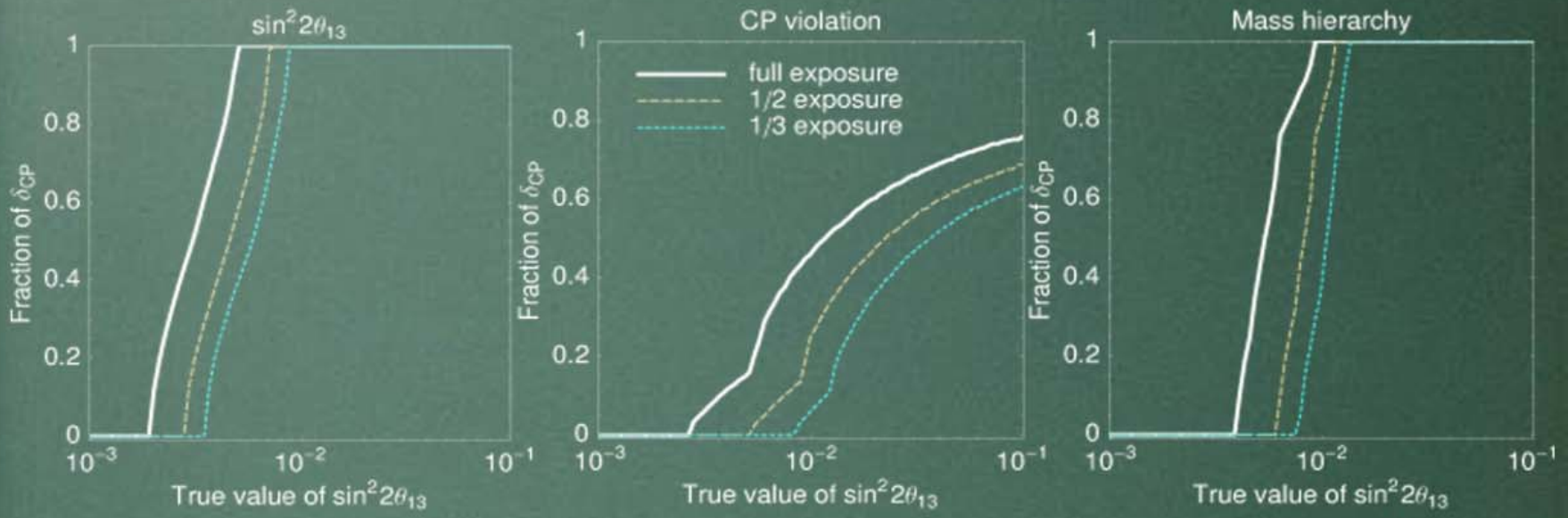



Sensitivity to CPV at 3σ
CP fraction = 0.75
True value of sin²2θ13
10⁻¹
10⁻²
10⁻³
500
1000
1500
2000
2500
3000
Baseline [km]

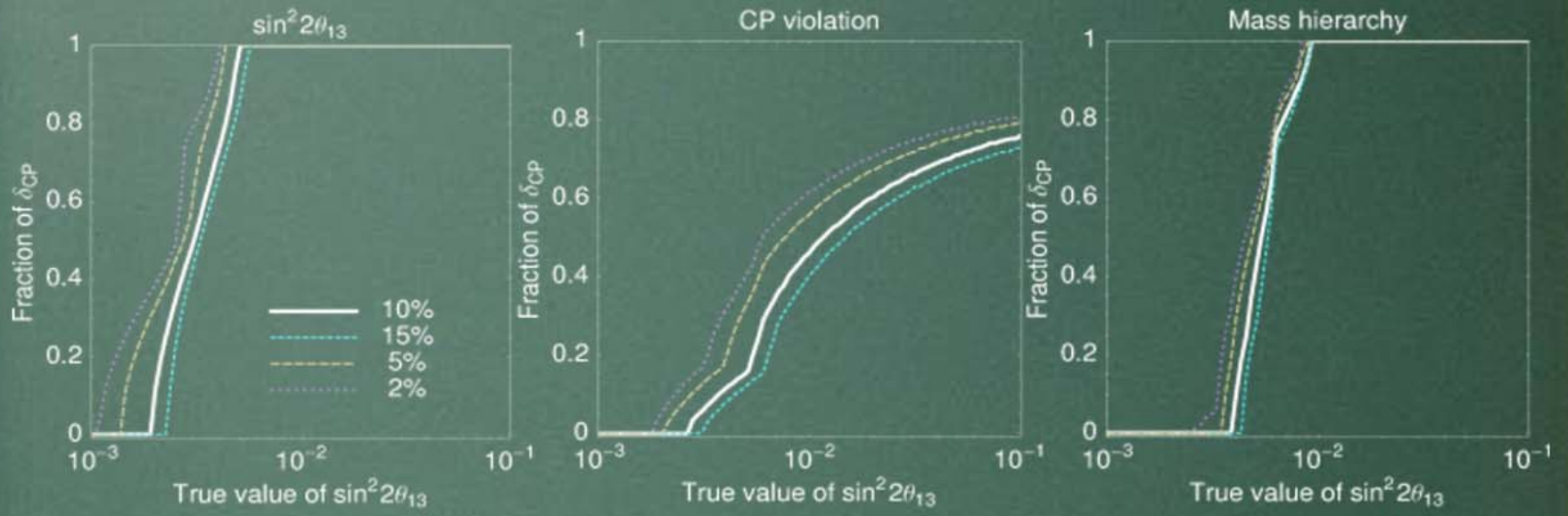
Discovery reach for the octant of θ_{23}



3σ sensitivities, L = 1300 km



3σ sensitivities, L = 1300 km



Bottom line

WWB (0-6 GeV)

+ 1 MW in neutrino mode for 5 years
+ 2 MW in antineutrino mode for 5 years
+ 300 kt water Cherenkov detector
+ L = 1300 km (FNAL to Homestake)
  or L = 1500 km (FNAL to Henderson)

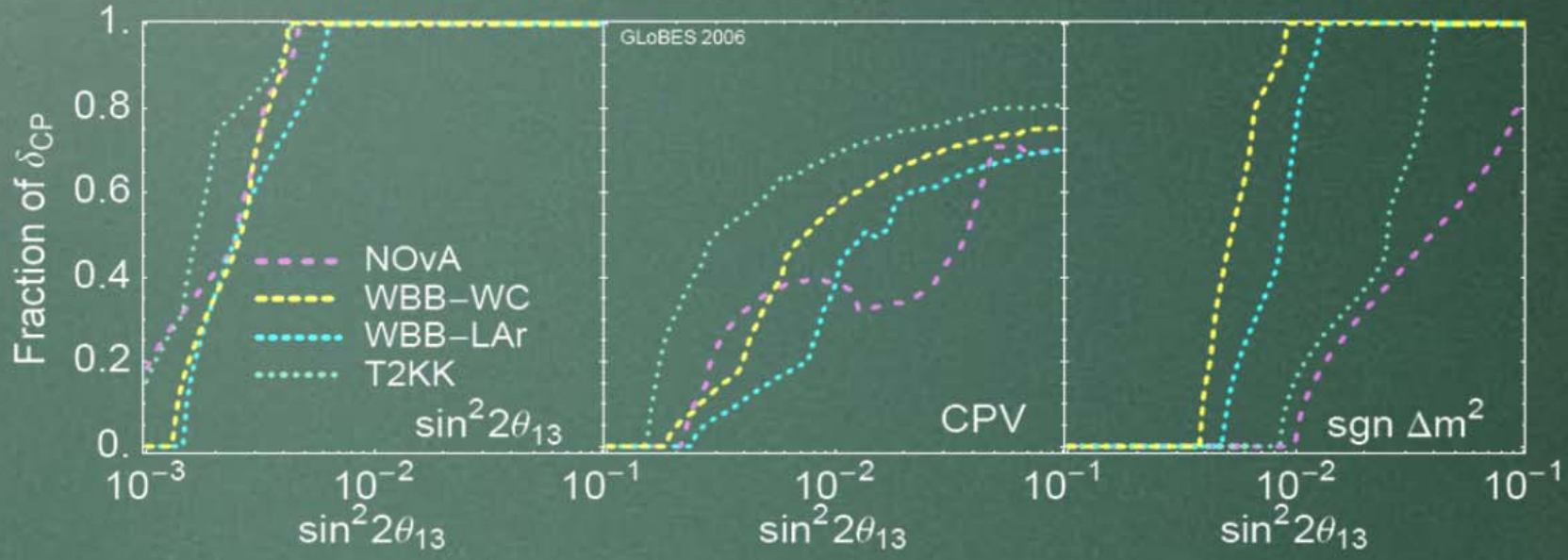
= nonzero θ_{13} + mass hierarchy + CP violation at 3σ C.L. for $\sin^2 2\theta_{13} > 0.008$

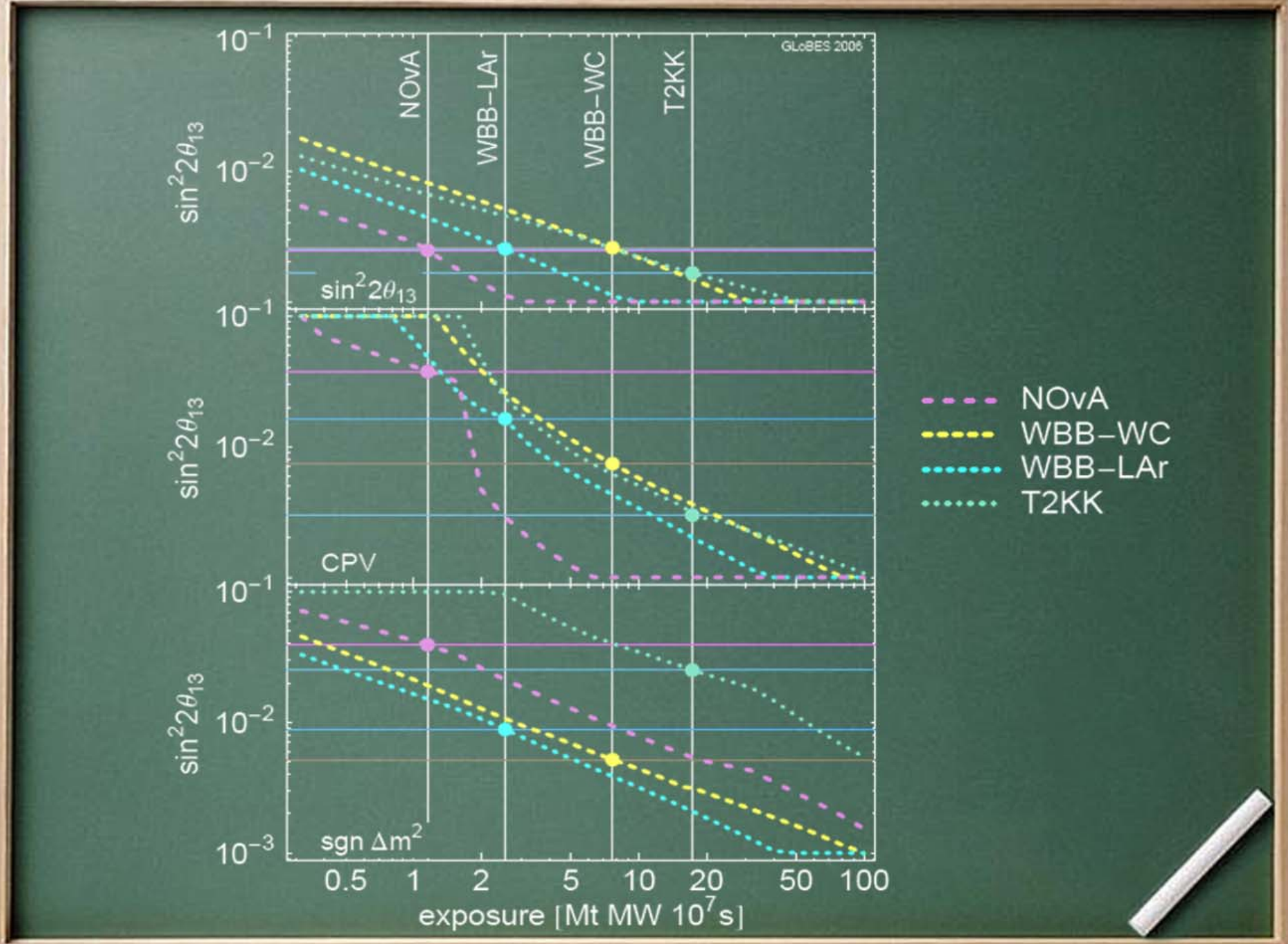
Eight-fold degeneracy broken to octant degeneracy without external input

Comparison with NOvA and T2KK

Setup	POT ν/yr	t_ν [yr]	POT $\bar{\nu}$/yr	$t_{\bar{\nu}}$ [yr]	P_{Target} [MW]	L [km]	Detector technology	m_{Det} [kt]	$\mathcal{L}$ [Mt MW 10^7 s]
NOνA	$10 \cdot 10^{20}$	3	$10 \cdot 10^{20}$	3	1	810	Liquid argon TPC	100	1.02
WBB+WC	$22.5 \cdot 10^{20}$	5	$45 \cdot 10^{20}$	5	1 (ν) +2 ($\bar{\nu}$)	1290	Water Cherenkov	300	7.65
WBB+LAr	$22.5 \cdot 10^{20}$	5	$45 \cdot 10^{20}$	5	1 (ν) +2 ($\bar{\nu}$)	1290	Liquid argon TPC	100	2.55
T2KK	$52 \cdot 10^{20}$	4	$52 \cdot 10^{20}$	4	4	295+1050	Water Cherenkov	270+270	17.28

3σ sensitivities




GLoBES 2006
NOvA
WBB–LAr
WBB–WC
T2KK
$\sin^2 2\theta_{13}$
$\sin^2 2\theta_{13}$
CPV
$\sin^2 2\theta_{13}$
sgn Δm^2
10^{-1}
10^{-2}
10^{-1}
10^{-2}
10^{-1}
10^{-2}
10^{-3}
0.5
1
2
5
10
20
50
100
exposure [Mt MW 10^7 s]
NOvA
WBB–WC
WBB–LAr
T2KK

Which physics concept?

For equal exposures

- NOvA better for nonzero θ_{13} and CPV
- WBB experiments better for mass hierarchy
- WBB and T2KK equivalent for CPV
- WBB-LAr better than WBB-WC if cost/Kt of LAr is smaller than cost/2.5 Kt of water