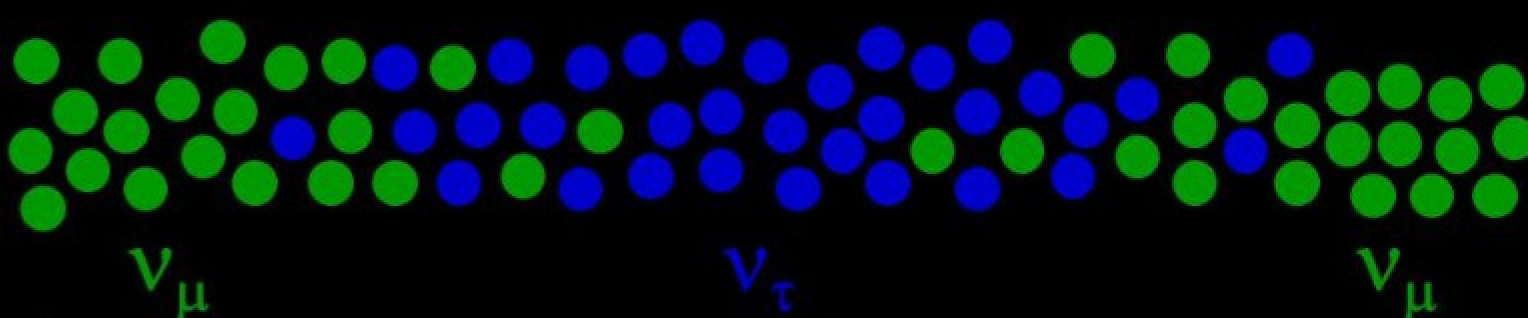
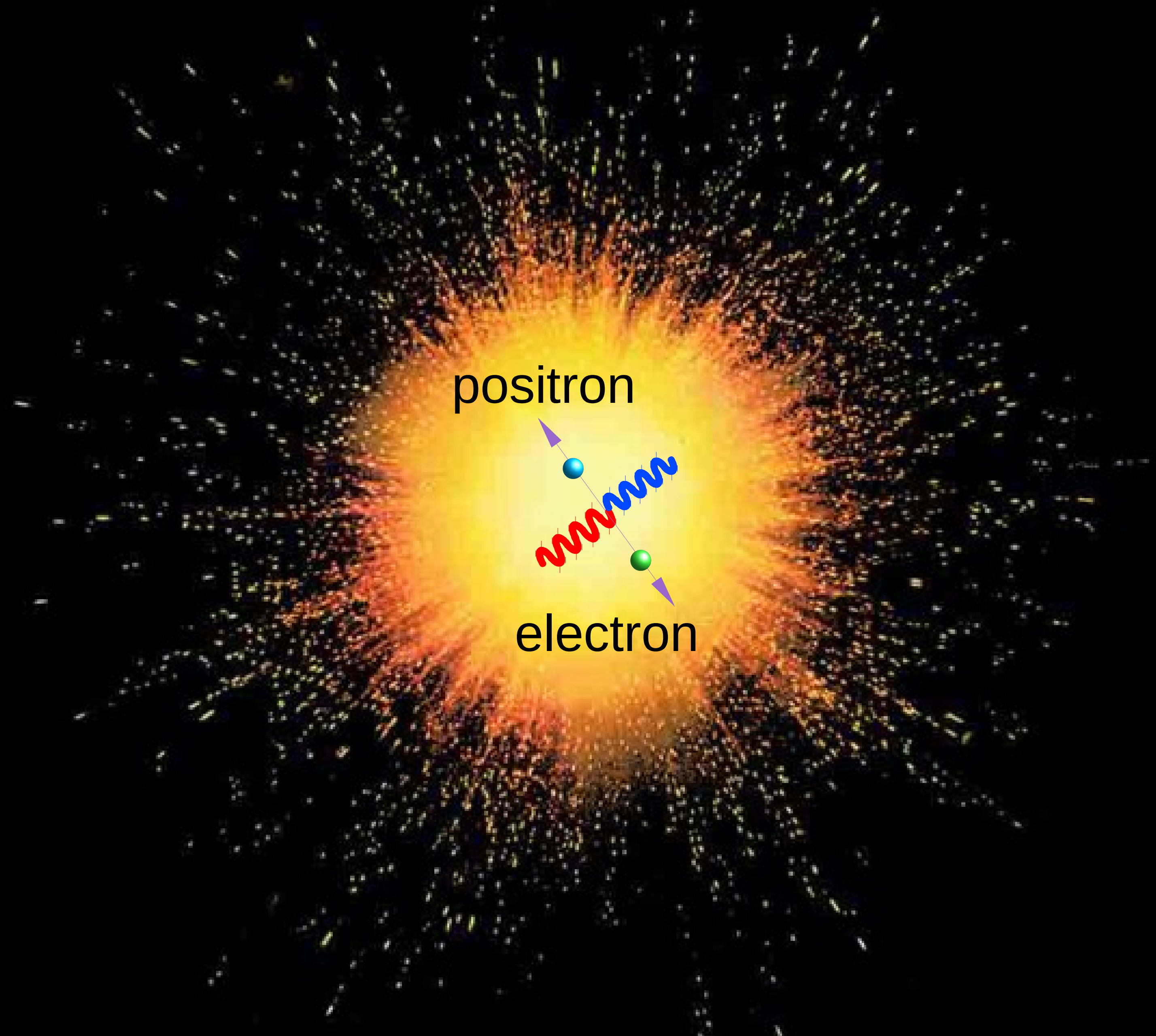
Steve Boyd

Neutrino Oscillations and the Case of the Missing Antimatter



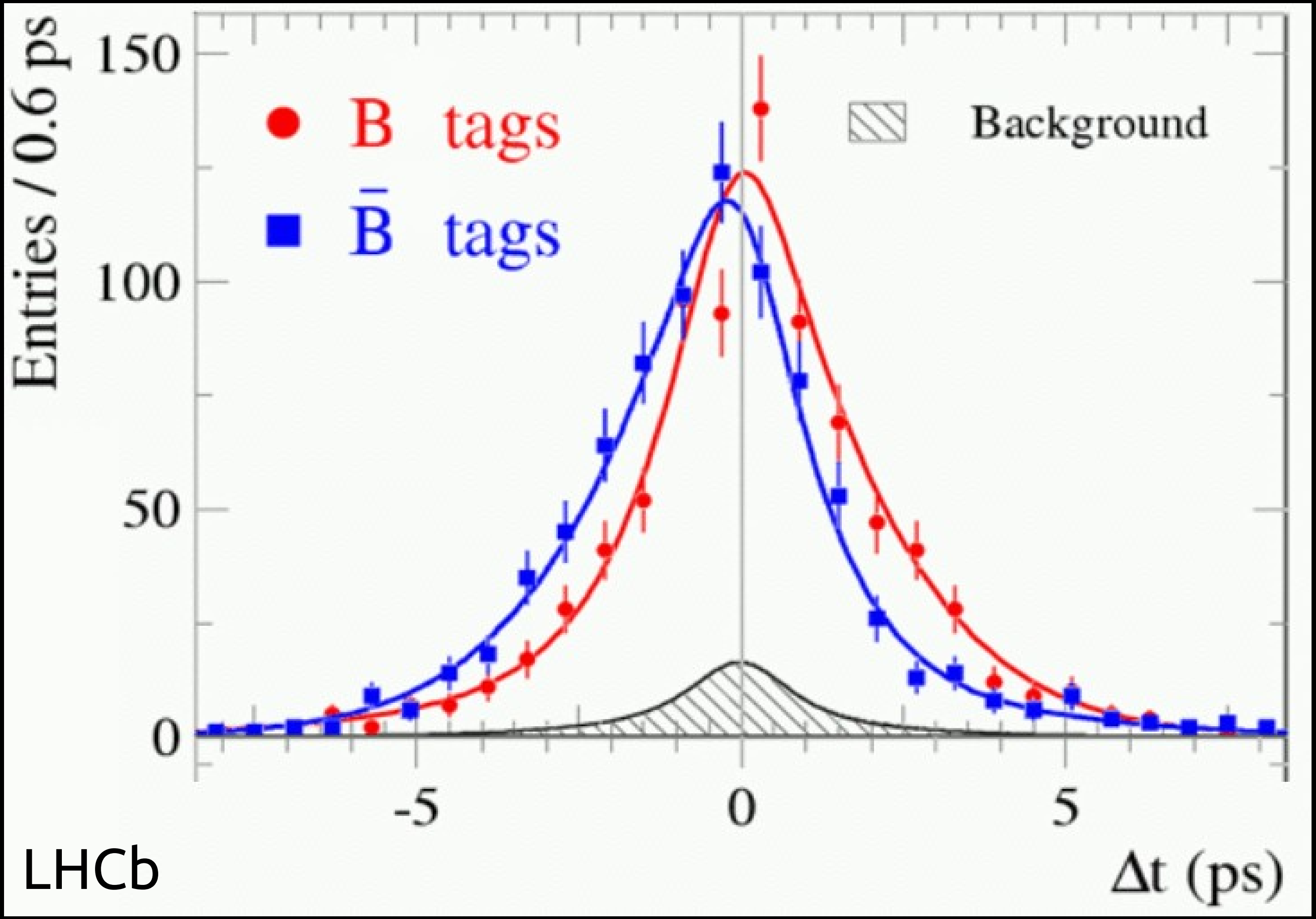

Where has all the antimatter gone?

Matter:Anti-matter was 1:1 in the early universe. Somehow most of the matter vanished with all of the antimatter.



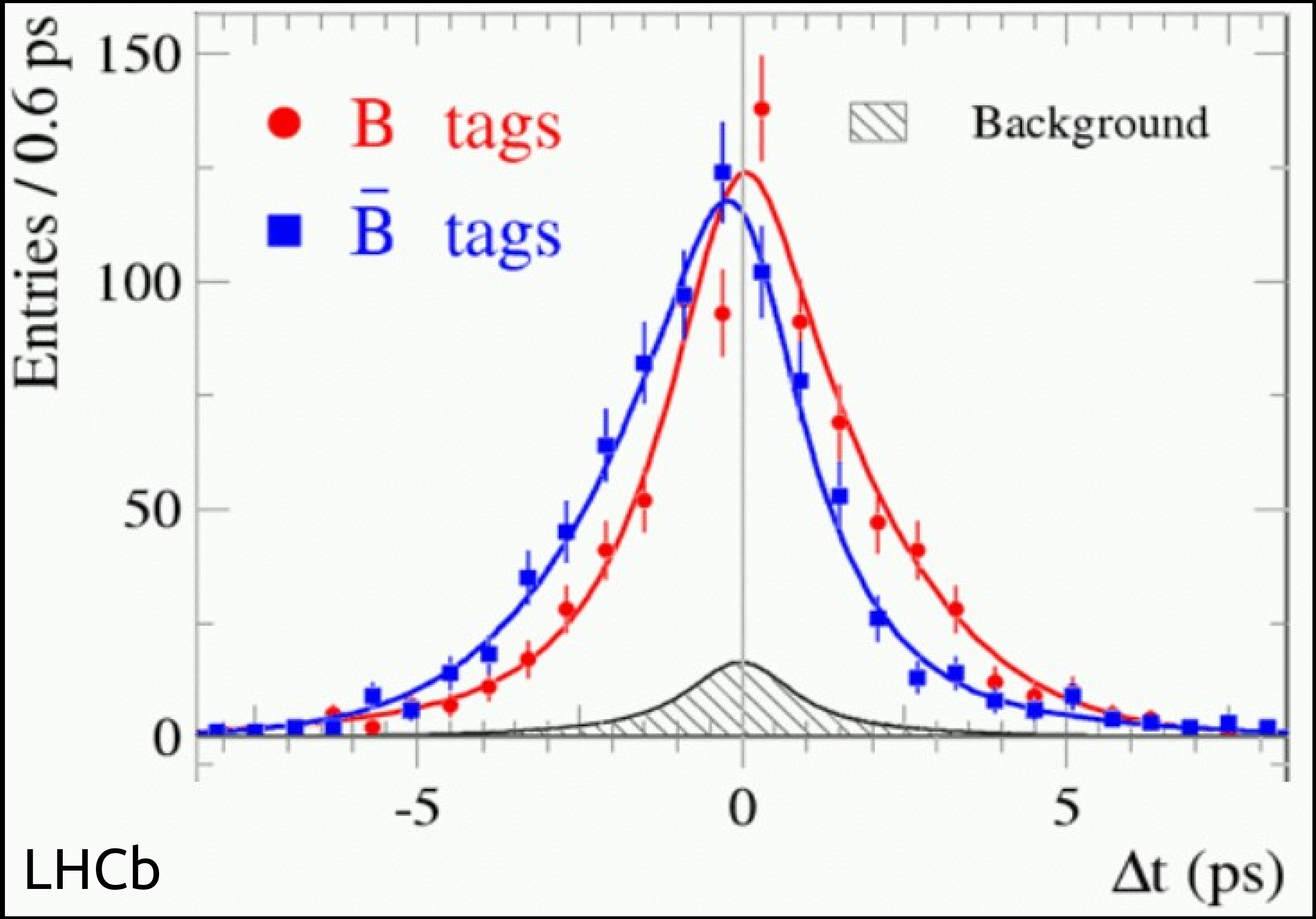
Is there a difference in the physics of matter and antimatter?

Matter / Antimatter Asymmetry



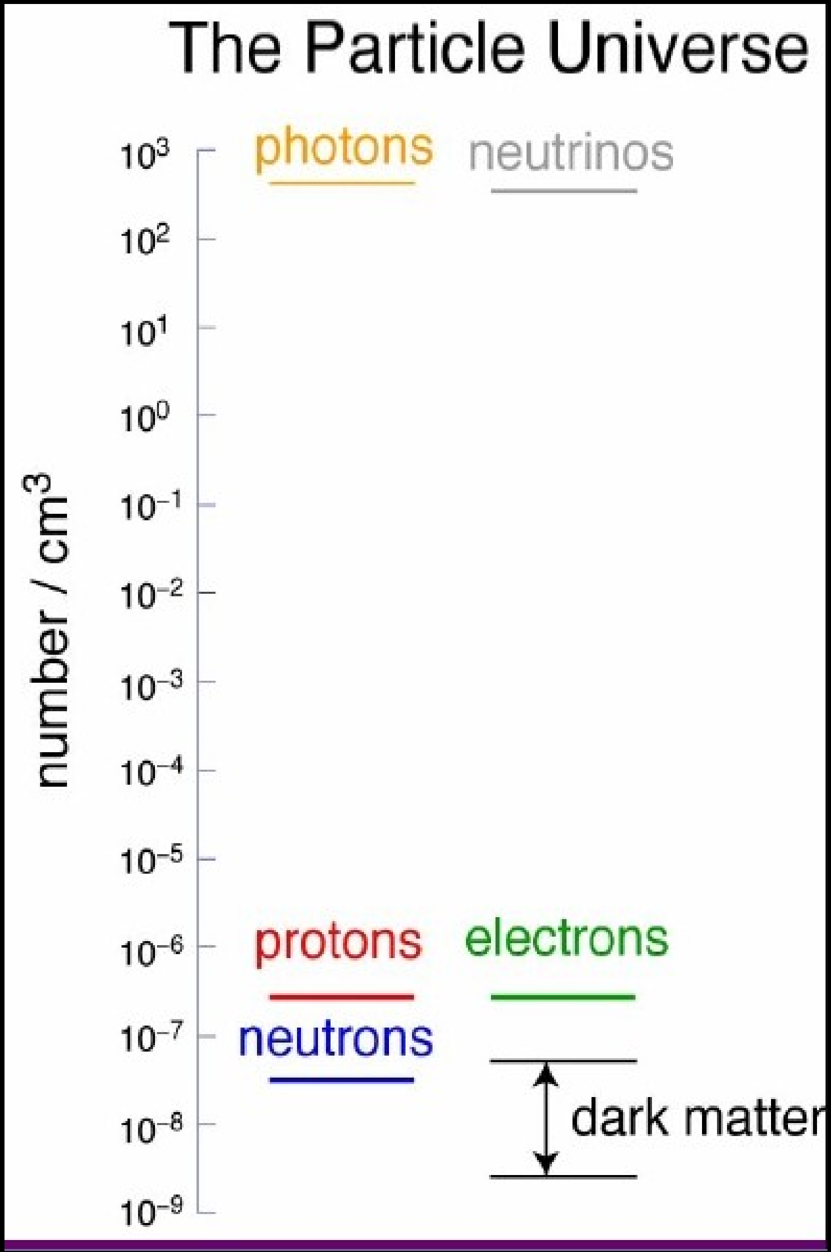
Quarks and anti-quarks behave differently → CP violation
But it is a subtle effect (a few percent) – and not enough to explain the observed asymmetry in the universe.

Matter / Antimatter Asymmetry



Part of the answer may lie, not with quarks, but with neutrinos

What is a neutrino?



- Spin 1/2, electrically neutral partner to a charged lepton
- Three **flavours** : ν_e, ν_μ, ν_τ
- Produced and interacts only through the weak interaction
- Almost massless
- Most common fermion in the universe
- Distinguished by very small interaction probabilities

"A neutrino produced by beta-decay could travel through the earth like a bullet through a bank of fog "

Hans Bethe

"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."

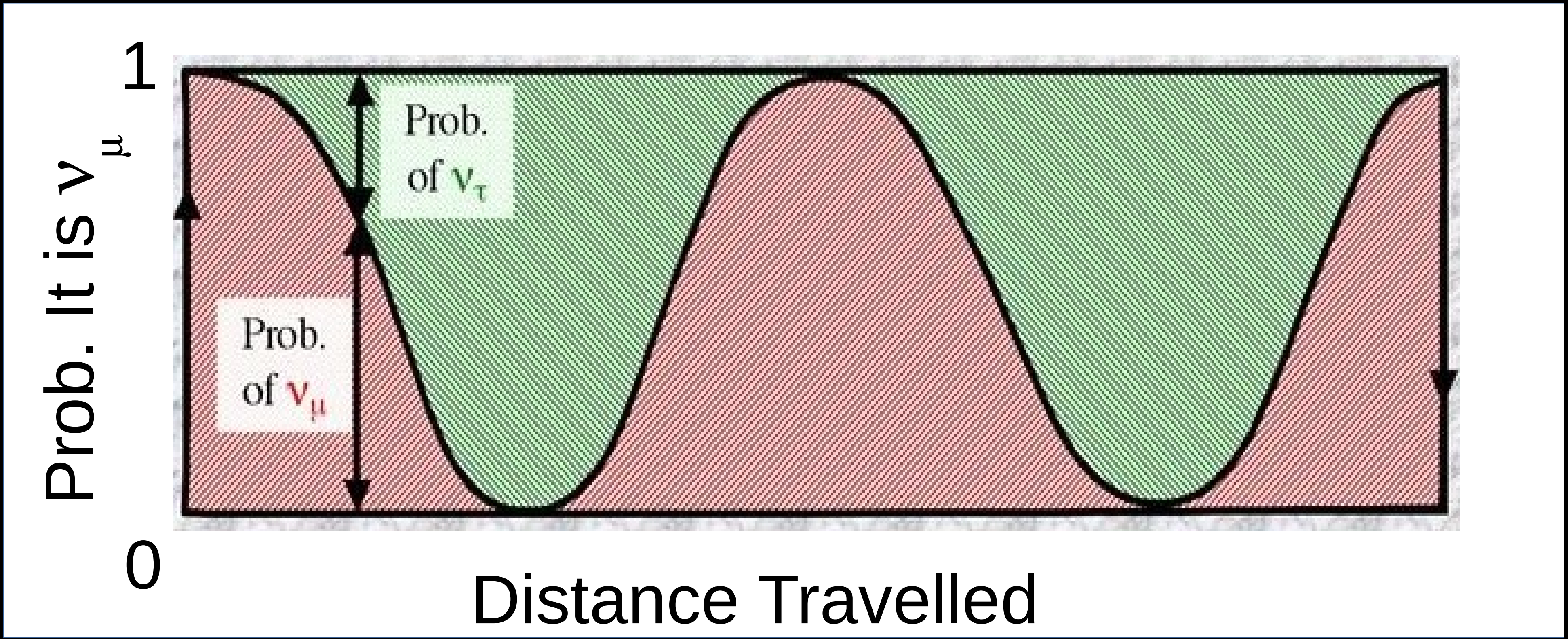
Douglas Adams

Probability $\approx 5 \times 10^{-13}$

Probability $\approx 1 \times 10^{-13}$

Neutrino Flavour Oscillations

Neutrinos can change flavour as the propagate from point to point



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(2.54\frac{L}{E}\Delta m^2\right)$$

Mass splitting : $\Delta m^2 = m_1^2 - m_2^2$

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They can do this because the thing we've always called the neutrino (flavour states with definite flavour) is actually made from 3 other things with definite mass (mass states).

We never know which mass state takes part in a given interaction. This uncertainty generates interference between the flavour states

Mixing parameter we have to measure

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Mass states — Mixing matrix — Flavour states

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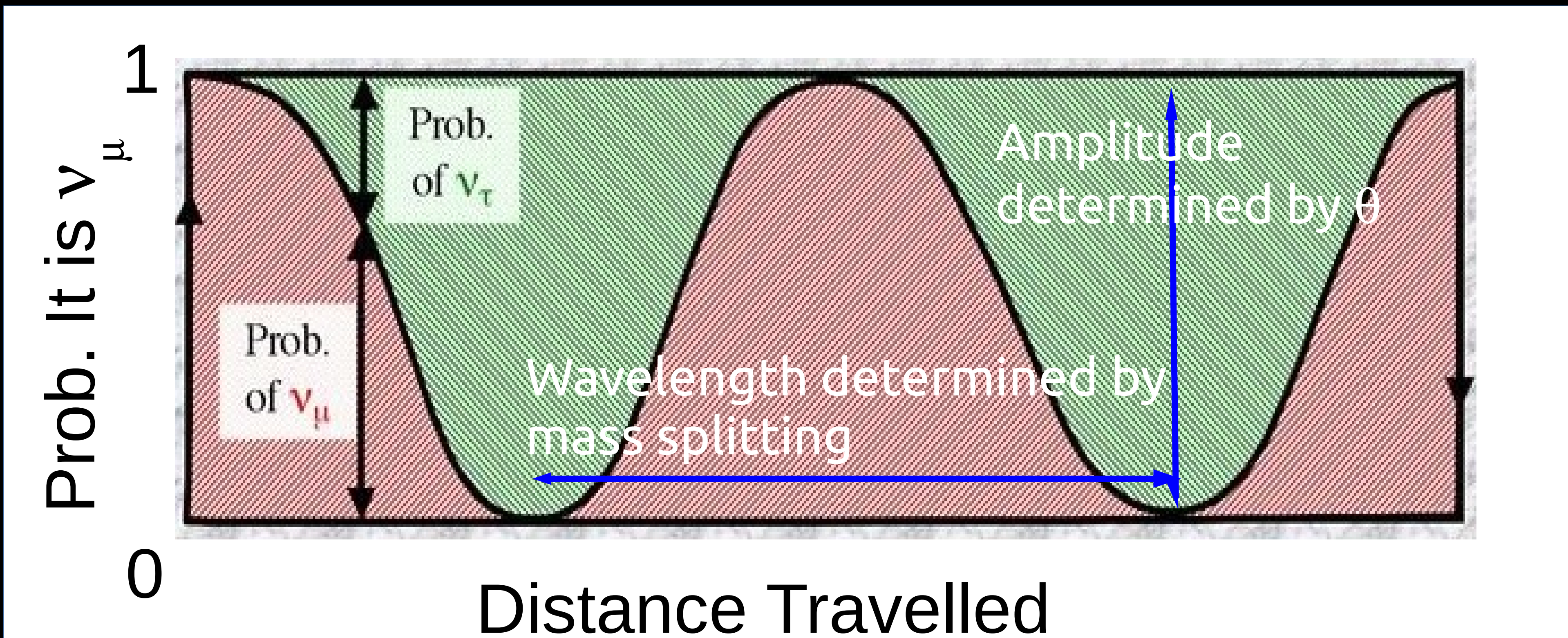

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There are 3 neutrinos

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Leftrightarrow U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

U is called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
In 3-dimensions, U can have complex parameters

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij} \qquad s_{ij} = \sin\theta_{ij}$

What we know...

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23 - sector

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

$\theta_{e\mu} = 45.0^\circ \pm 2.4^\circ$

13-sector

$\nu_\mu \rightarrow \nu_e$

$\theta_{13} = 9.7^\circ \pm 2.0^\circ$

12-sector

$\nu_\mu \rightarrow \nu_e$

$\theta_{e\mu} = 32.5^\circ \pm 2.4^\circ$

$$\Delta m^2_{12} = 7.1 \times 10^{-5}\, eV^2 \qquad \Delta m^2_{13} = \Delta m^2_{23} = \left|2.8 \times 10^{-3}\right| eV^2$$

...and what we don't

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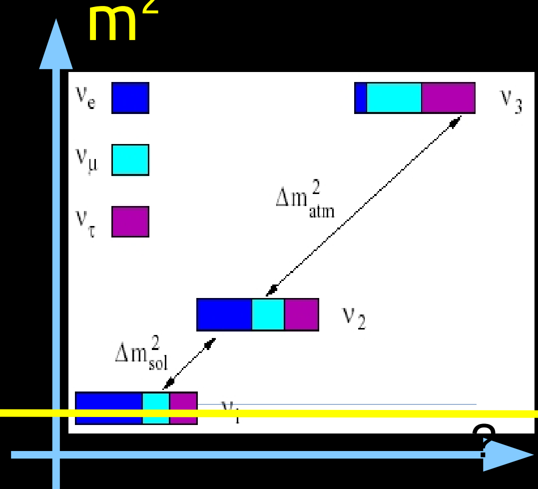
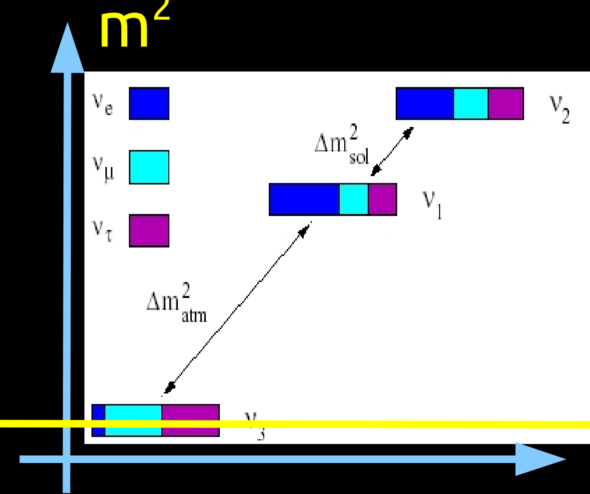
δ_{CP} controls the level of CP violation

Mass heirarchy



Normal



Inverted

baseline mass ???

Why does it matter?

There is an idea floating about out there called Leptogenesis

It goes

1. Once upon a time in the very early universe there lived very heavy partners to our neutrino called (wait for it) “heavy neutrinos”.

2. CP violation in decays of the heavy neutrino were able to generate a lepton number asymmetry

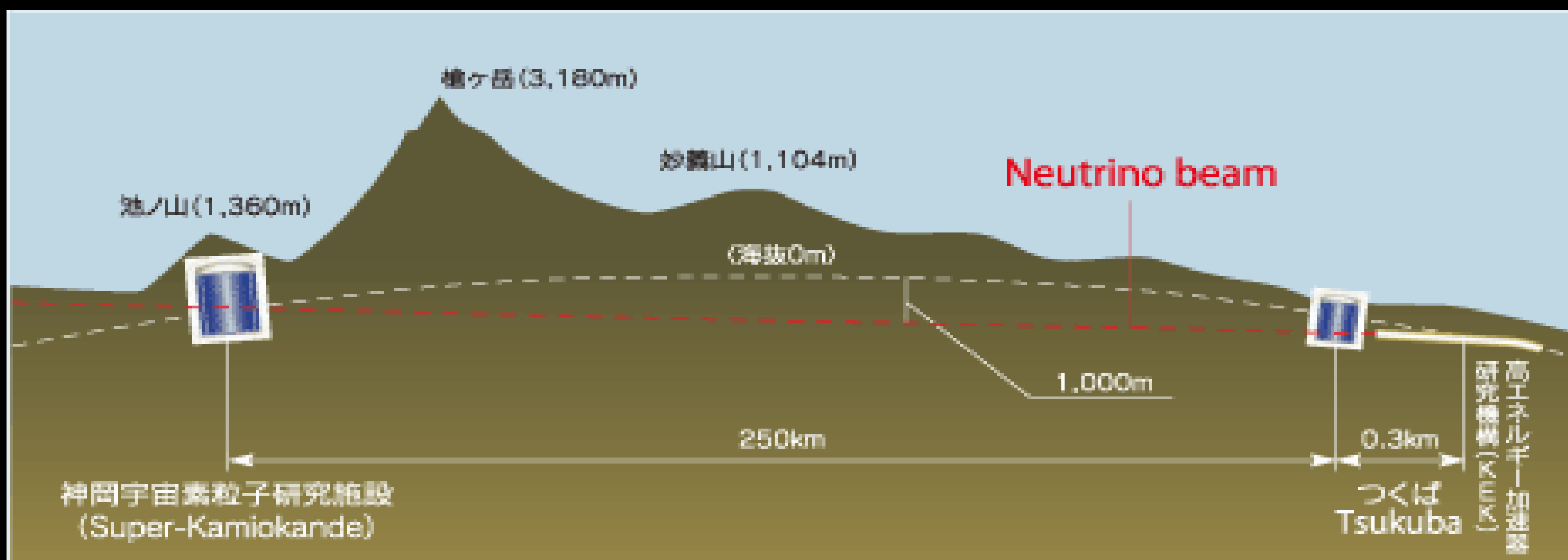
3. Sphaleron transitions (¯_(ツ)_/¯) conserve B-L, so if L is not conserved, neither is B

4. Observed baryon asymmetry is generated, at least in part, from CP violation in the leptons

5. Should look for CP violation in the neutrino sector.

Long baseline experiments

One way of studying these issues uses neutrino beams of known flavour content and measures their flavour mix after the neutrinos have travelled a long distance

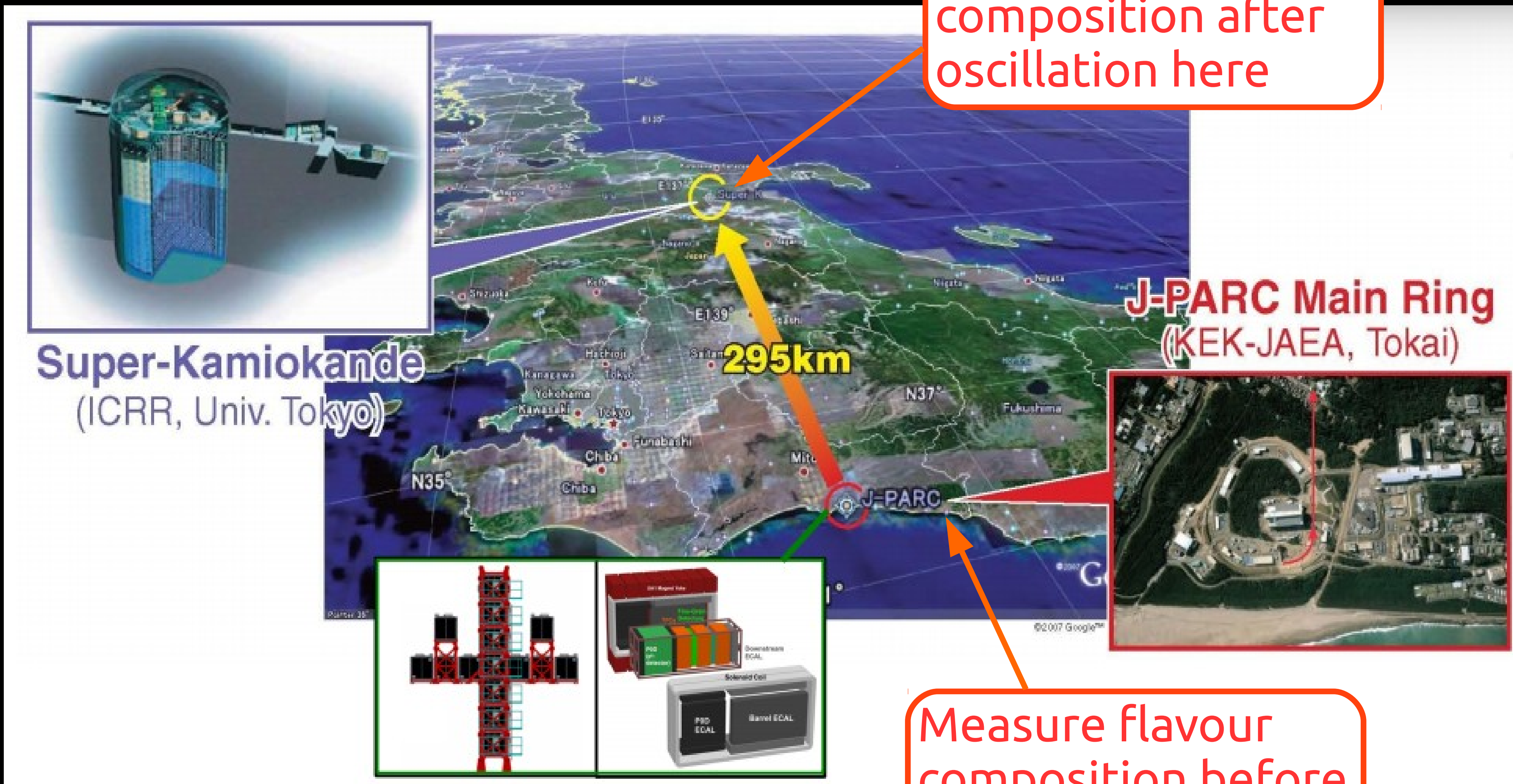


Two types of measurements :

$$Disappearance : P\left(\nu_\mu \rightarrow \nu_\mu\right)$$

$$Appearance : P\left(\nu_\mu \rightarrow \nu_e\right)$$

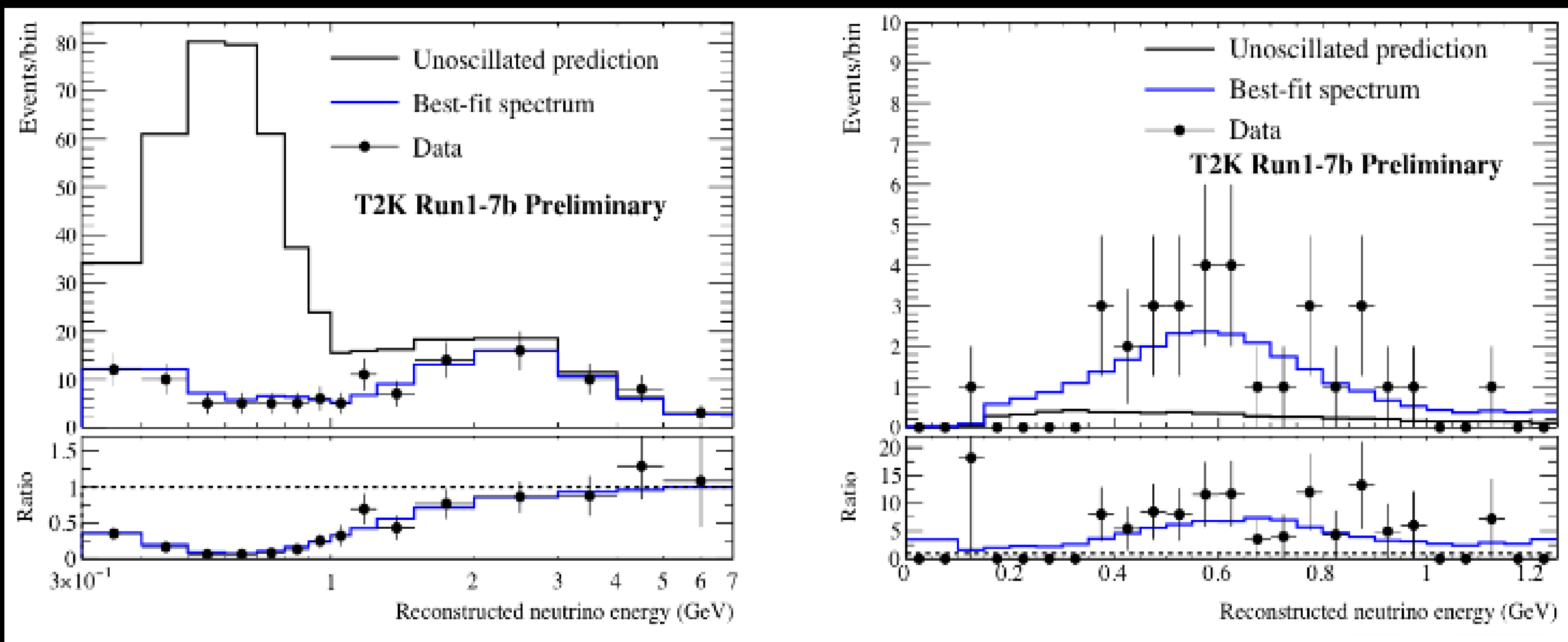
T2K



Measure flavour composition after oscillation here

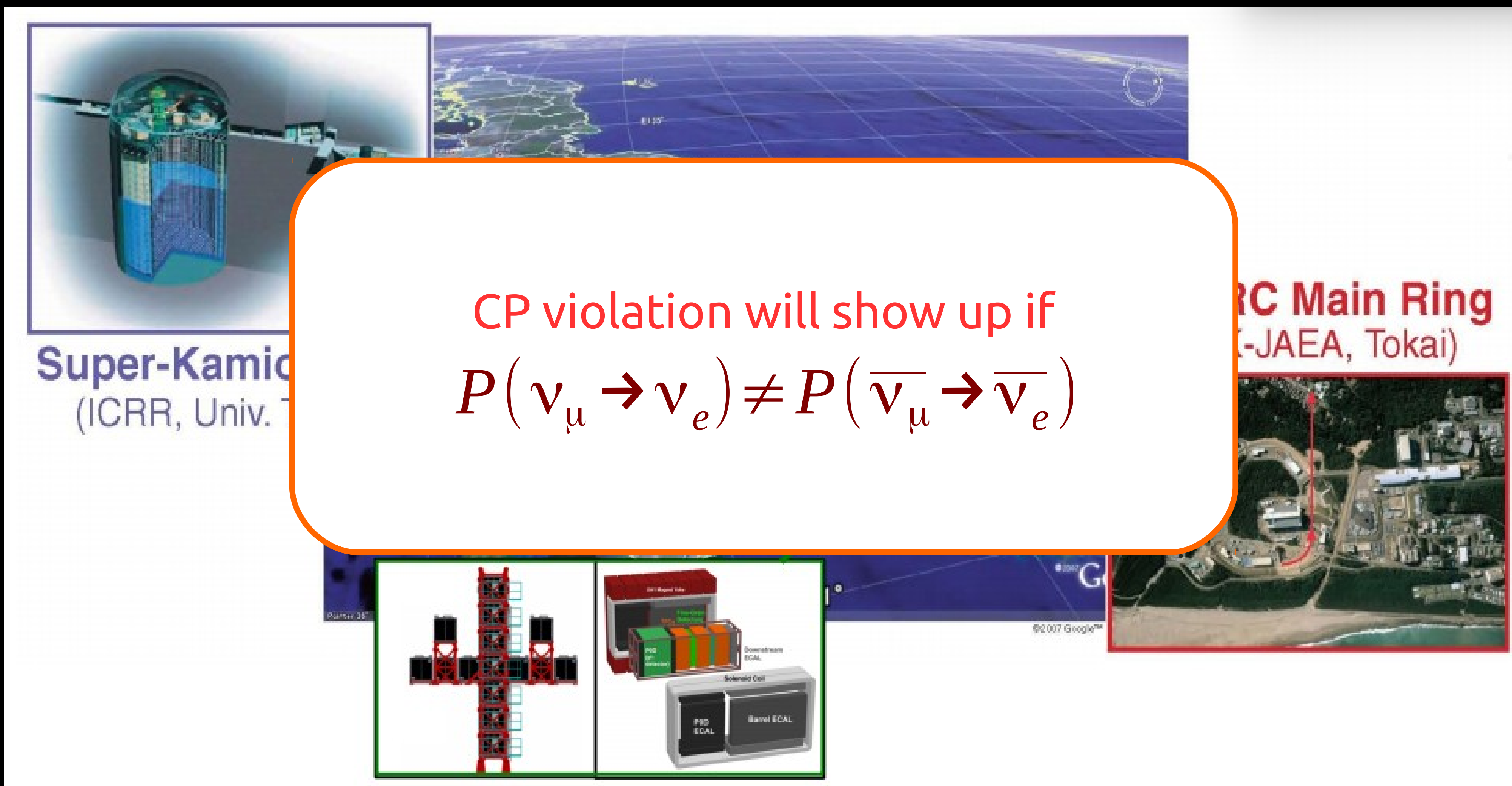
Measure flavour composition before oscillation here

Long baseline experiments



ν_μ Disappearance Measurement ν_e Appearance Measurement

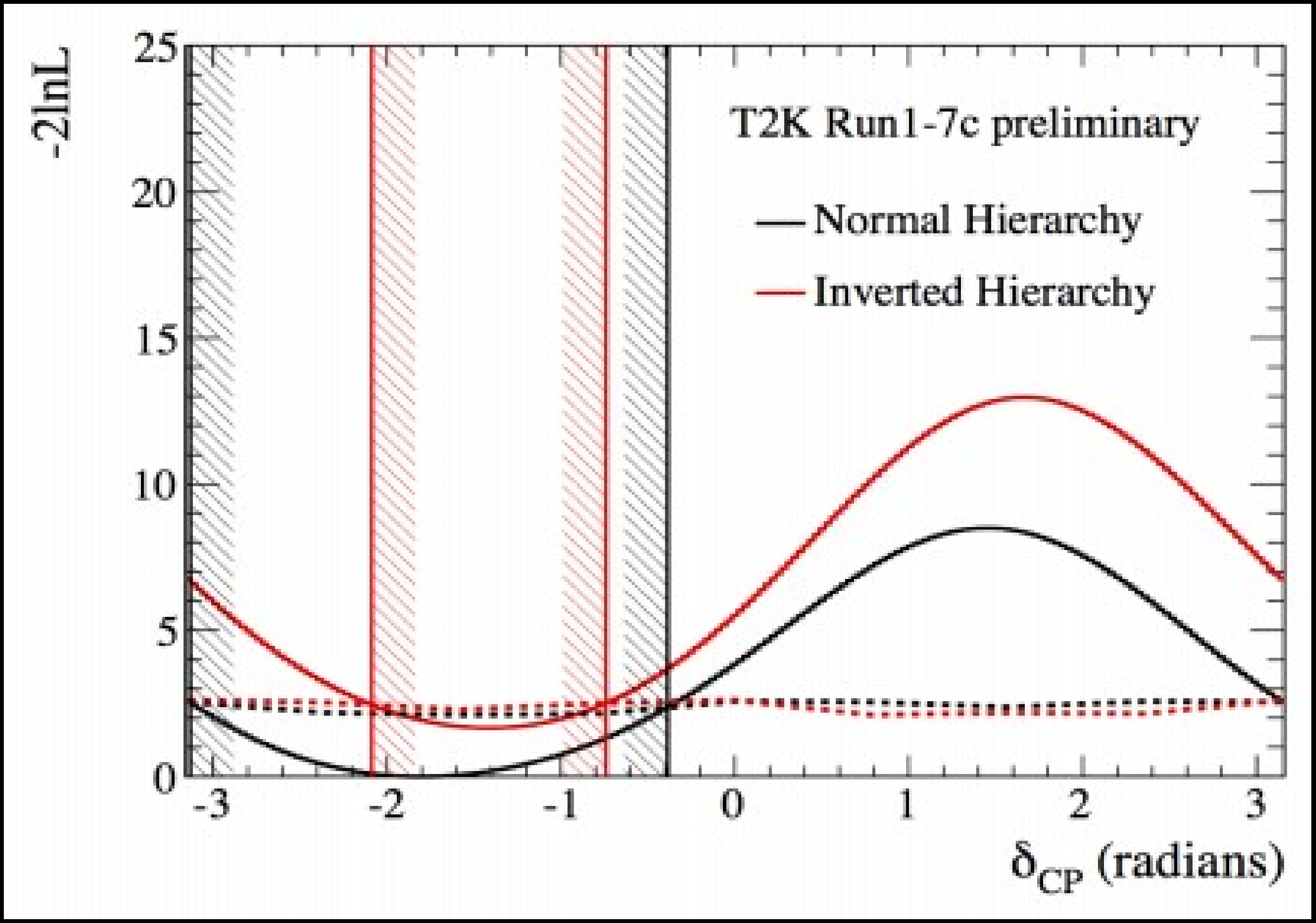
T2K



CP violation will show up if

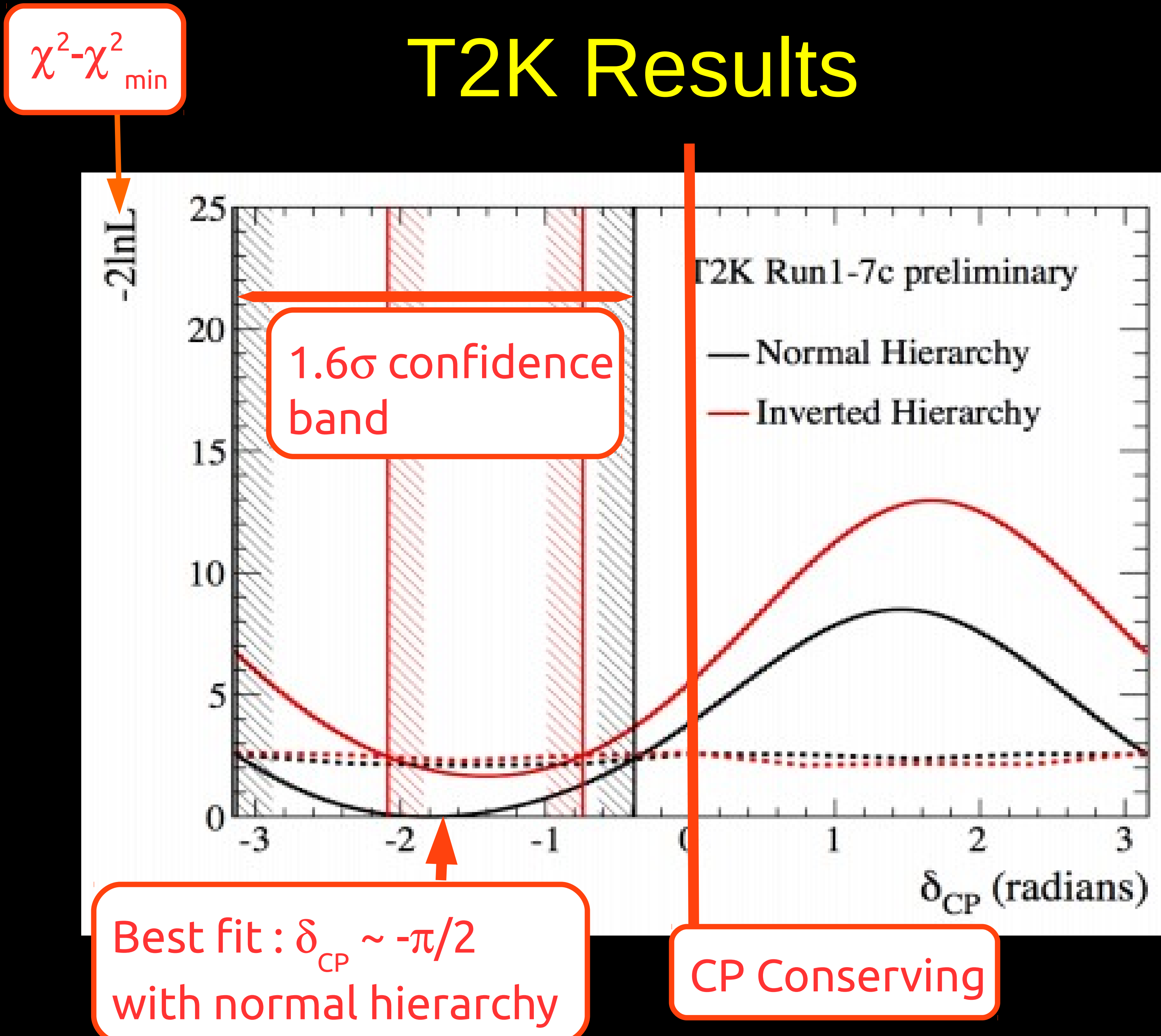
$$P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$$

T2K Results



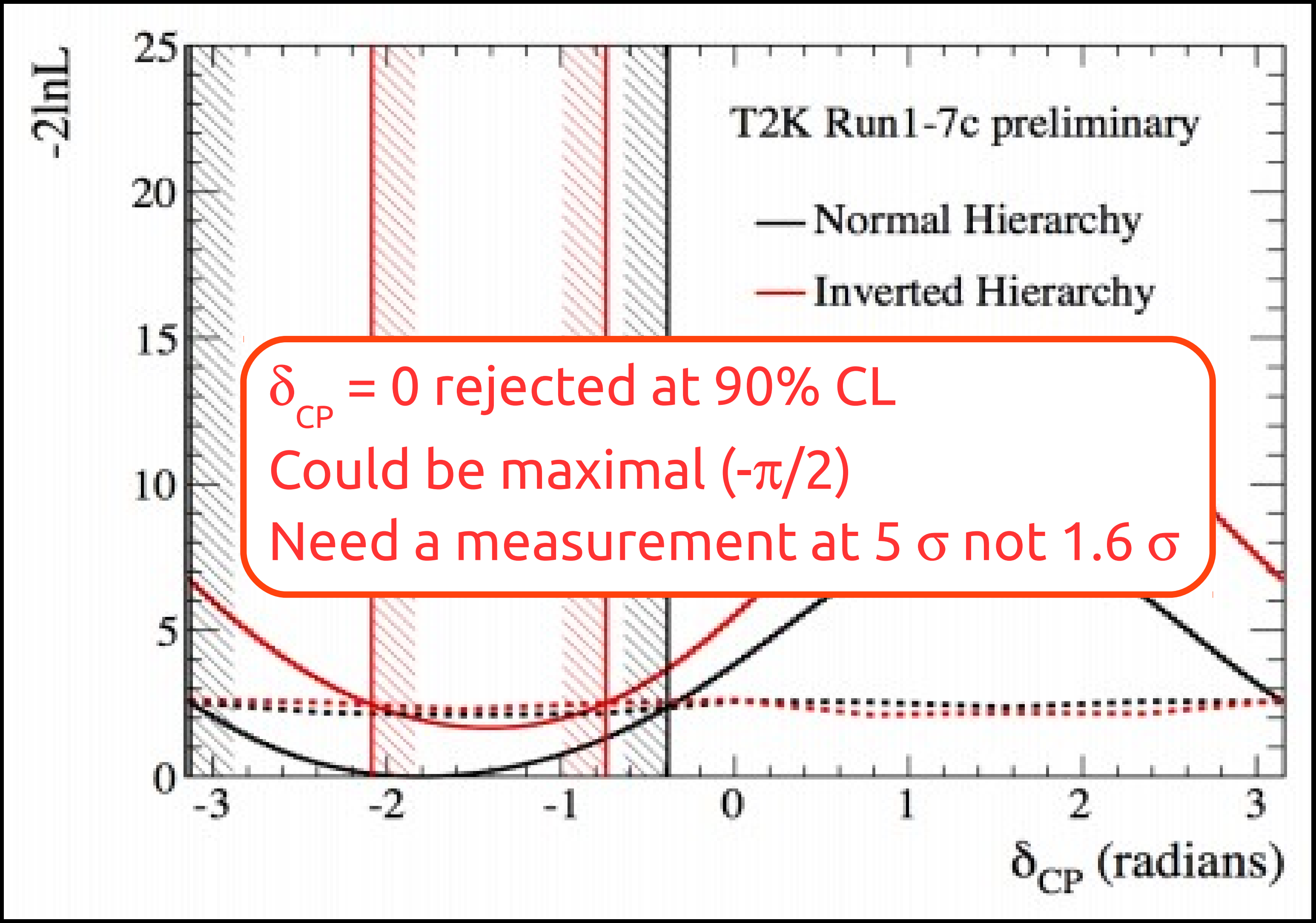
-2lnL
25
20
15
10
5
0
-3
-2
-1
0
1
2
3
δ_{CP} (radians)
T2K Run1-7c preliminary
Normal Hierarchy
Inverted Hierarchy

T2K Results



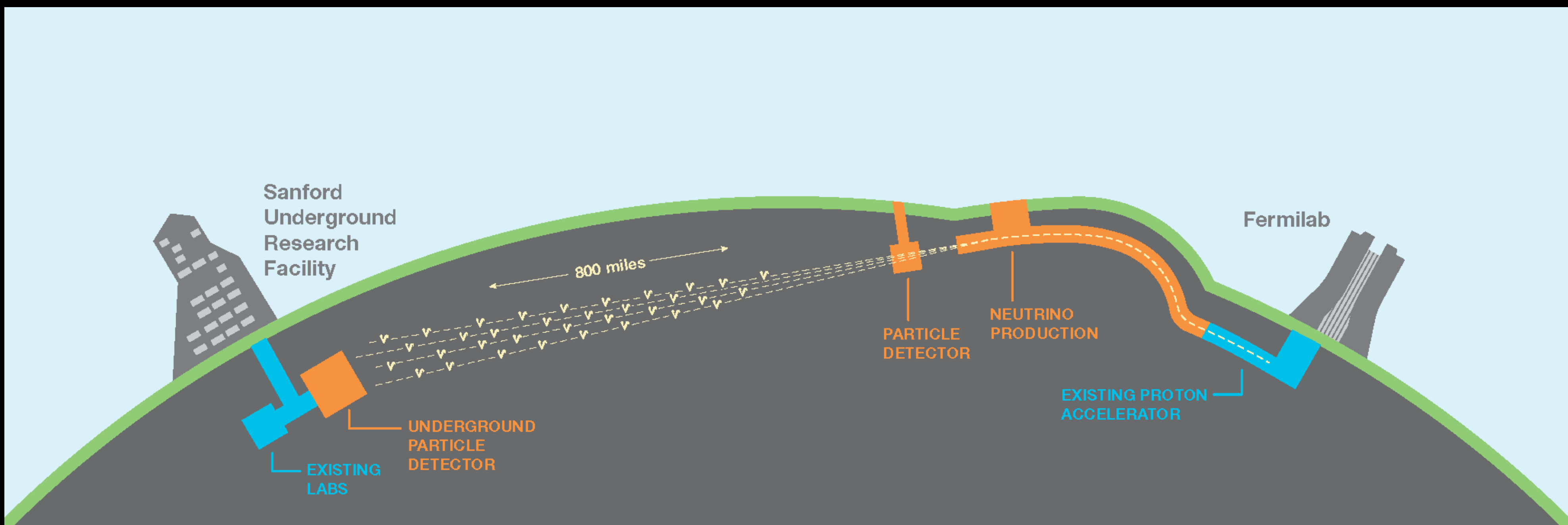
χ^2-χ^2_{min}
-2lnL
T2K Run1-7c preliminary
Normal Hierarchy
Inverted Hierarchy
1.6σ confidence band
δ_{CP} (radians)
Best fit : δ_{CP} ~ -π/2 with normal hierarchy
CP Conserving

T2K Results



δ_{CP} = 0 rejected at 90% CL
Could be maximal ($-\pi/2$)
Need a measurement at 5 σ not 1.6 σ

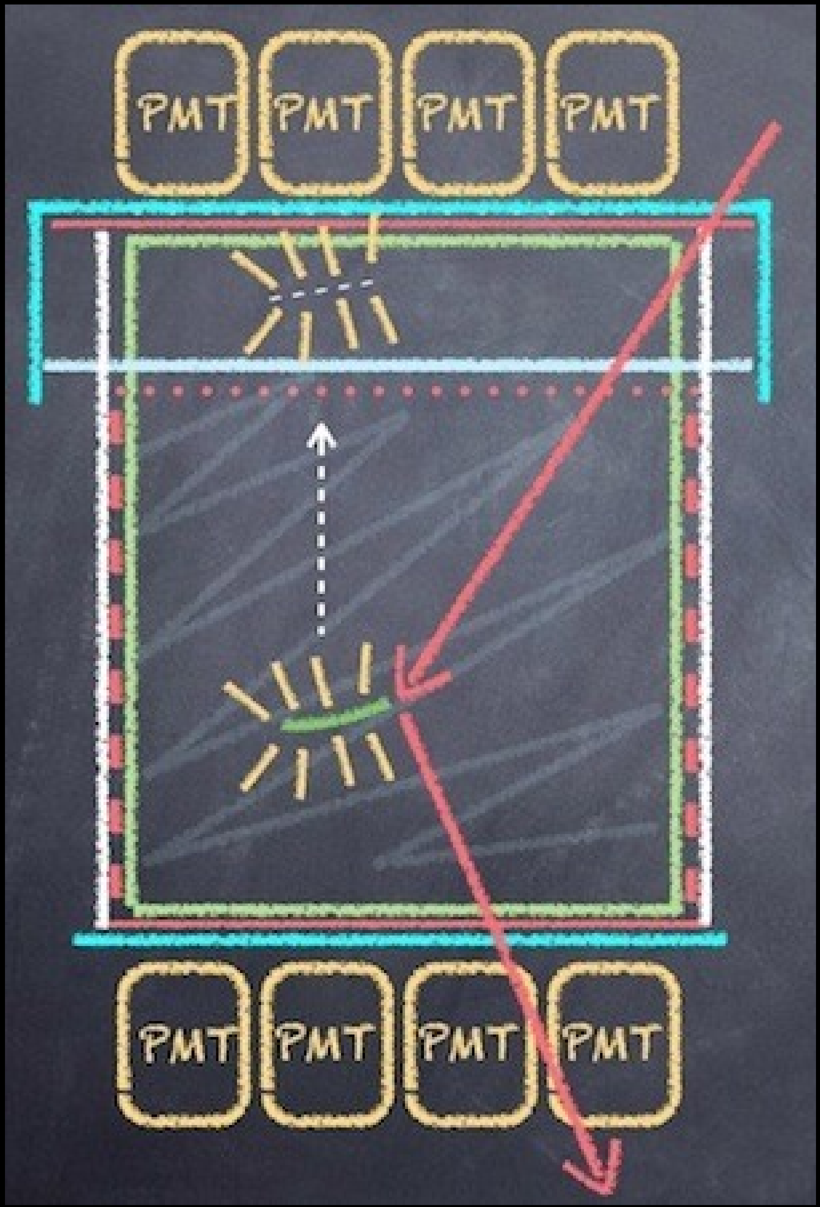
New experiments : DUNE and HyperK



DUNE (Deep Underground Neutrino Experiment)

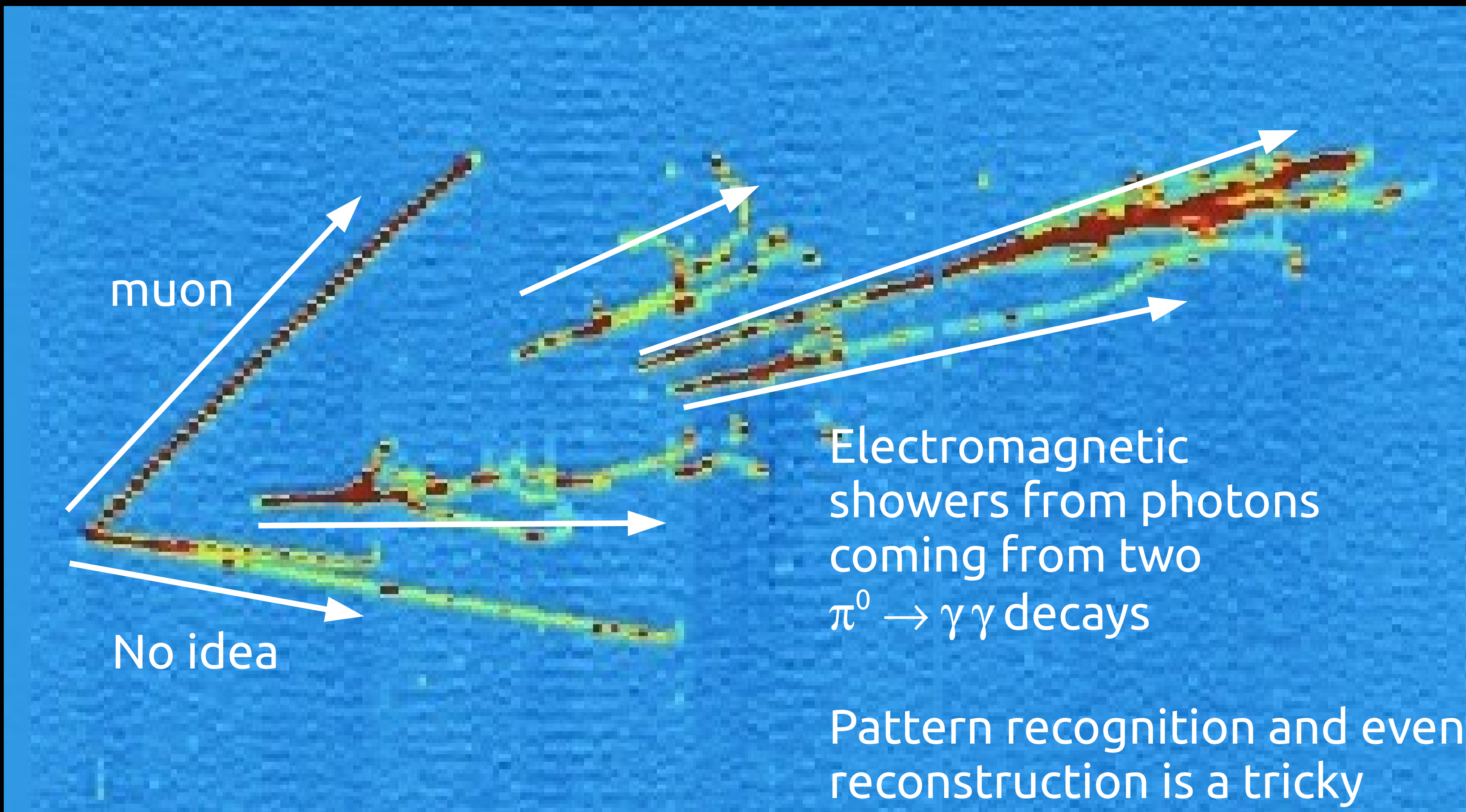
Baseline : 1300 km from Fermilab (Chicago) to Soudan (South Dakota)
Liquid Argon technology

Liquid Argon TPC



- TPC technology is not new
- TPCs usually use gas to generate ionisation electrons
- Neutrino detectors need to use liquid to get more events
- LAr is a new technology being trialled in various prototypes
- DUNE plans 4 TPC modules containing 17 kton of LAr
- Largest LAr TPCs ever built

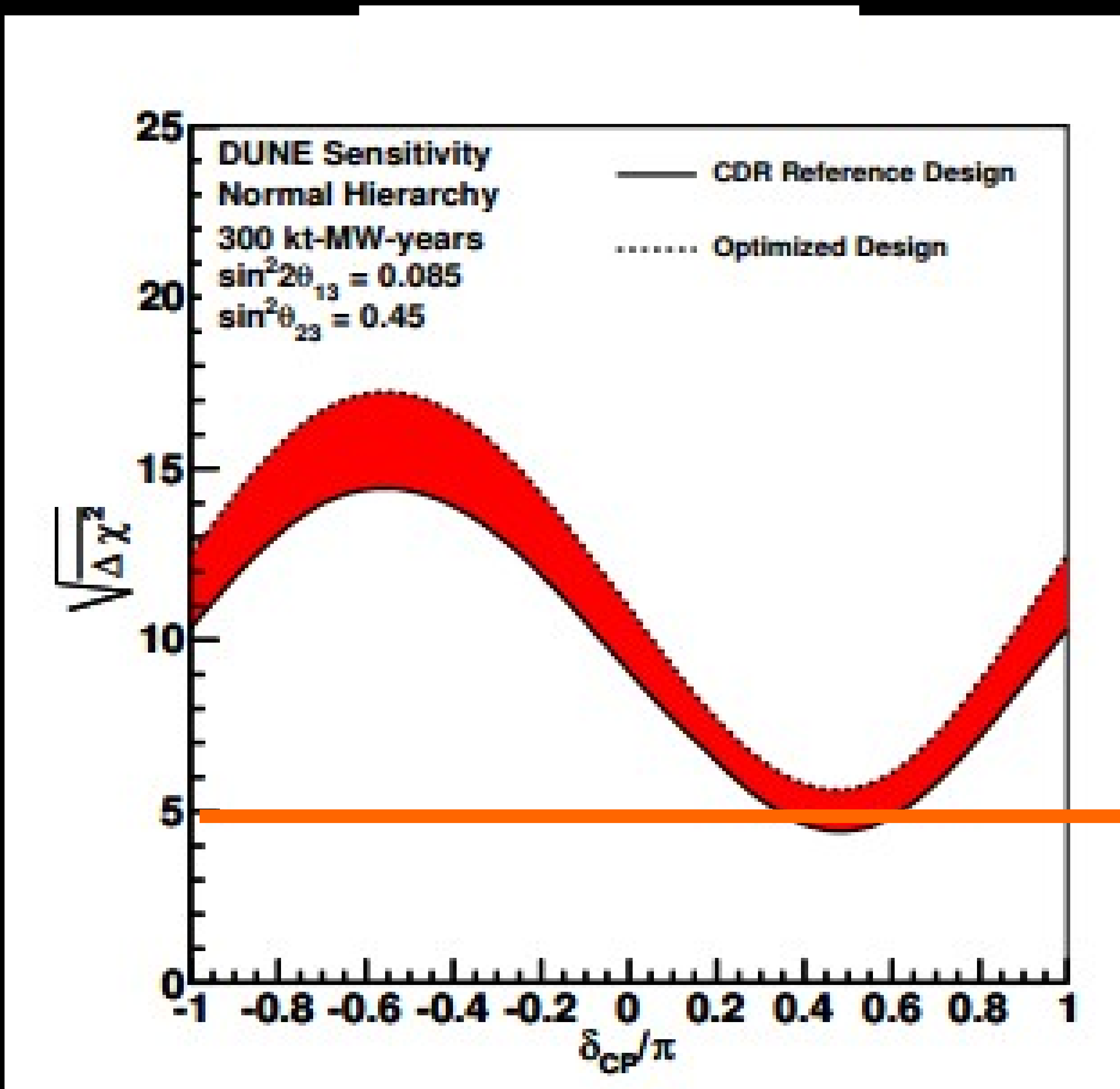
Liquid Argon Time Projection Chamber



Electromagnetic showers from photons coming from two $\pi^0 \rightarrow \gamma\gamma$ decays

Pattern recognition and event reconstruction is a tricky computational problem

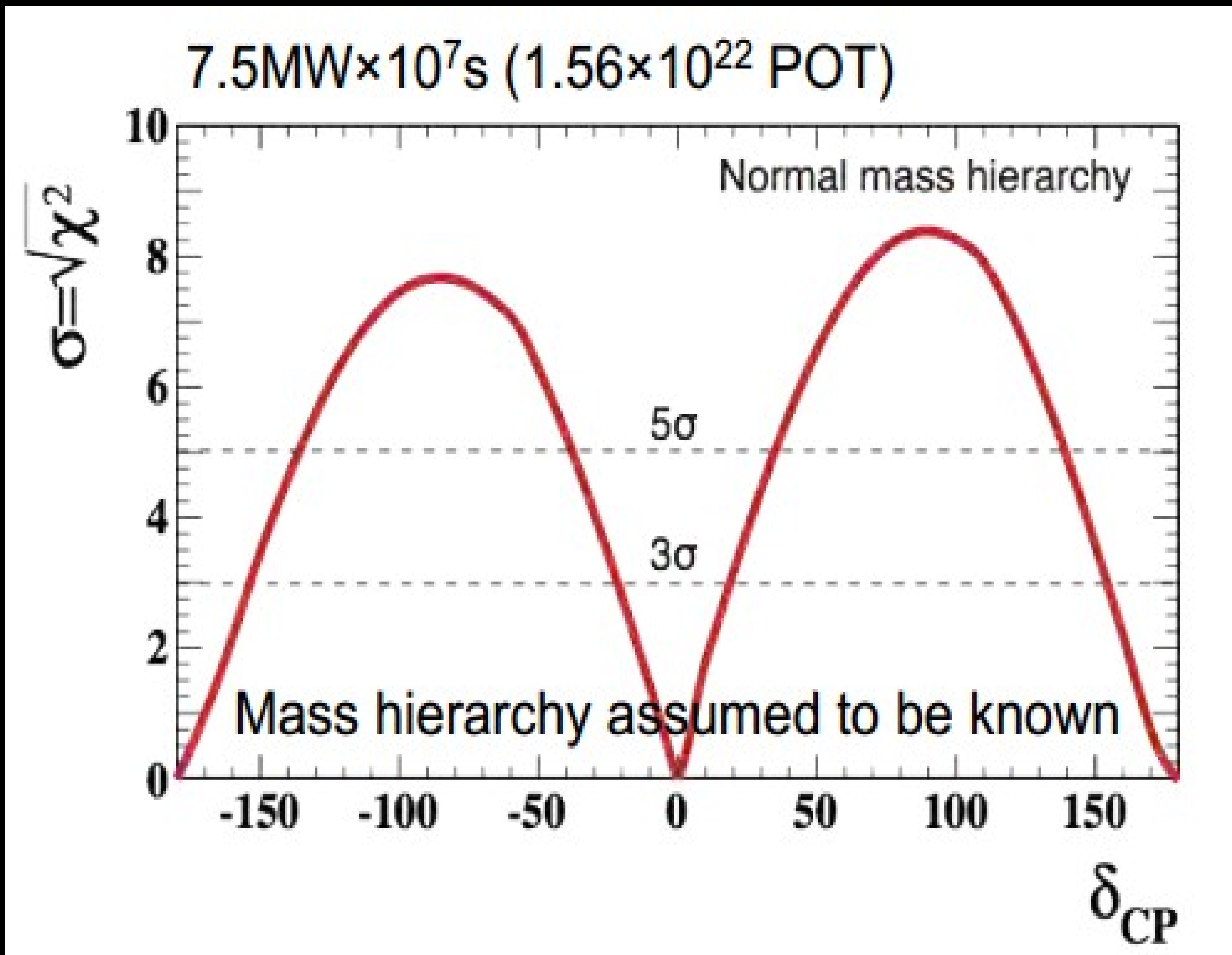
DUNE Predictions : Mass Hierarchy



- After 4 years of operation

5 σ determination of mass hierarchy over entire range of δ_{CP}

DUNE Predictions : δ_{CP}



5 σ significance for sin $\delta_{CP} \neq 0$ over 56% of δ_{CP} space

20% precision at δ_{CP} = -90 degrees

Timeline

2018 : Technology prototyping programme at CERN

2019 : Delivery of Technical Design Report to funding agencies

2020 : Detector fabrication hubs ready and logistics program defined

2024 : Construction and installation of Far Detectors

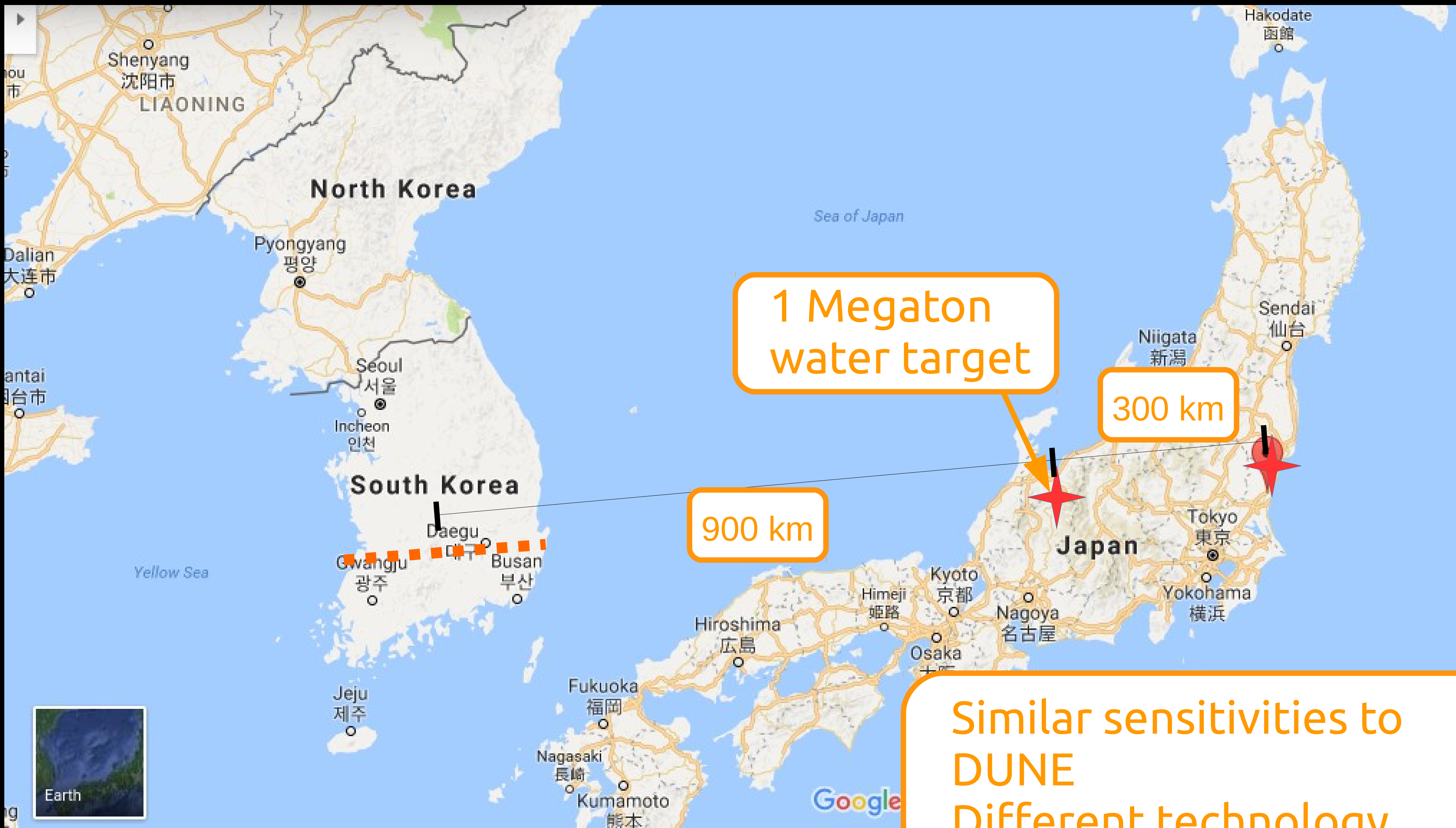
2025 : Commissioning of Far Detectors

2026 : Delivery of neutrino beam to Far site. Physics starts.

2028 : Preliminary results on mass hierarchy and δ_{CP}

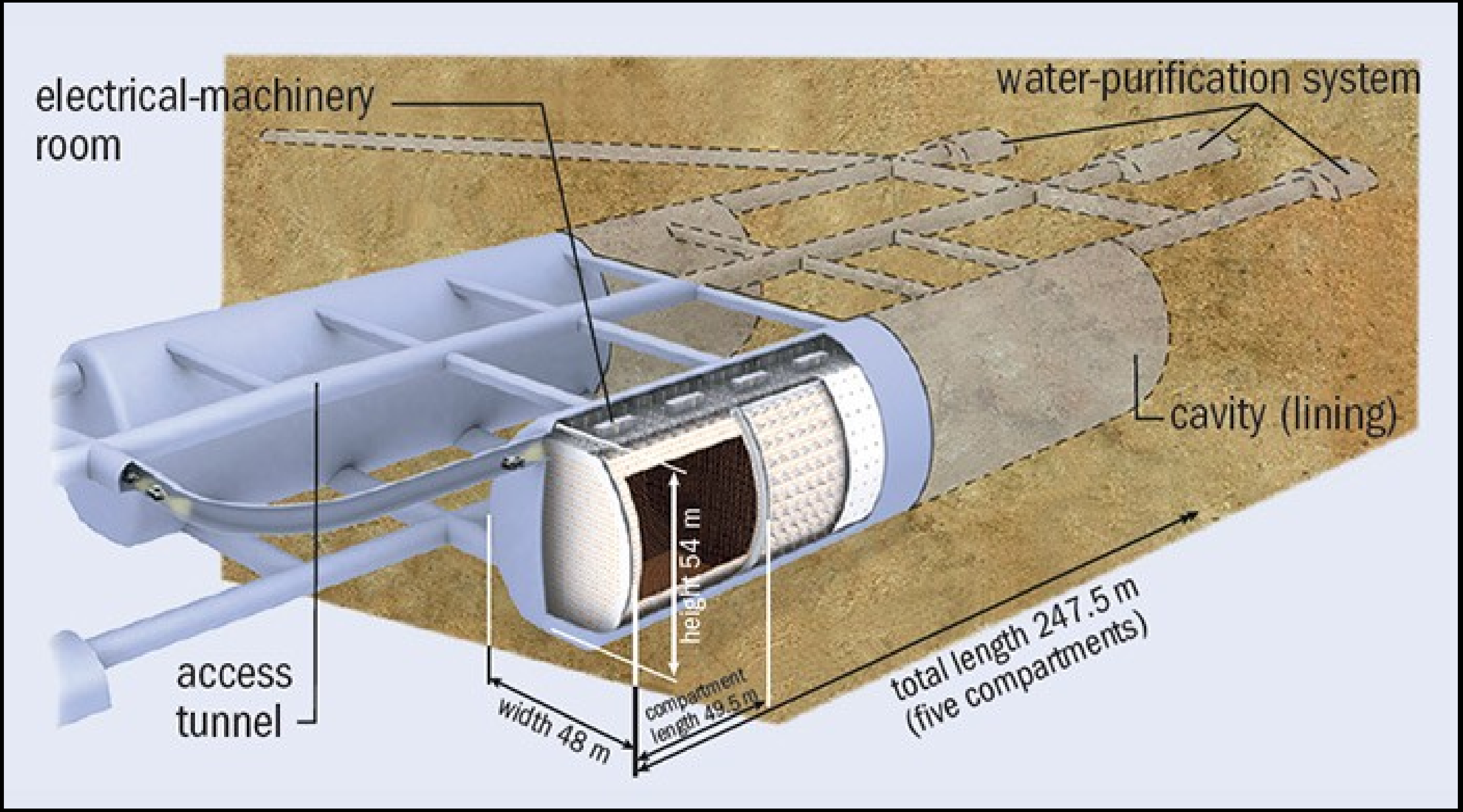
2030 : Final results

Hyper-Kamiokande (The opposition)



Similar sensitivities to DUNE
Different technology
Timescale less advanced

Hyper-K Far Detector



Summary

Particle physics has studied CP violation in the quarks for years

We are only beginning to look at the leptons....and early indications are that the leptons behave significantly differently

We get all this information from long baseline experiments which are only beginning to reach the era of high-precision neutrino physics

Still 20 years of work to understand what is going on...

Assume 1 billion people eat an egg sandwich every 3 months	1.67×10^{7} egg sandwiches/day
Let's say that 3 months of the year people can eat outside, and that they picnic once a month	140,000 external egg sandwiches/day
egg sandwich lifetime – 20 minutes	3000 egg sandwiches at any time
Area of egg sandwich – 15 cm x 15cm	62 m^2 total egg-sandwich area
Surface area of earth	500 million km^2
Suppose flight paths cover area of earth uniformly	Probability of egg-sandwich/ ball bearing intersection 1×10^{-13}

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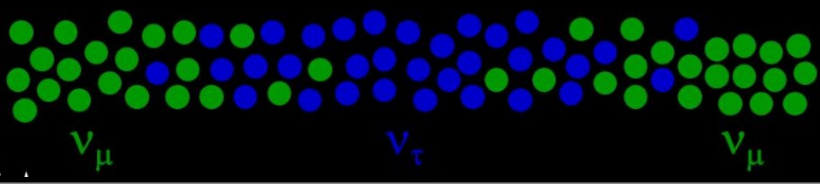


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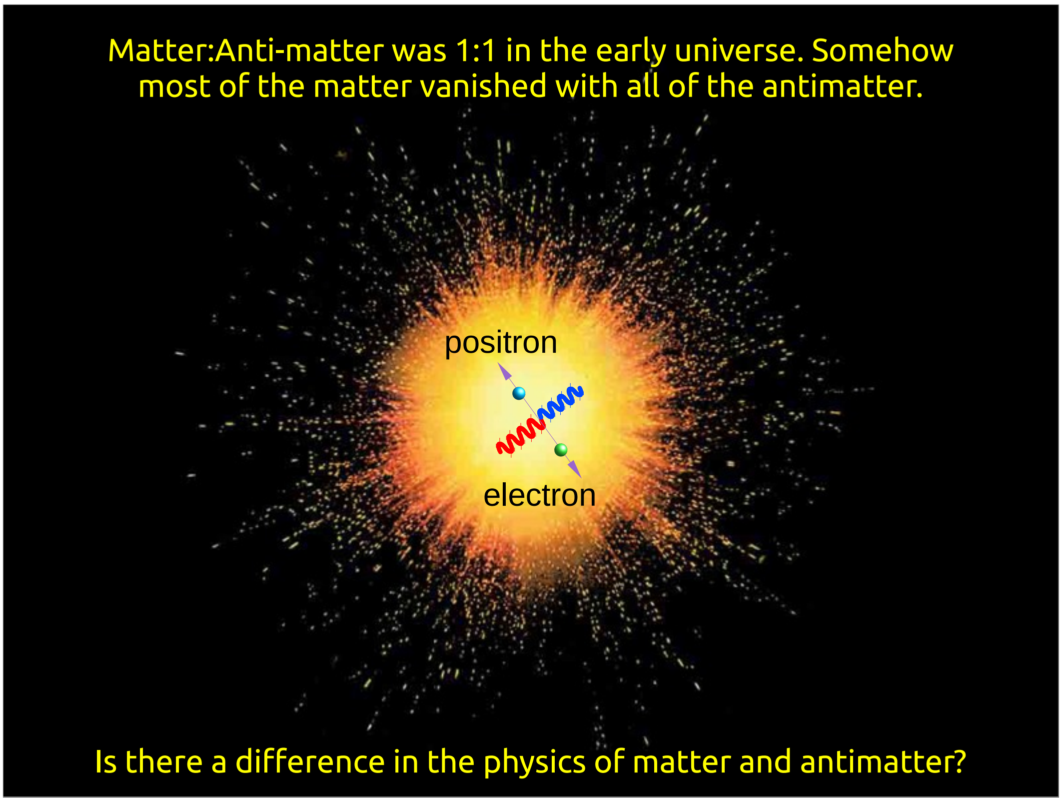
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positron
electron
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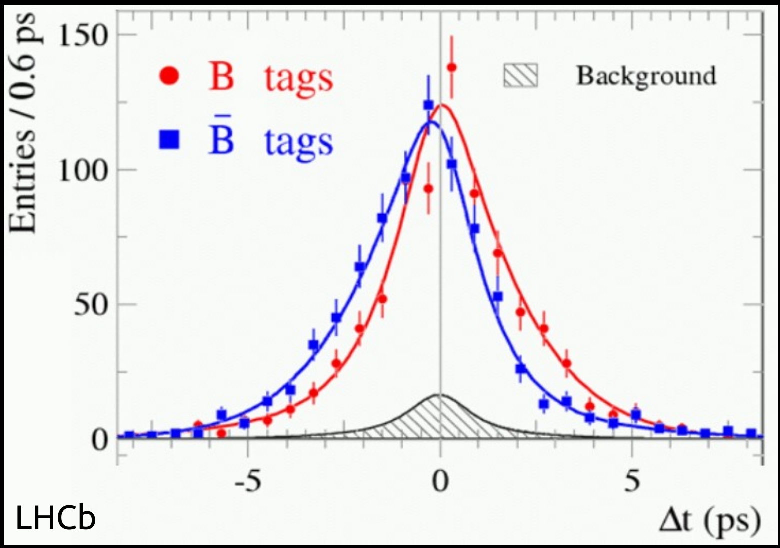

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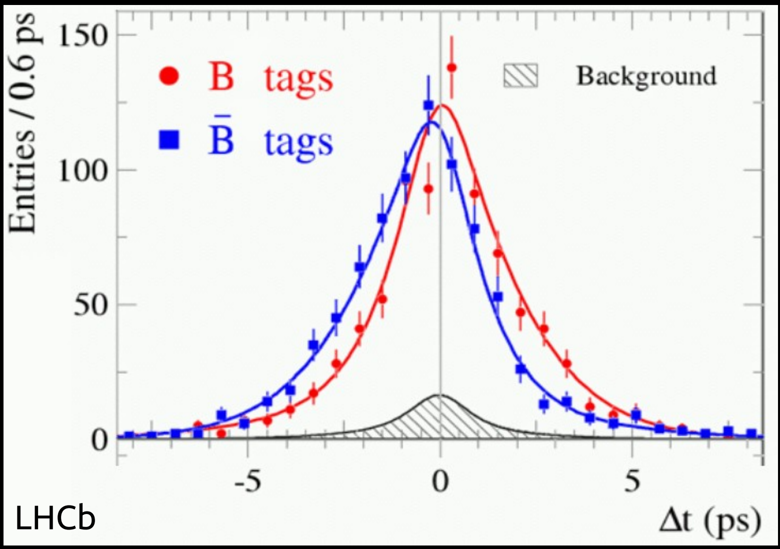
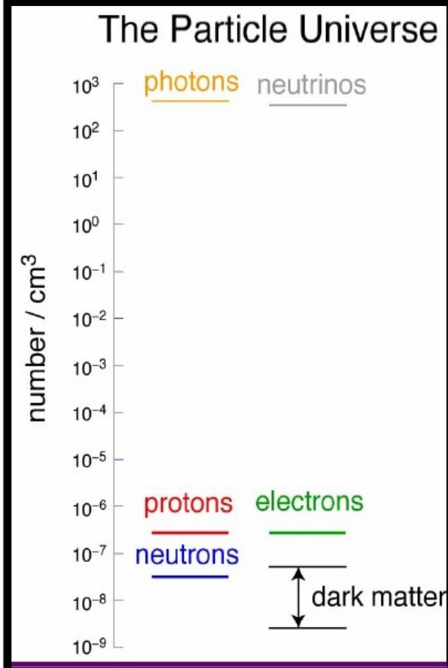


Part of the answer may lie, not with quarks, but with neutrinos

What is a neutrino?



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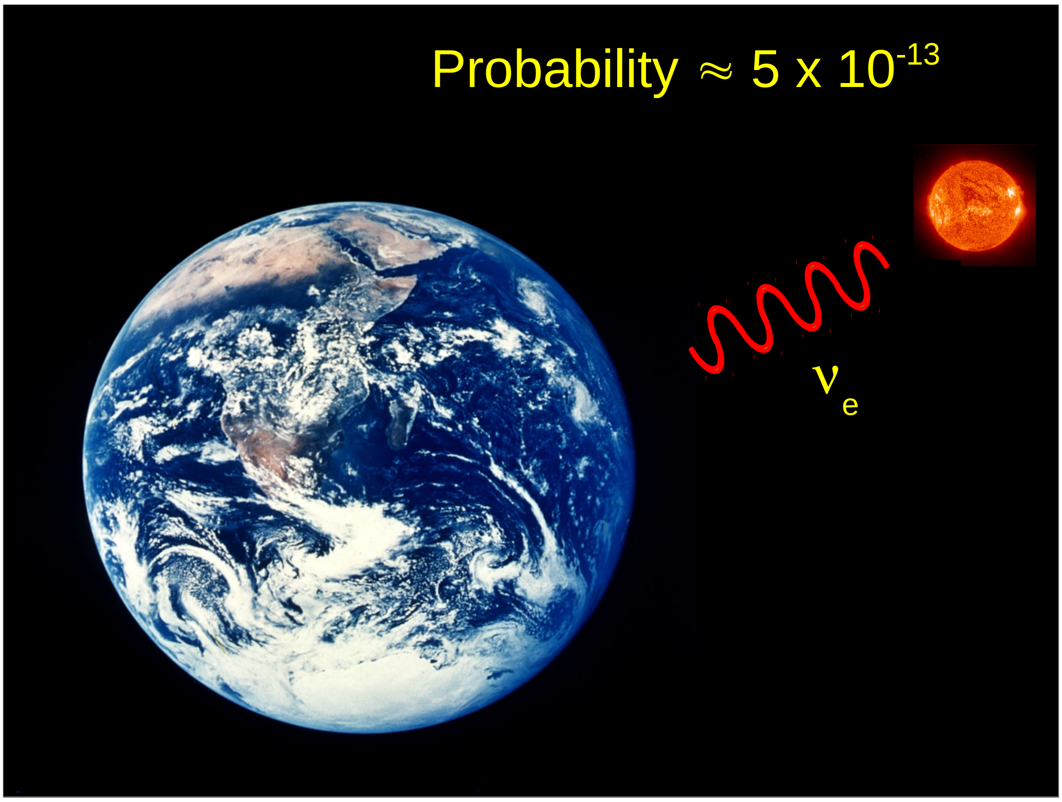
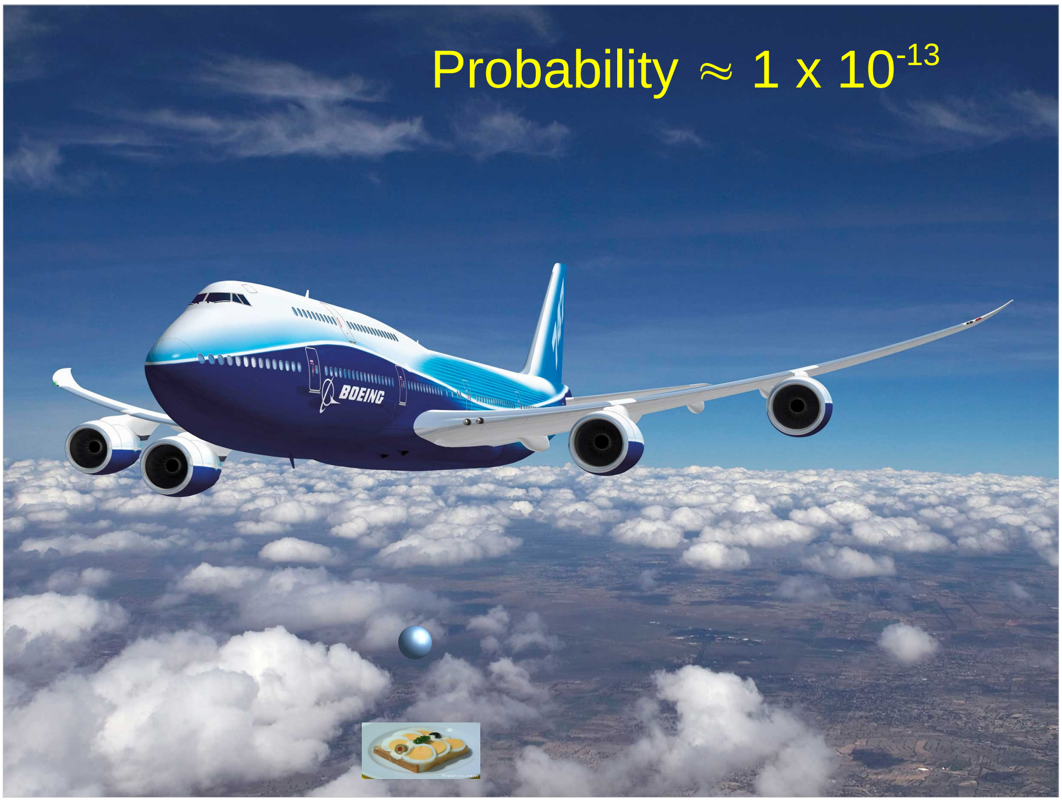


Probability ≈ 5 x 10-13
νe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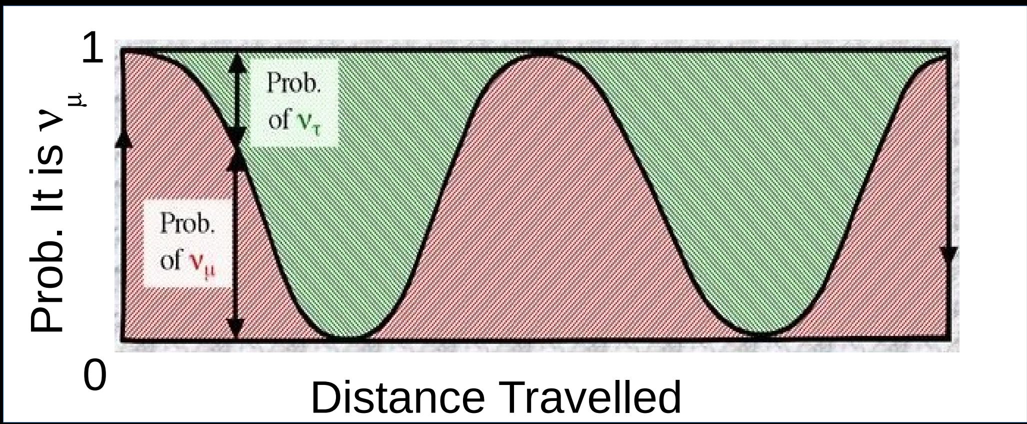

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Mass states | Mixing matrix | Flavour states

Neutrino Flavour Oscillations

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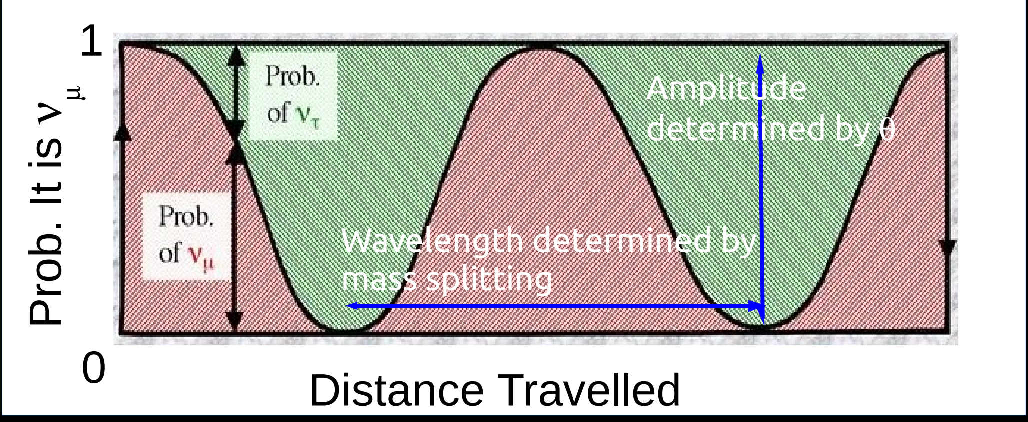

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What we know...

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...and what we don't

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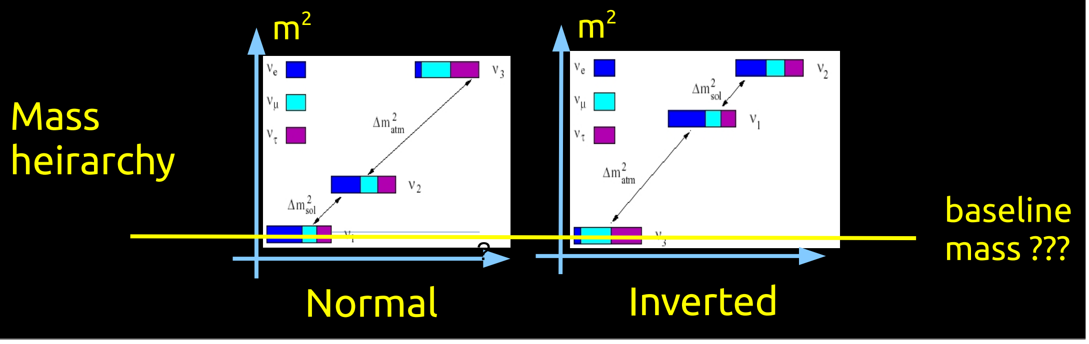
δ_{CP} controls the level of CP violation



Why does it matter?

There is an idea floating about out there called Leptogenesis

It goes

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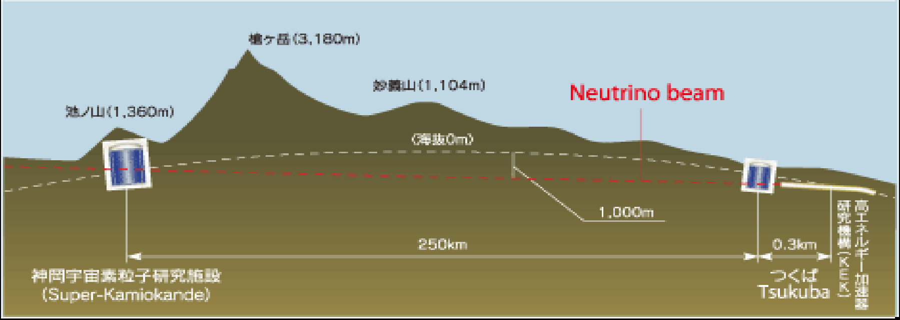

Two types of measurements : $Disappearance: P(\nu_\mu \rightarrow \nu_\mu)$

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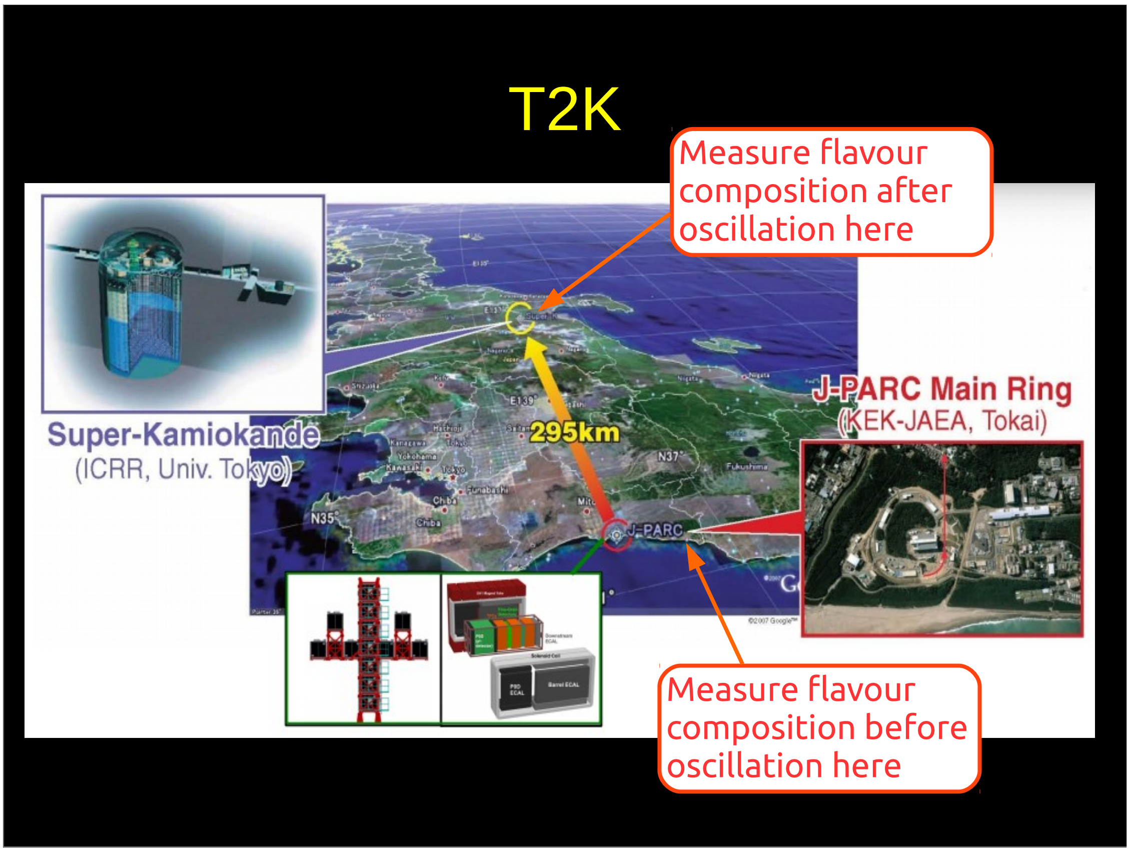
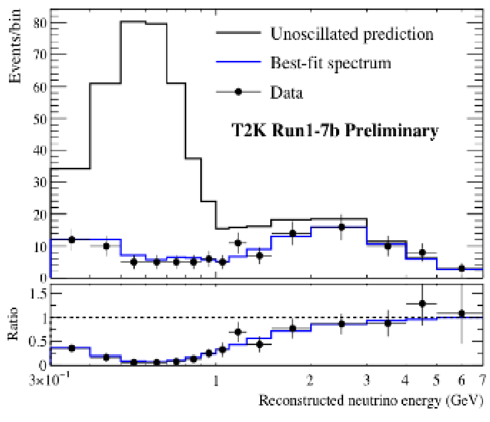
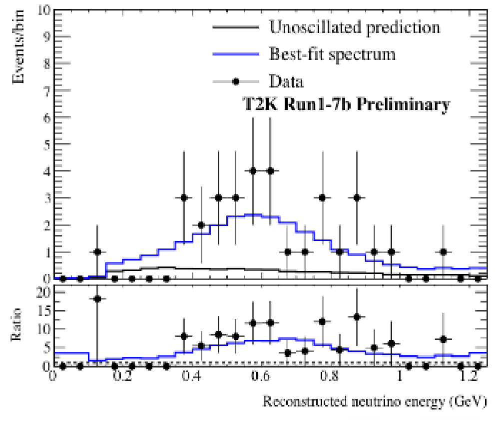

T2K
Measure flavour composition after oscillation here
Super-Kamiokande
(ICRR, Univ. Tokyo)
295km
J-PARC
J-PARC Main Ring
(KEK-JAEA, Tokai)
Measure flavour composition before oscillation here

Long baseline experiments

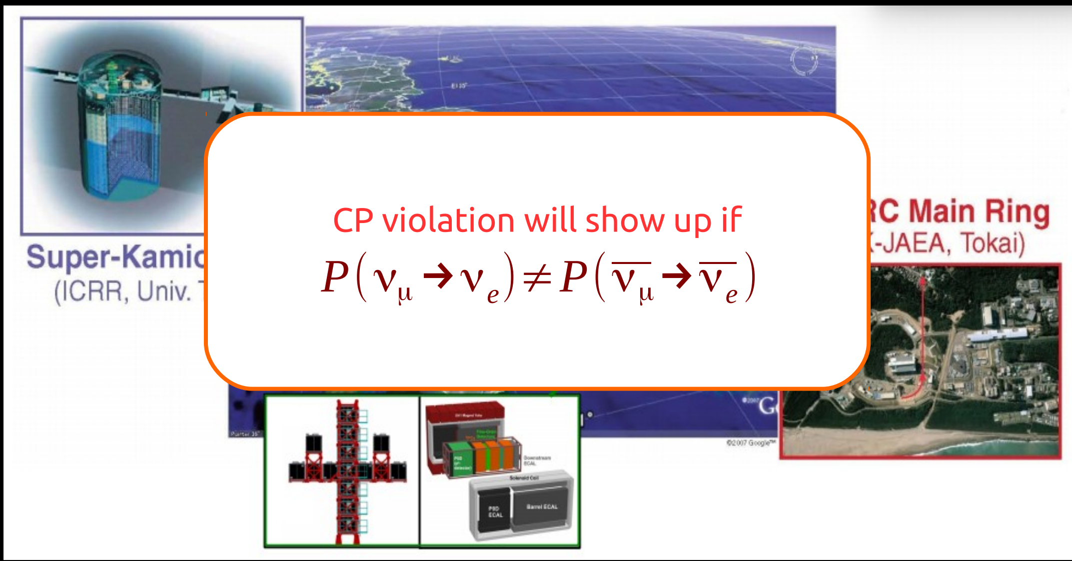


ν_μ Disappearance Measurement



ν_e Appearance Measurement

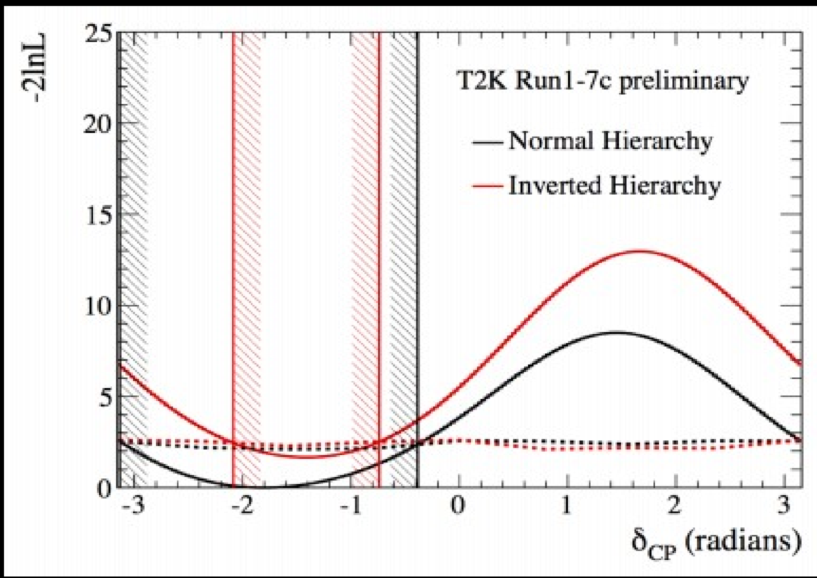
T2K



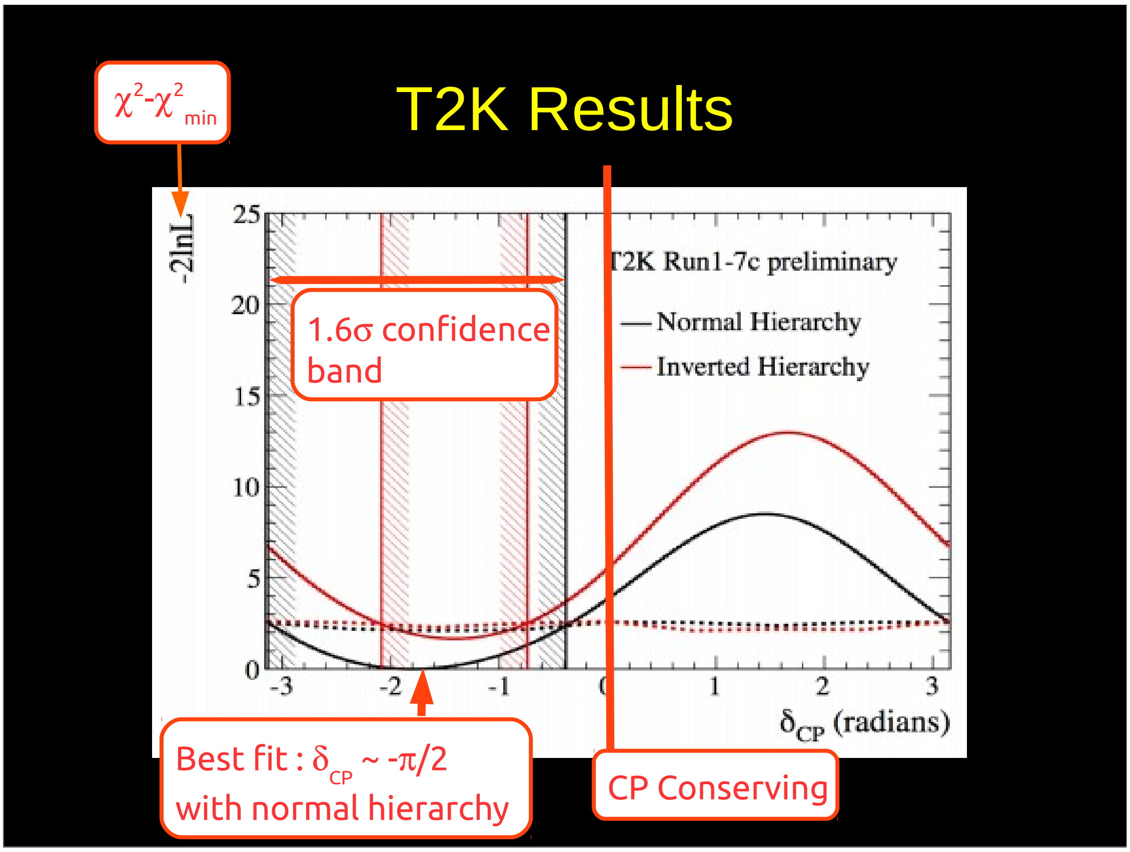
CP violation will show up if

$$P\left(\nu_{\mu} \rightarrow \nu_{e}\right) \neq P\left(\overline{\nu_{\mu}} \rightarrow \overline{\nu_{e}}\right)$$

T2K Results

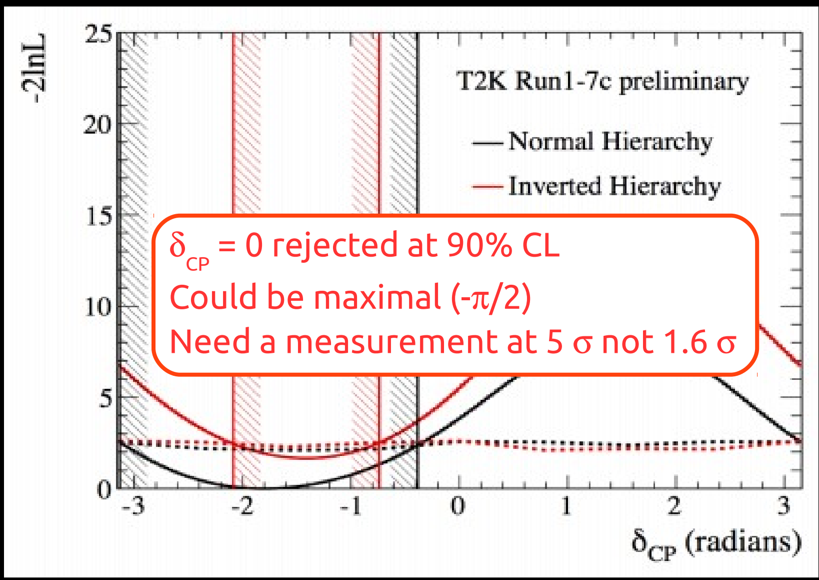


T2K Run1-7c preliminary
Normal Hierarchy
Inverted Hierarchy
-2lnL
25
20
15
10
5
0
-3
-2
-1
0
1
2
3
δCP (radians)



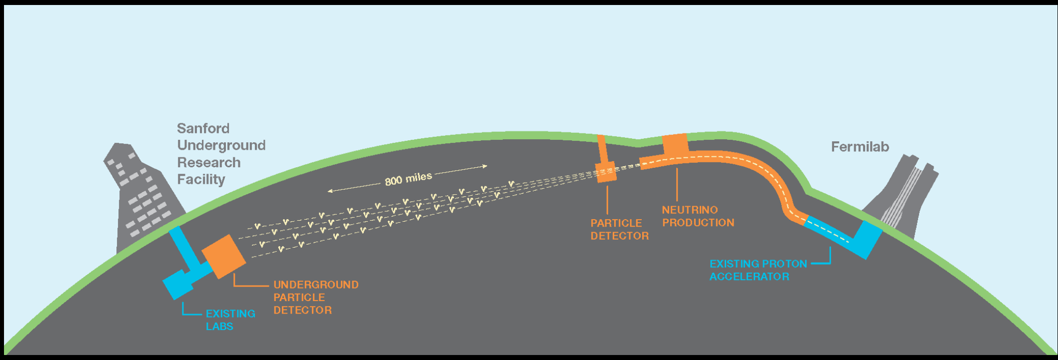
T2K Results
χ2-χ2 min
-2lnL
1.6σ confidence band
T2K Run1-7c preliminary
Normal Hierarchy
Inverted Hierarchy
δCP (radians)
Best fit : δCP ~ -π/2
with normal hierarchy
CP Conserving

T2K Results



-2lnL
25
20
15
10
5
0
-3
-2
-1
0
1
2
3
δ_CP (radians)
T2K Run1-7c preliminary
Normal Hierarchy
Inverted Hierarchy
δ_CP = 0 rejected at 90% CL
Could be maximal (-π/2)
Need a measurement at 5 σ not 1.6 σ

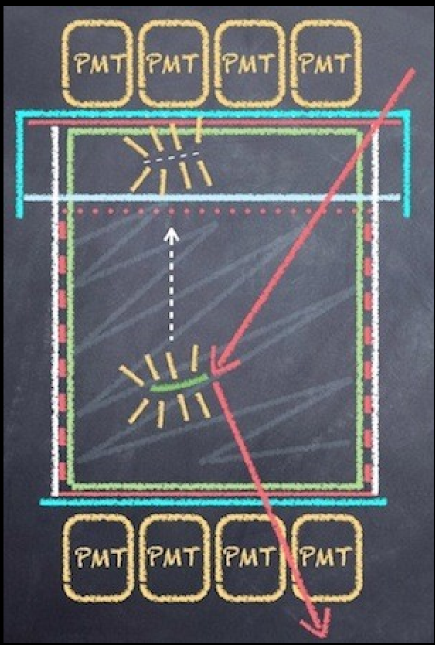
New experiments : DUNE and HyperK



DUNE (Deep Underground Neutrino Experiment)

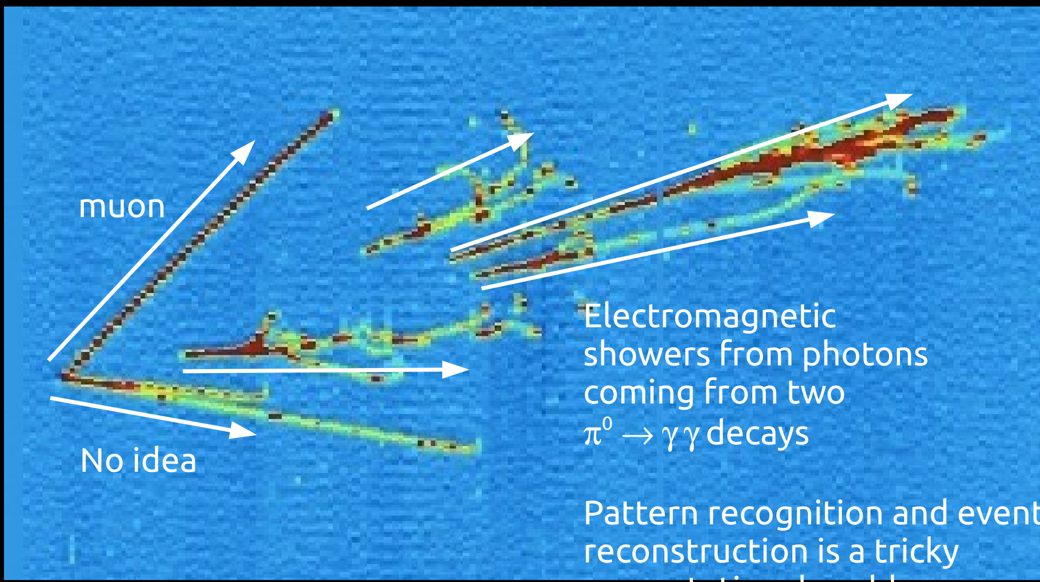
Baseline : 1300 km from Fermilab (Chicago) to Soudan (South Dakota)
Liquid Argon technology

Liquid Argon TPC

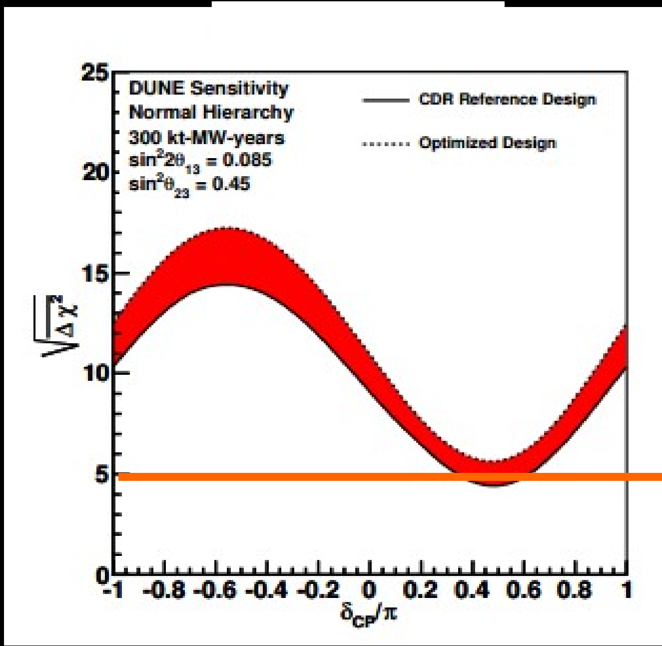


- TPC technology is not new
- TPCs usually use gas to generate ionisation electrons
- Neutrino detectors need to use liquid to get more events
- LAr is a new technology being trialled in various prototypes
- DUNE plans 4 TPC modules containing 17 kton of LAr
- Largest LAr TPCs ever built

Liquid Argon Time Projection Chamber



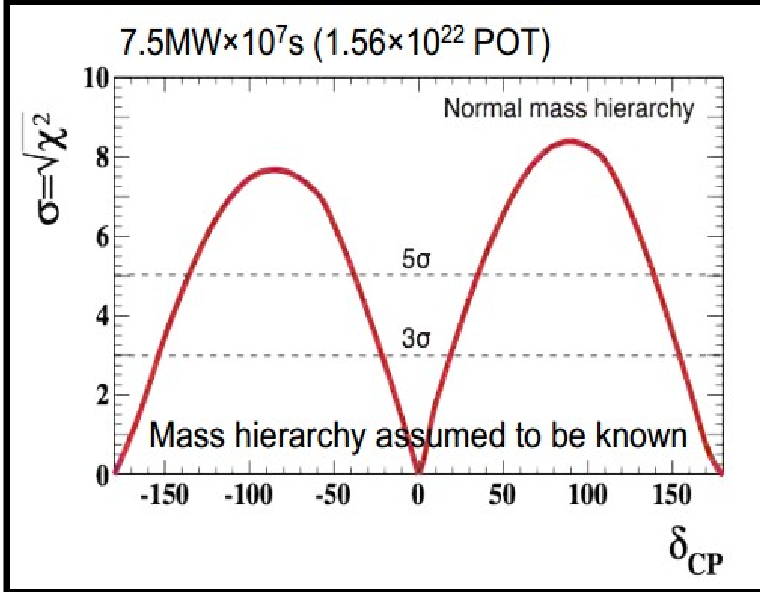
DUNE Predictions : Mass Hierarchy



- After 4 years of operation

5 σ determination of mass hierarchy over entire range of δ_{CP}

DUNE Predictions : δ_{CP}



5 σ significance for sin $\delta_{CP} \neq 0$ over 56% of δ_{CP} space

20% precision at δ_{CP} = -90 degrees

Timeline

2018 : Technology prototyping programme at CERN

2019 : Delivery of Technical Design Report to funding agencies

2020 : Detector fabrication hubs ready and logistics program defined

2024 : Construction and installation of Far Detectors

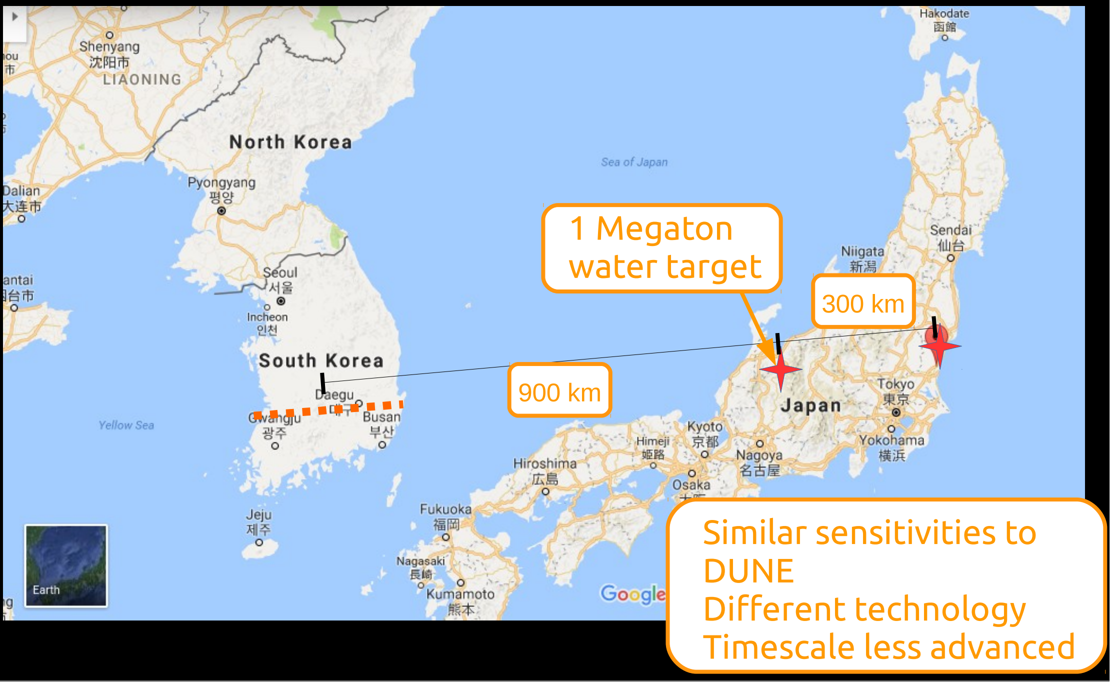
2025 : Commissioning of Far Detectors

2026 : Delivery of neutrino beam to Far site. Physics starts.

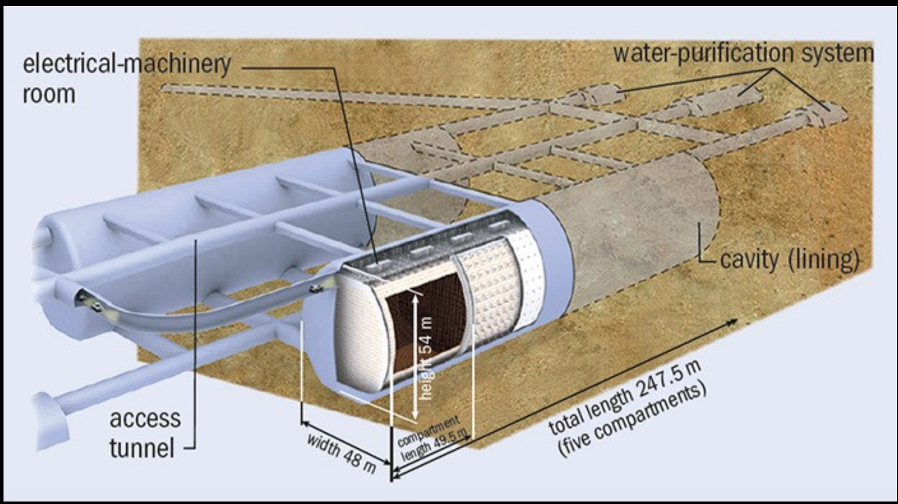
2028 : Preliminary results on mass hierarchy and δ_{CP}

2030 : Final results

Hyper-Kamiokande (The opposition)



Hyper-K Far Detector



Summary

Particle physics has studied CP violation in the quarks for years

We are only beginning to look at the leptons....and early indications are that the leptons behave significantly differently

We get all this information from long baseline experiments which are only beginning to reach the era of high-precision neutrino physics

Still 20 years of work to understand what is going on...

Assume 1 billion people eat an egg sandwich every 3 months	1.67×10^{7} egg sandwiches/day
Let's say that 3 months of the year people can eat outside, and that they picnic once a month	140,000 external egg sandwiches/day
egg sandwich lifetime – 20 minutes	3000 egg sandwiches at any time
Area of egg sandwich – 15 cm x 15cm	62 m^2 total egg-sandwich area
Surface area of earth	500 million km^2
Suppose flight paths cover area of earth uniformly	Probability of egg-sandwich/ ball bearing intersection 1×10^{-13}