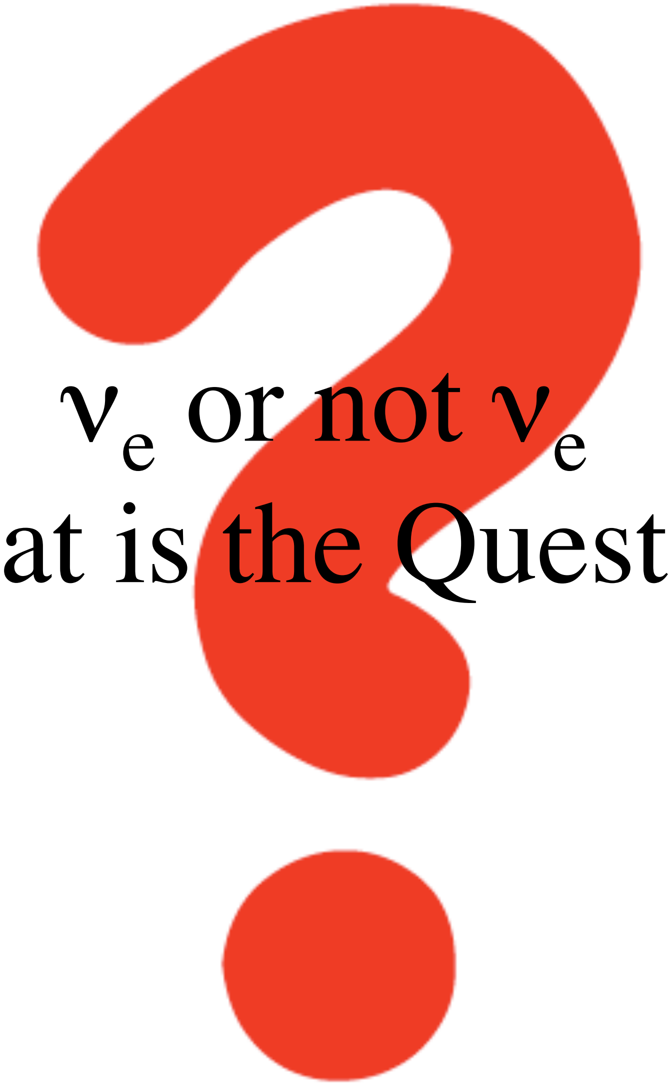


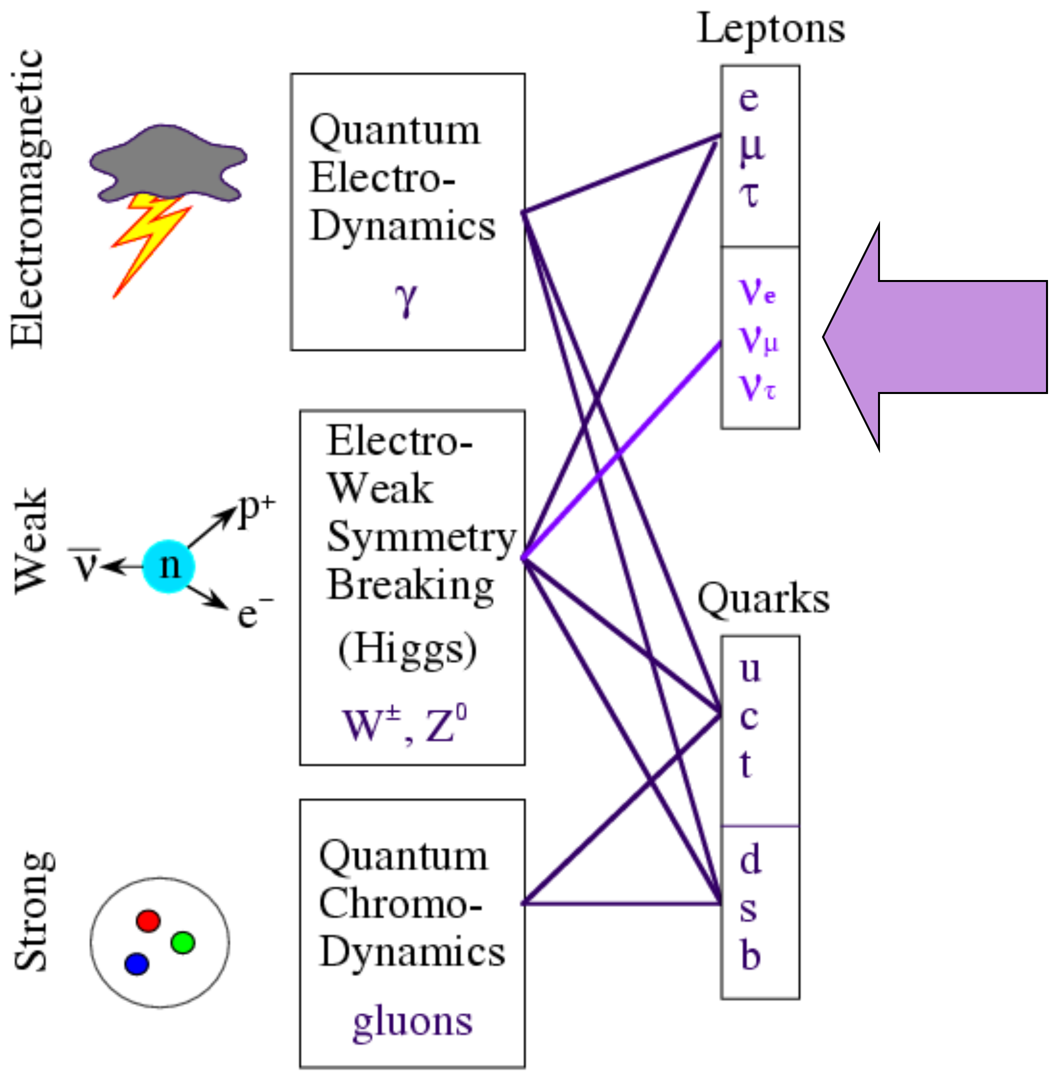
ν_e or not ν_e
…that is the Question!

Janet Conrad
MIT

Three mysteries about observing (or not observing) electron neutrino interactions…

Chapter 1:	Setting the stage…
Chapter 2:	Presenting the mysteries…
Chapter 3:	Speculating on how the plot may unfold (with a *new and improved* potential ending!)

The Standard Model



Electromagnetic

Quantum Electro-Dynamics

γ

Weak

$\bar{\nu}$ n p^+ e^-

Electro-Weak Symmetry Breaking

(Higgs)

$W^\pm$, Z^0

Strong

Quantum Chromo-Dynamics

gluons

Leptons

e μ τ

ν_e ν_μ ν_τ

Quarks

u c t

d s b

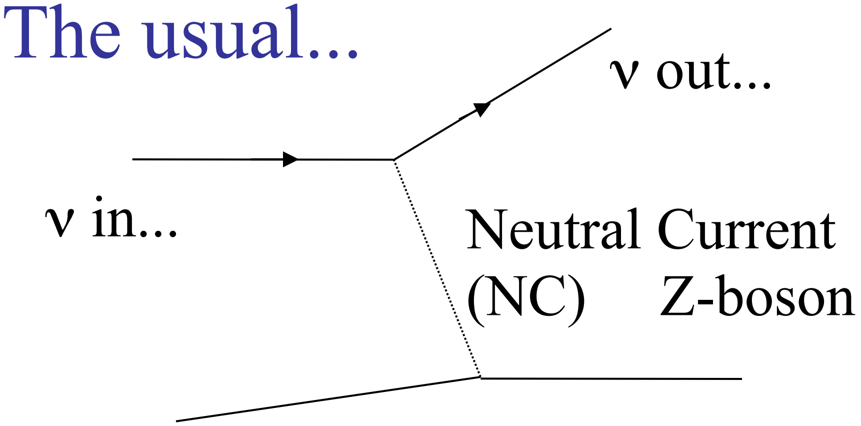
We've known about neutrinos since the 1930's

The electron flavor was the first predicted and first observed!

Neutrinos
interact via

Only the
Weak Interaction

The usual...

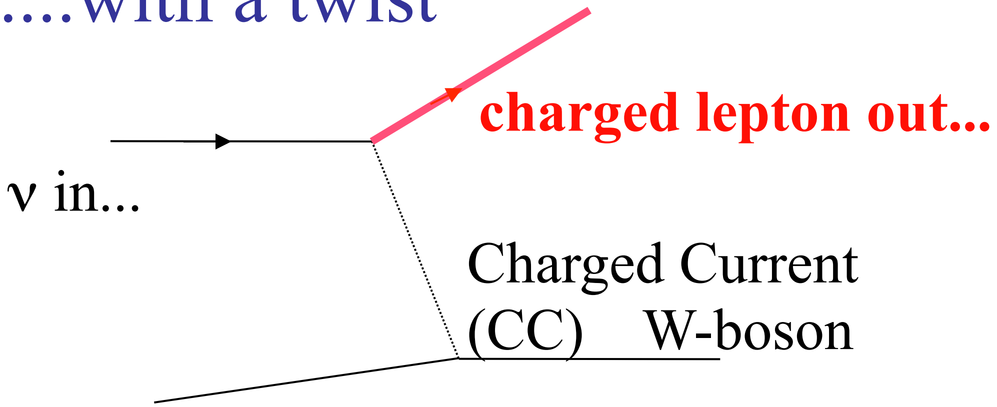


ν out...

ν in...

Neutral Current
(NC)   Z-boson

....with a twist

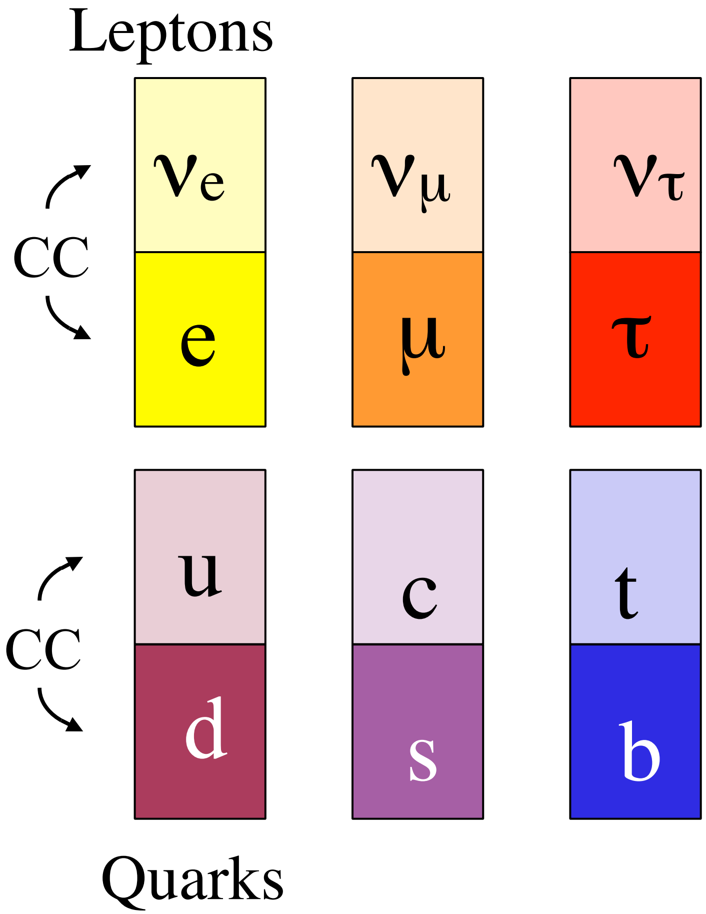


charged lepton out...

ν in...

Charged Current
(CC)   W-boson

There are 3 types,
which form “weak doublets” with the charged leptons



Leptons

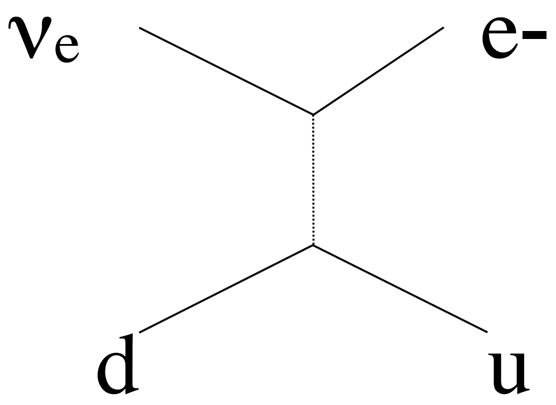
CC

ν_e	ν_μ	ν_τ
e	μ	τ

CC

u	c	t
d	s	b

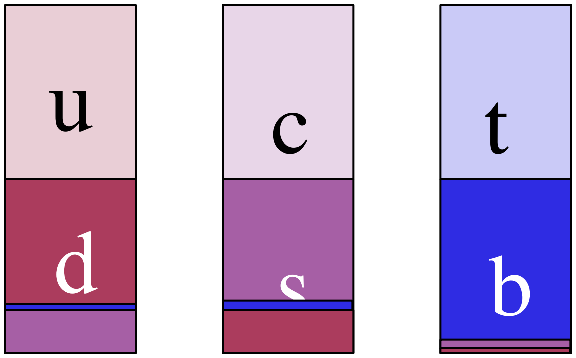
Quarks



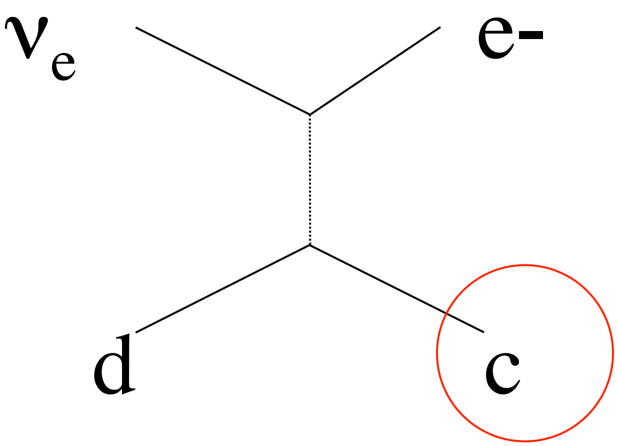
We identify the
neutrino flavor
via the CC interaction

Actually, with a modification in the quark sector:

MIXING: quark mass eigenstates $\neq$ quark weak eigenstates



Small effect, but clearly seen in weak interactions...



$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

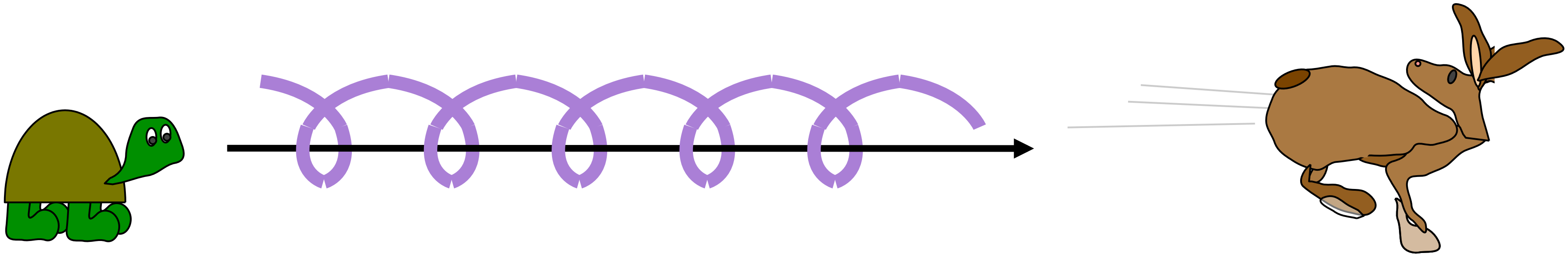
The CKM Matrix

... and kaon decays, D meson decays, etc.

Another feature: “handedness” … but first, helicity

All spin 1/2 particles have “helicity”

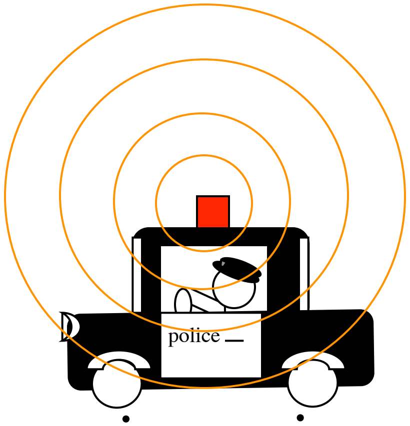
The operator: $\sigma \cdot \mathbf{p}$



Handedness (or chirality) is the Lorentz-invariant counterpart

Identical to helicity for massless particles (standard model ν's)

Experimental observation of Parity Violation
Neutrinos are LH (and antineutrinos RH) … always



How do you enforce the law of left-handedness?

Well… what couples left-handed particles to right?

A Dirac mass term
in the SM Lagrangian:

$$m(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$$

If you want to build parity violation into “the law”
you want keep this term out of the Lagrangian…
a simple solution is: m=0

in the Standard Model, neutrinos are massless

The problem is…

apparently that’s wrong!

It has long been known that neutrinos can, in principle, oscillate…

If we postulate:

- Neutrinos have (different) masses
- The Weak Eigenstate is a mixture of Mass Eigenstates:

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

Then a pure ν_μ beam at $t = 0$,
may evolve a ν_e component with time!

The Probability for Oscillations…

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

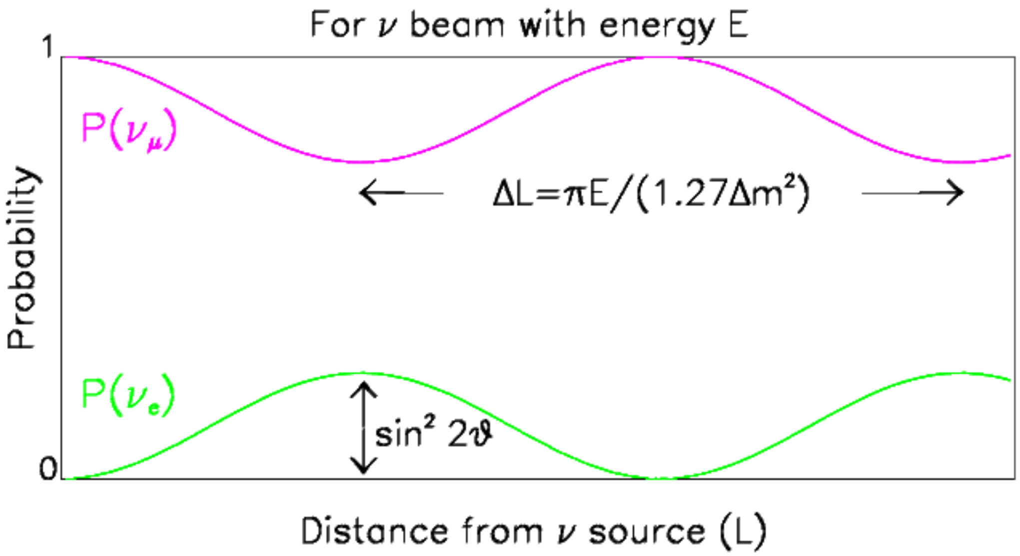
$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$

...Depends Upon Two Experimental Parameters:

- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:

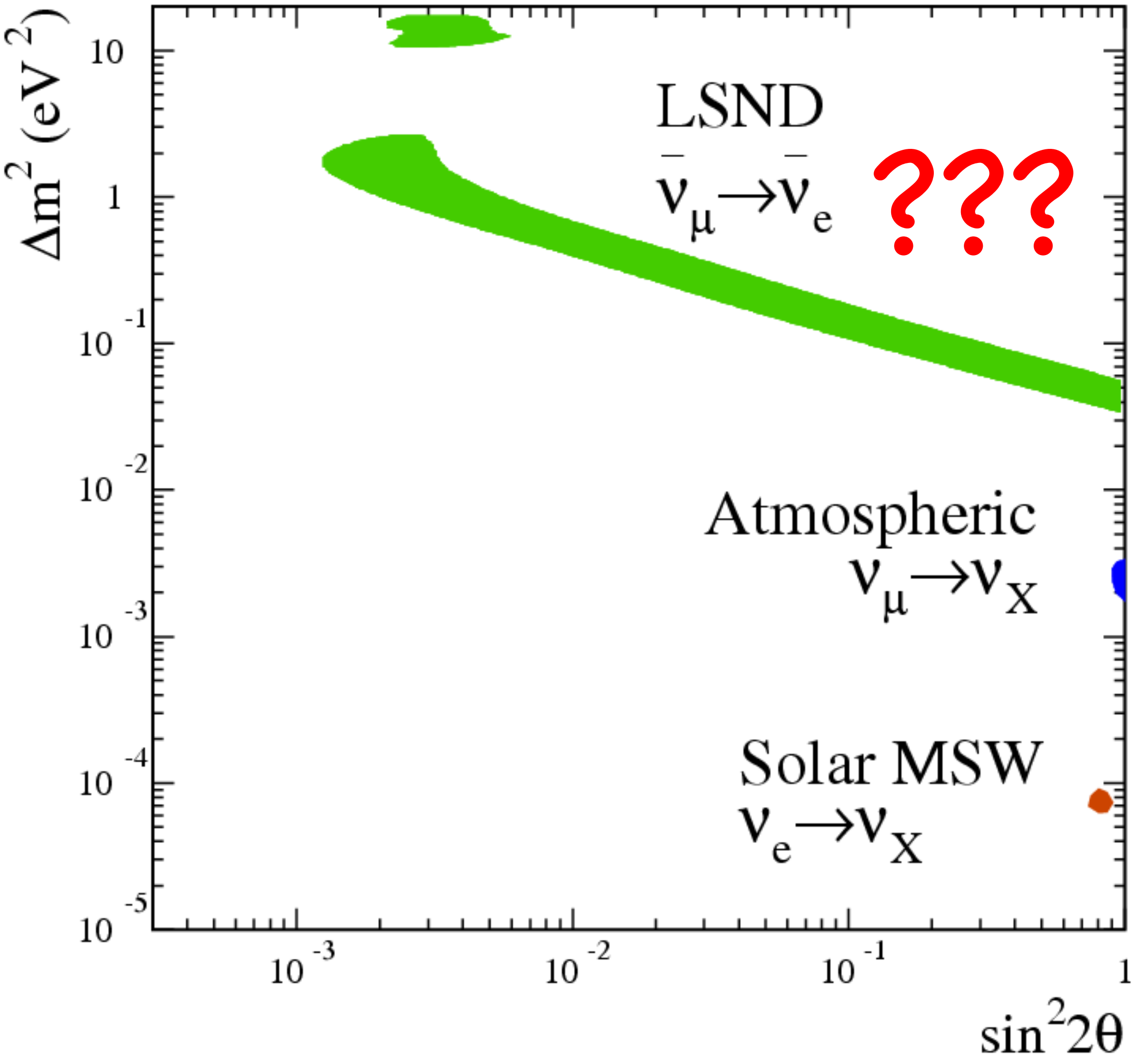
- $\Delta m^2 = m_1^2 - m_2^2 \quad (eV^2)$
- $\sin^2 2\theta$



ν_μ ***Disappearance***

ν_e ***Appearance***

A mystery that I will only touch on… High Δm^2

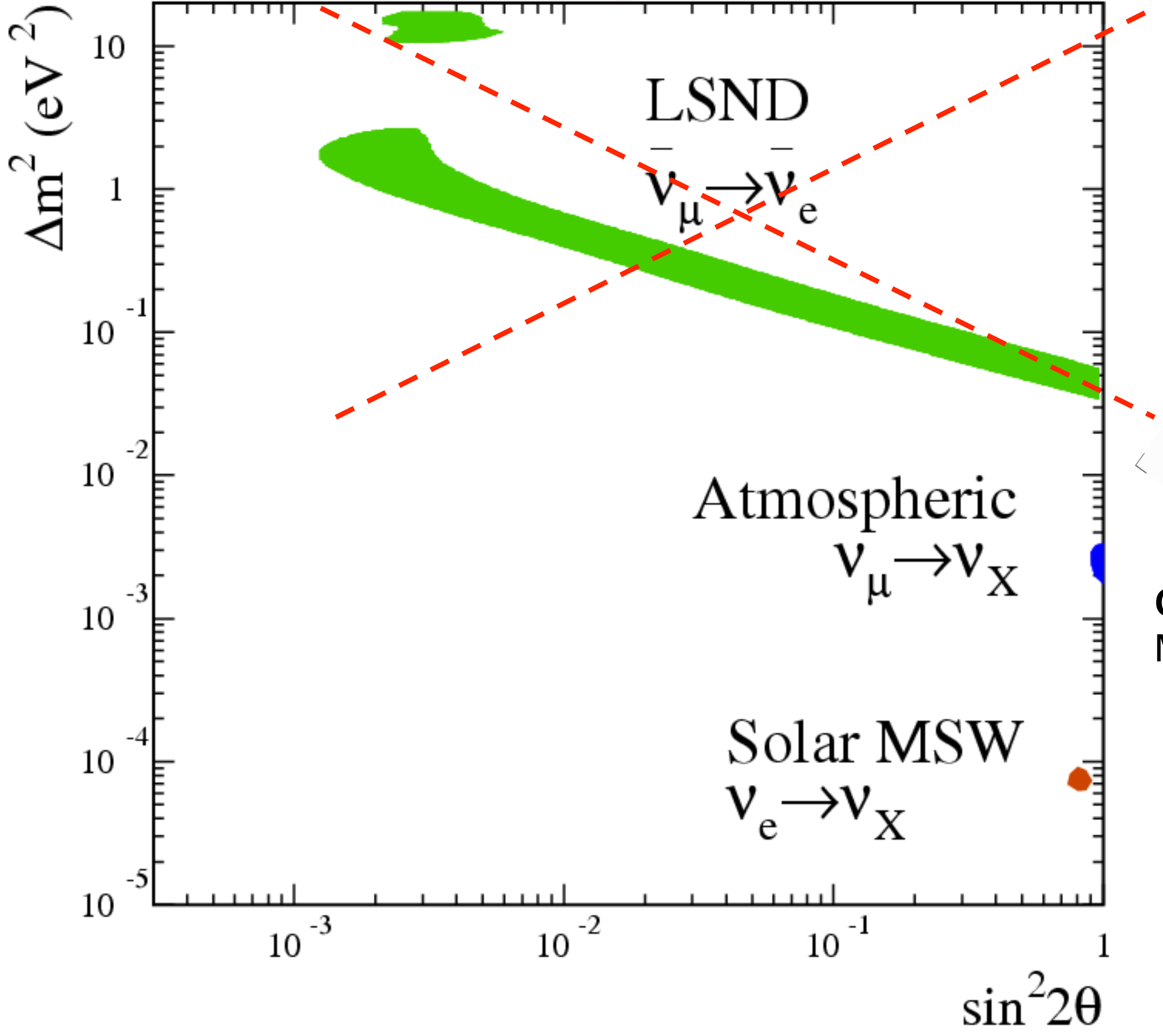


Ruled out by
MiniBooNE in ν-mode
But in $\bar{\nu}$ mode there may be
a signal??

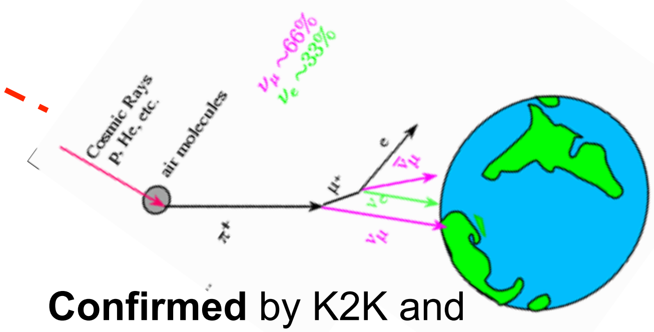
And a reanalysis of
$\bar{\nu}$ production from reactors
may also indicate a
high Δm^2 signal at $>2\sigma$!

The community is
developing the strategy
for the next round of attack!

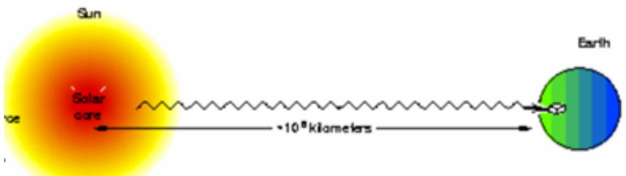
lets skip this for now…



Other oscillation signals are well-confirmed!

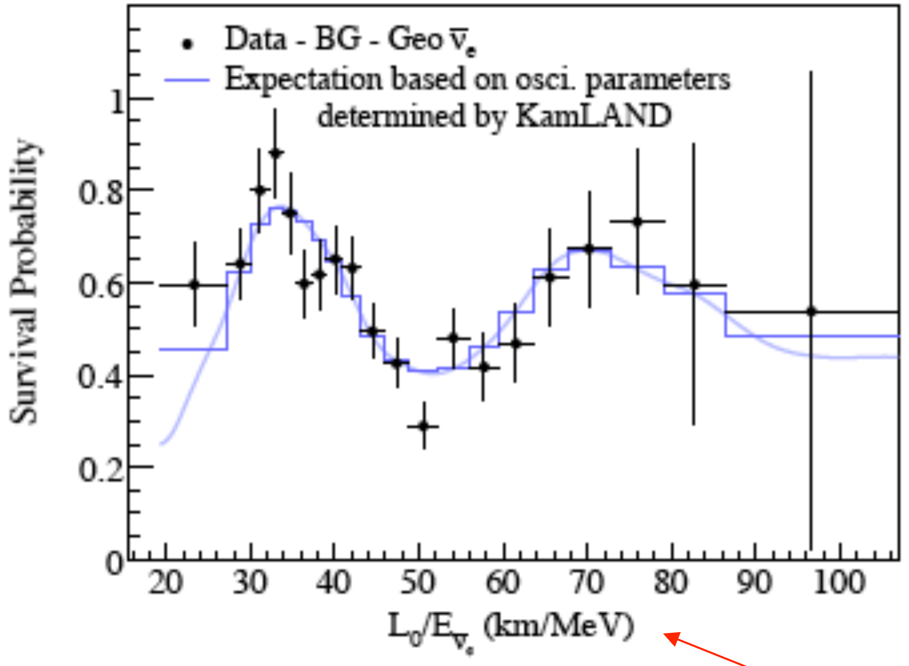


Confirmed by K2K and Minos accelerator neutrino exps



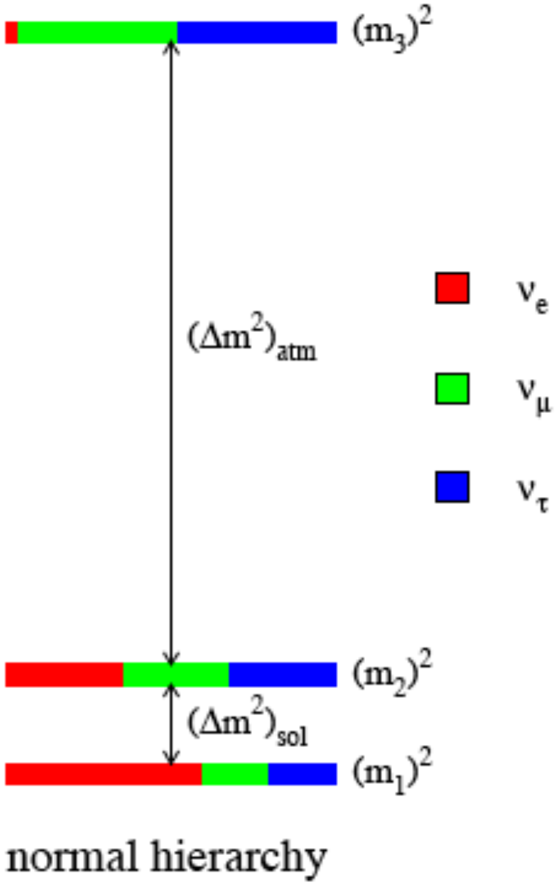
Confirmed by SNO and by Kamland reactor neutrino exp

The result from the Kamland reactor experiment
also shows the L/E dependence one expects from oscillations!



$$P_{Osc} = \sin^2 2\theta \, \sin^2\left(1.27\Delta m^2 L/E\right)$$

arXiv:0801.4589



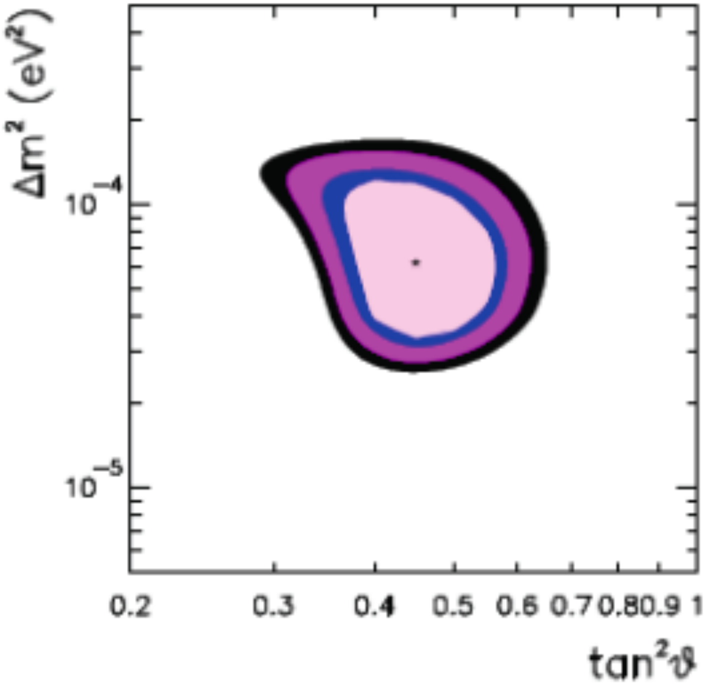
We have a fully self-consistent model
for how neutrinos behave…

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

"mixing" between neutrinos
is parameterized by
three "mixing angles"
$\theta_{12}, \theta_{13}, \theta_{23}$

This model is predictive!

Allowed region for
solar neutrino oscillation
measurements,



fit by Gonzalez-Garcia

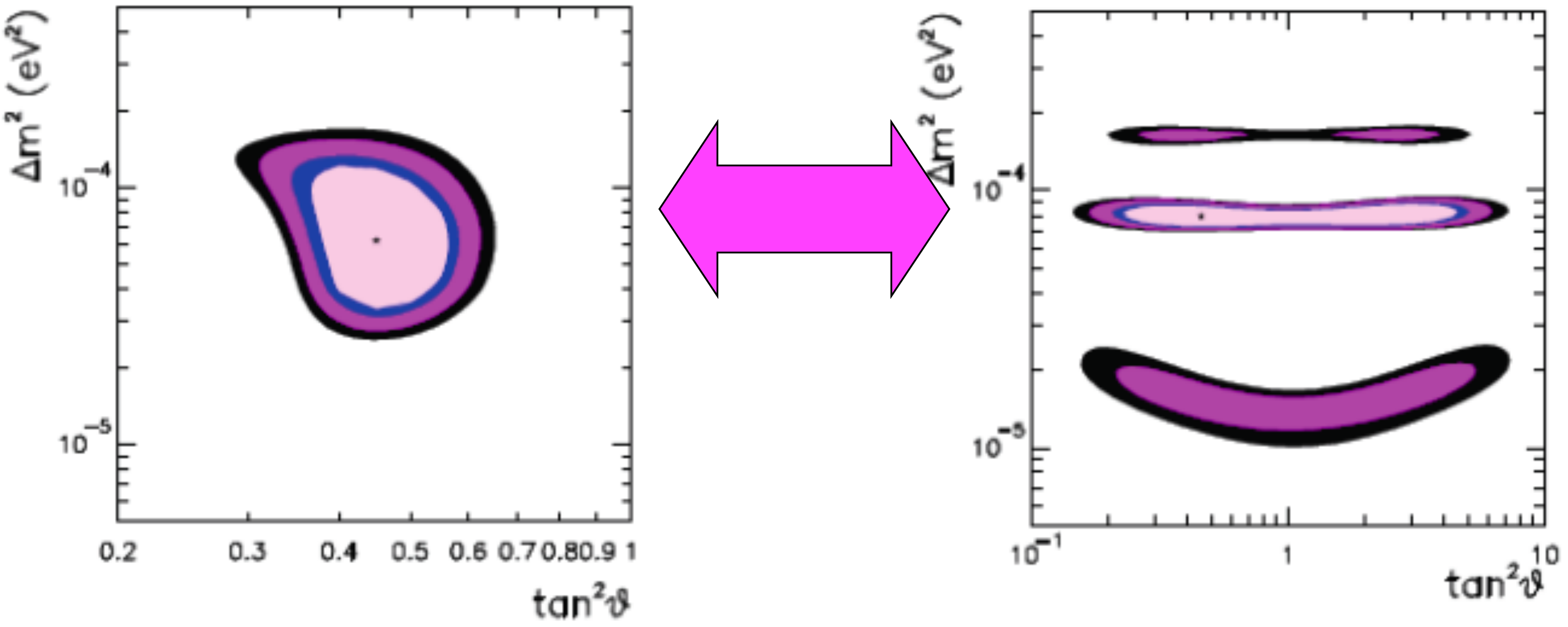
if this is due to $\nu_e \rightarrow \nu_{\text{other}}$

Then $\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$
should be observable
with the same wavelength

This model is predictive!

Allowed region for
solar neutrino oscillation
measurements,

Allowed region for the
Kamland reactor
$\bar{\nu}_e \rightarrow \bar{\nu}_{\text{other}}$ Experiment!

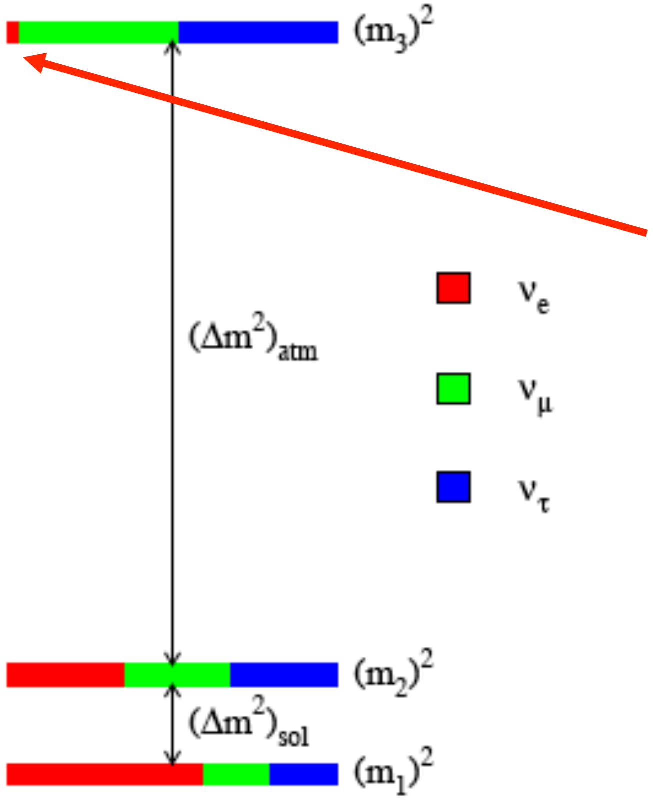


fits by Gonzalez-Garcia, an old plot, but illustrative!

Three mysteries about the ν_e

Our Model

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



normal hierarchy

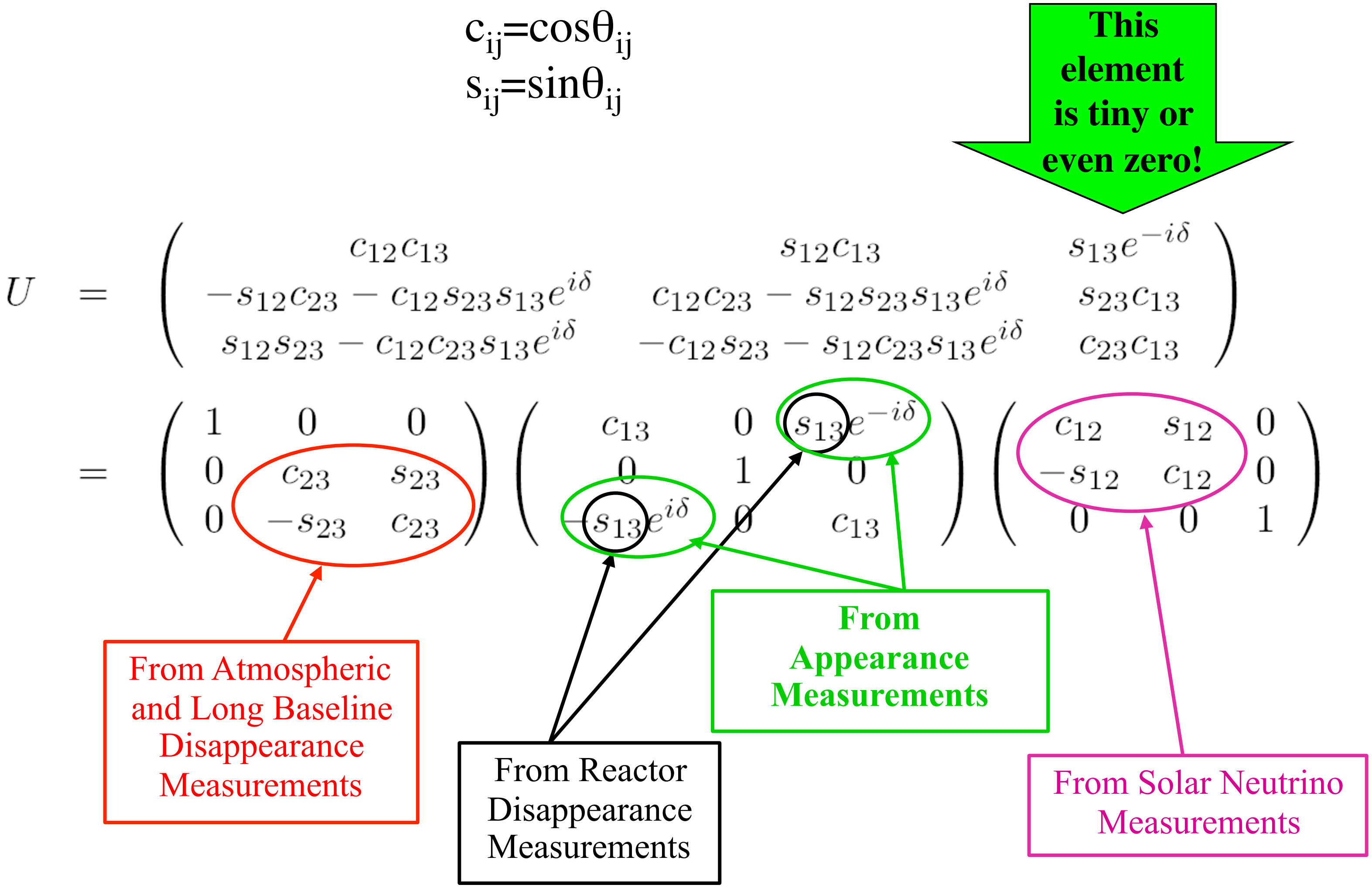
Mystery 1:

What's happening here?

Is there any ν_e content at all?

Writing that mixing matrix more explicitly…

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



This element is tiny or even zero!

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

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

From Atmospheric and Long Baseline Disappearance Measurements

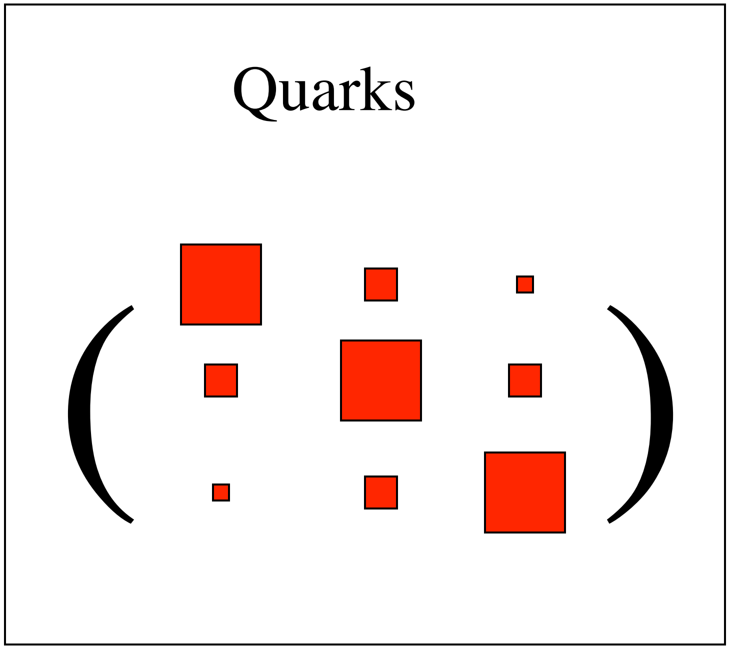
From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

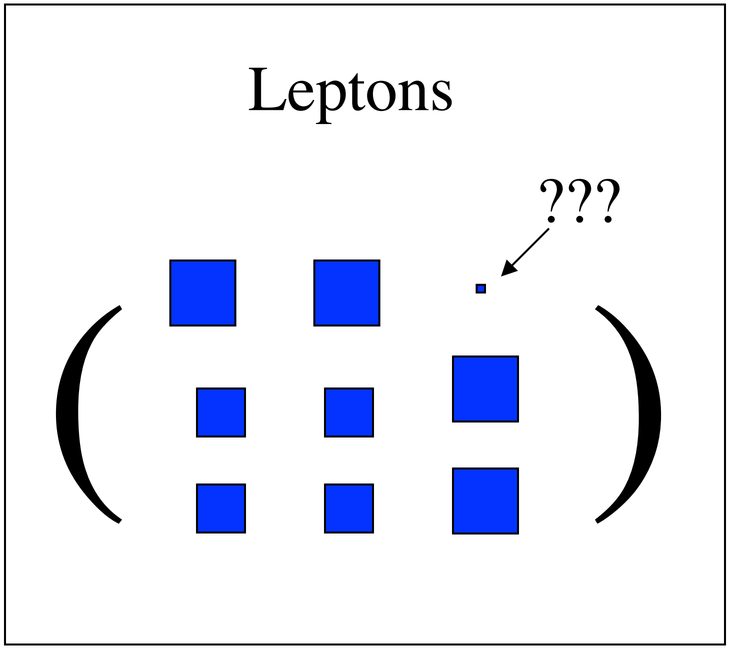
The lepton mixing matrix is NOT like the quark matrix!

(WHY???)



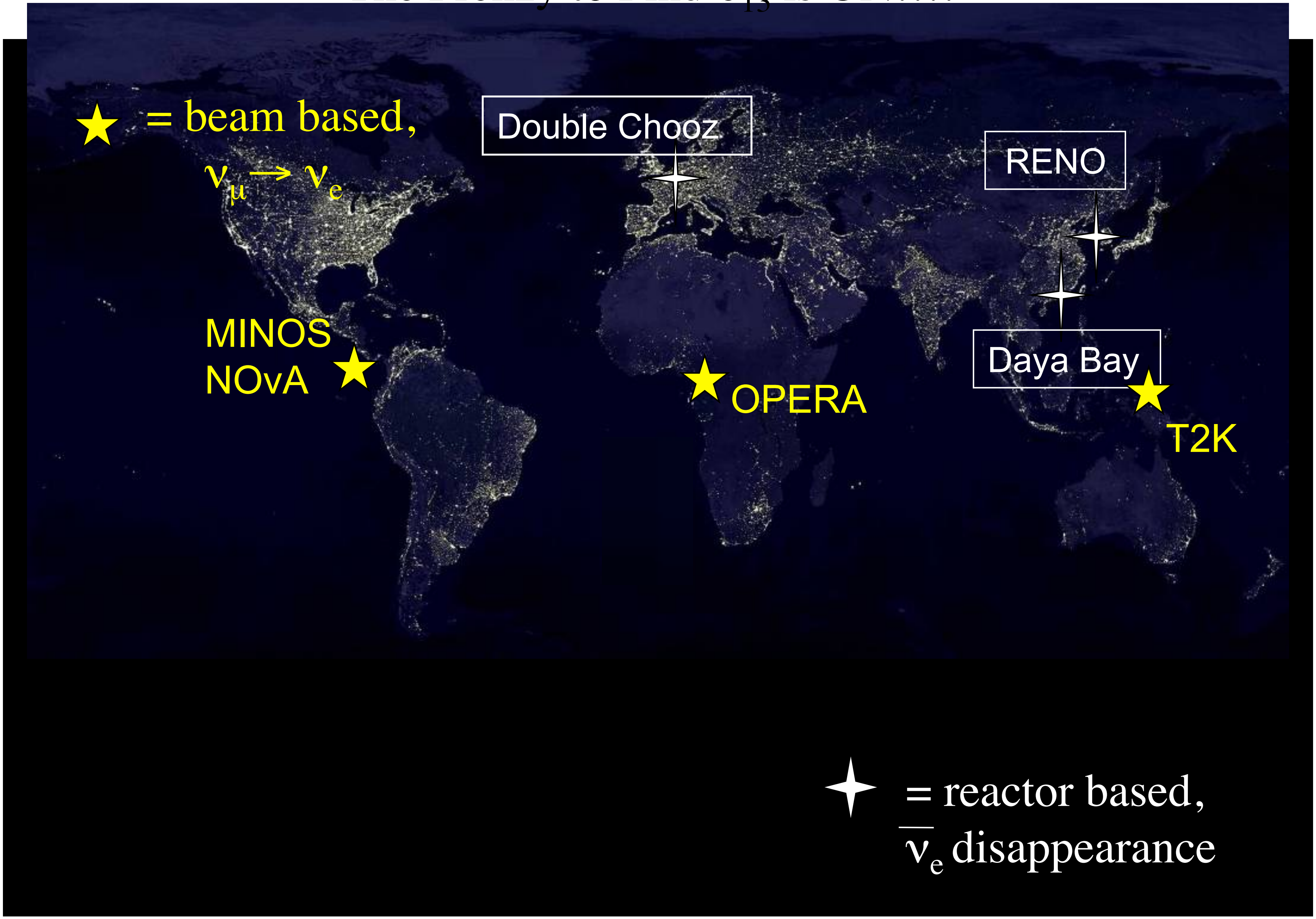
Large entries on diagonal
small off diagonal

vs.



Moderately large entries
except for one,
which might be zero!

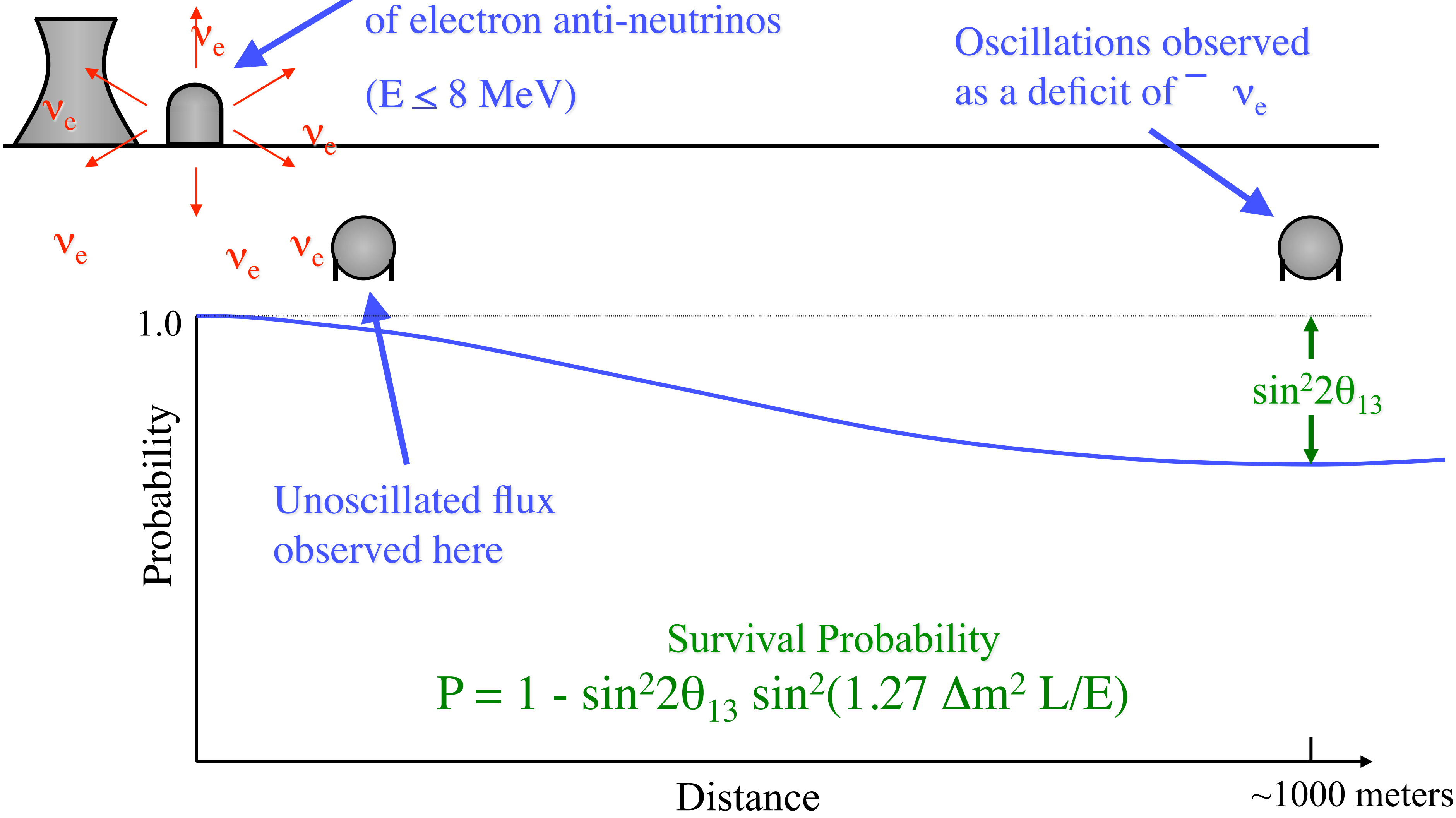
The Frenzy to Find θ_{13} is ON!!!!



★ = beam based, $\nu_\mu \rightarrow \nu_e$

✦ = reactor based, $\bar{\nu}_e$ disappearance

How θ_{13} reactor experiments are designed:



Well understood, isotropic source of electron anti-neutrinos

(E ≤ 8 MeV)

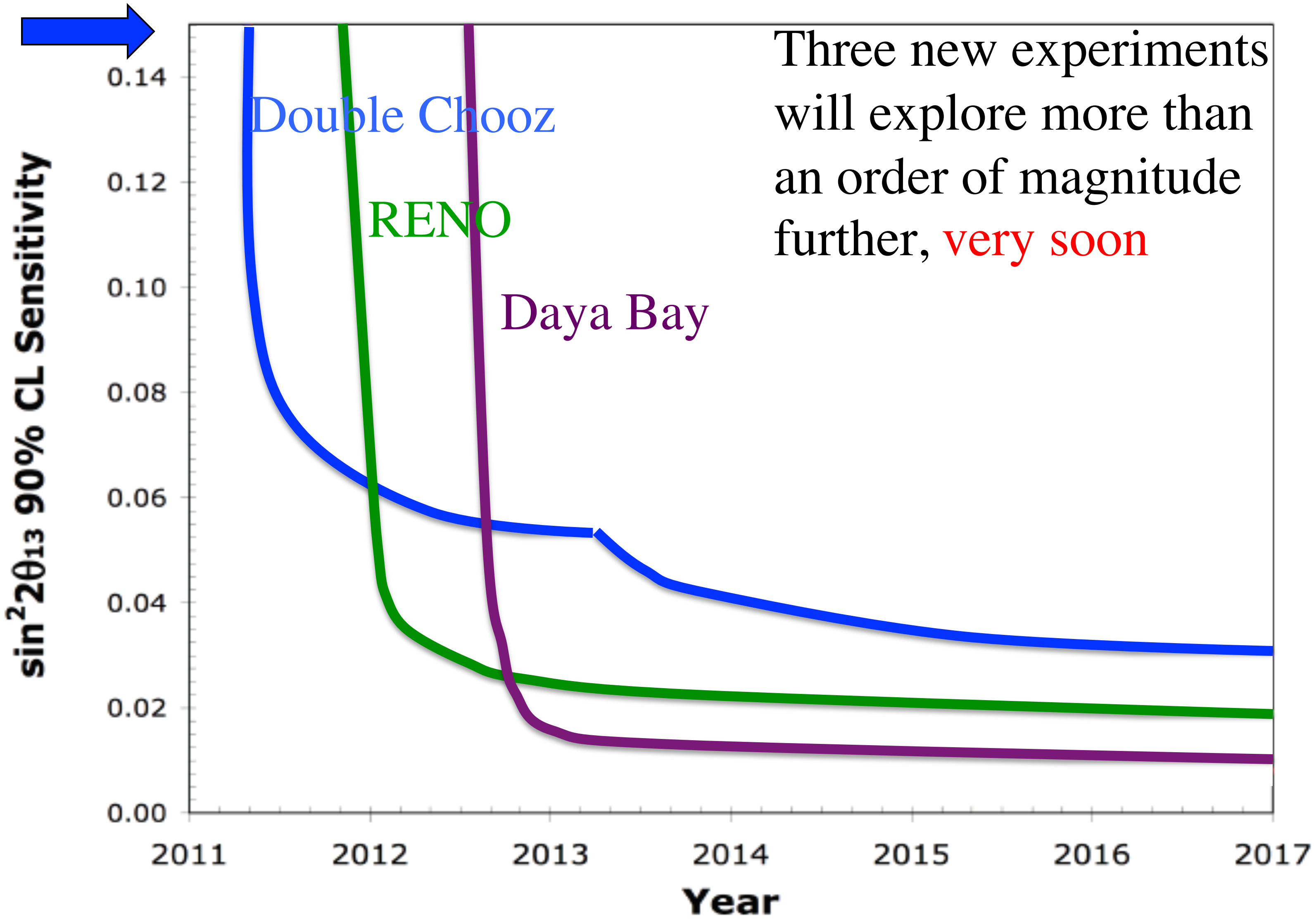
Oscillations observed as a deficit of $\bar{\nu}_e$

Unoscillated flux observed here

Survival Probability

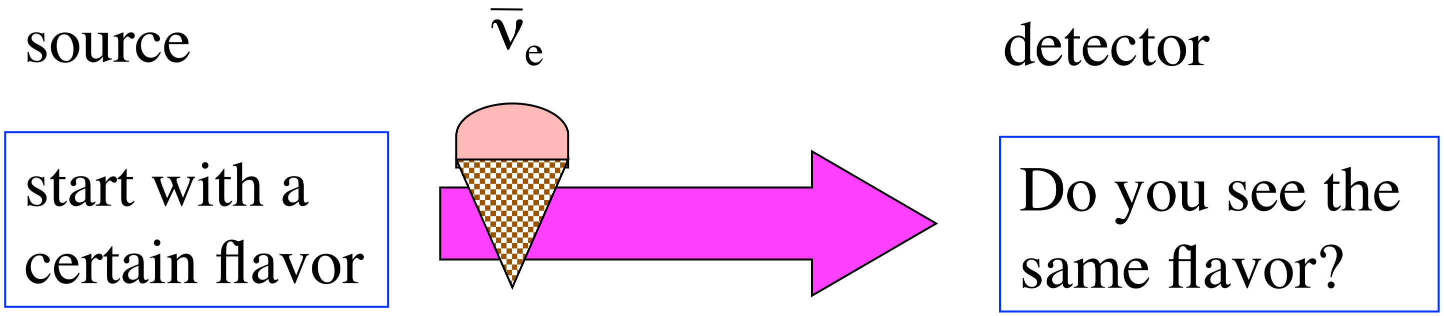
$$P = 1 - \sin^2 2\theta_{13} \sin^2(1.27\ \Delta m^2\ L/E)$$

Today, the
Limit from
Reactors is here



Three new experiments will explore more than an order of magnitude further, very soon

Reactor Experiments are disappearance experiments



source

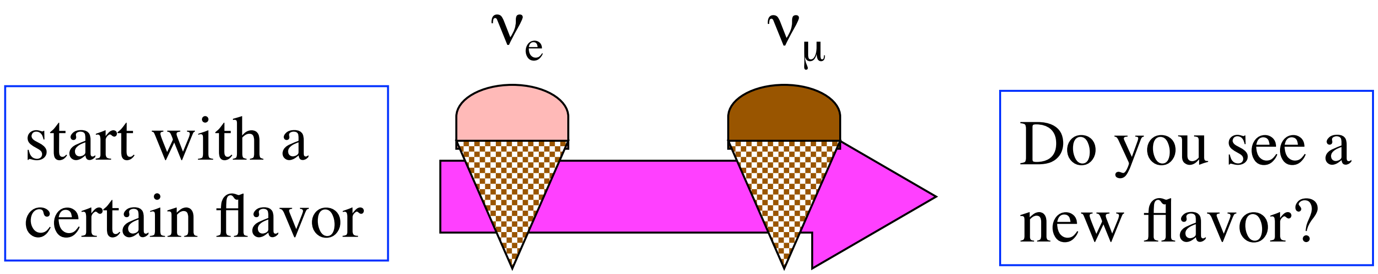
$\bar{\nu}_e$

detector

start with a certain flavor

Do you see the same flavor?

You can also search with appearance experiments



ν_e

ν_μ

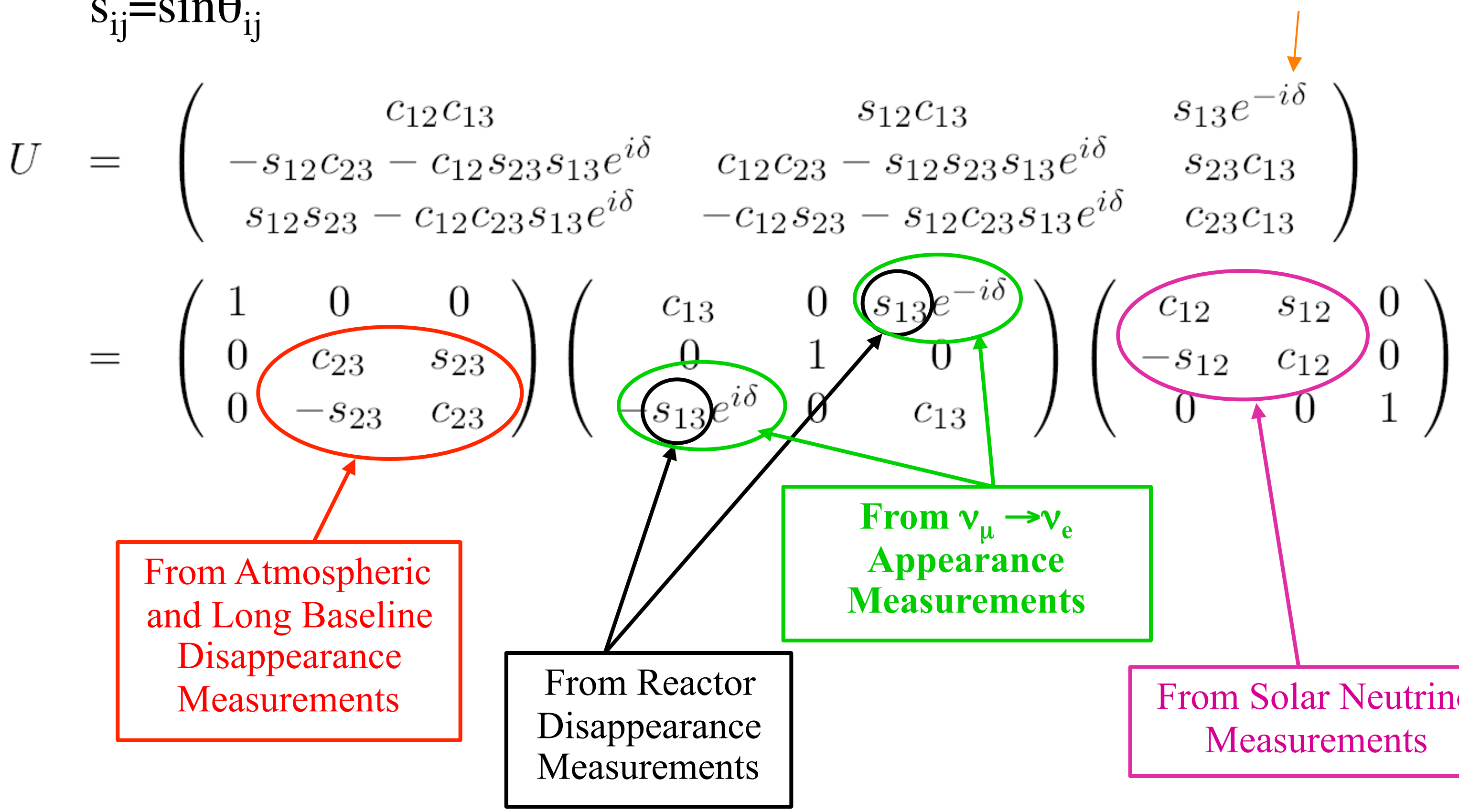
start with a certain flavor

Do you see a new flavor?

But appearance is more complicated because of mysteries 2 and 3!

Mystery 2: Is there CP Violation in the Mixing Matrix Too?

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



The CP Violation Parameter

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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From $\nu_\mu \rightarrow \nu_e$ Appearance Measurements

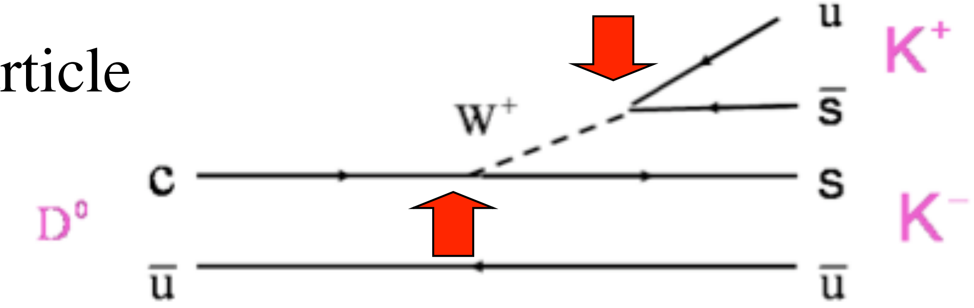
From Solar Neutrino Measurements

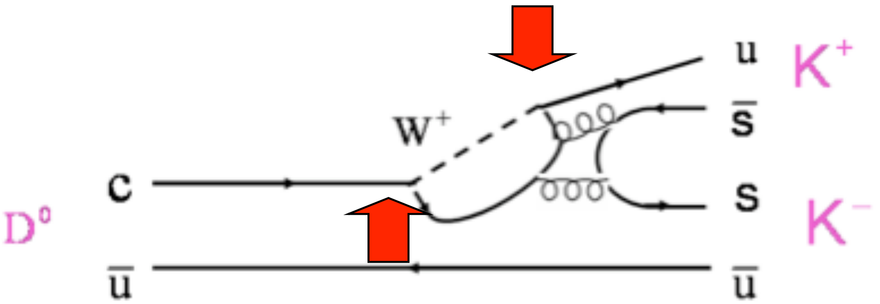
If so, is it like the quark sector? or not? *(Why???)*

In the quark sector, CP violation can show up as a difference in rates of decay for particles vs. antiparticles.

The effect shows up
when you have 2 paths to the same outcome…

Particle

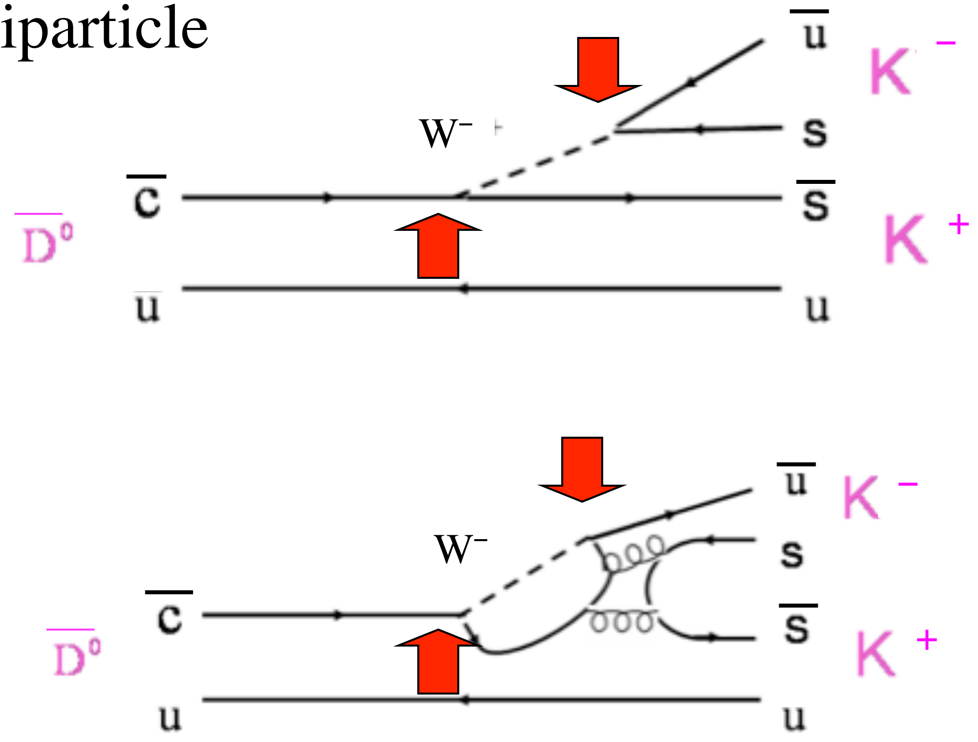




You will get an
interference term
in the decay probability…

Now consider the $\overline{D}^0$

antiparticle



There are still 2 paths
to the outcome.

Compared to the D^0
the interference
term changes sign!

e.g. D^0 and $\overline{D}^0$ decays can have different decay rates
if δ is nonzero!

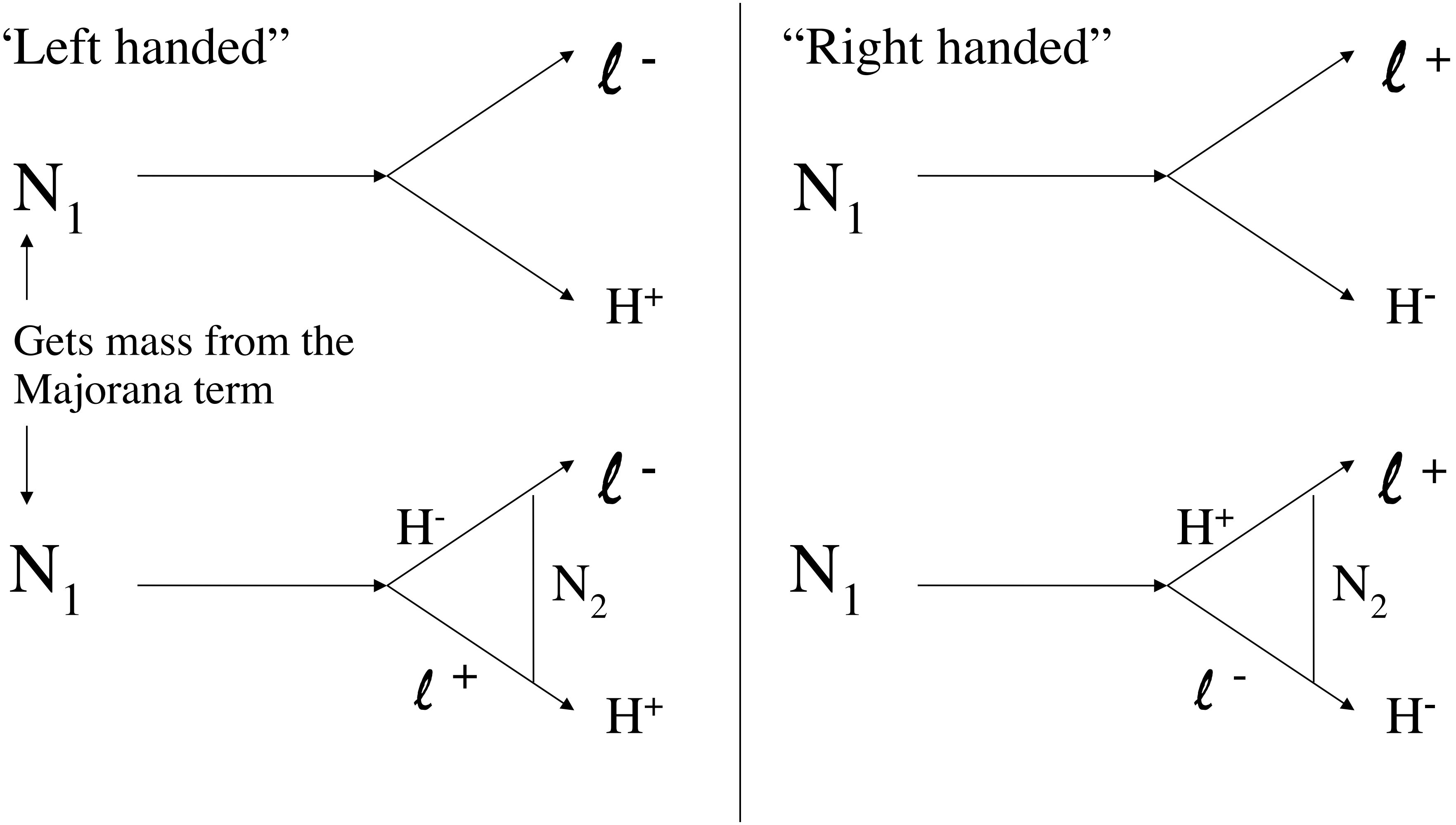
Nonzero δ has been seen in the quark mixing matrix,
but it is a relatively small effect

But what about the lepton sector???
In a model where…

1. Neutrinos are Majorana particles
2. With GUT scale partners
3. And there is CP violation…

Then…
CP violation in the neutrino sector may explain the matter-antimatter asymmetry in the universe!

Before the electroweak phase transition…



"Left handed"

"Right handed"

Gets mass from the Majorana term

The interference terms will have opposite sign!

Are neutrinos the reason we exist?

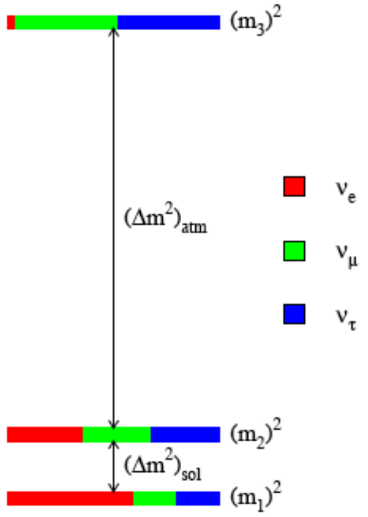
It’s a big question and
it turns out to be
very hard to answer!

A first step would be observation
of CP violation in the light neutrinos

How would CP violation manifest itself?

In oscillation of muon-flavor to electron-flavor at the atmospheric Δm^2

… it's all about the ν_e events again!



Recall the
2ν osc formula: $P_{Osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$

For 3 ν oscillations, in a vacuum, with CP Violation…

$$\begin{aligned} P = & \quad (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31}) \\ & \mp \underline{\sin\delta}\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21}) \\ & + \underline{\cos\delta}\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\ & \quad + (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}). \end{aligned}$$

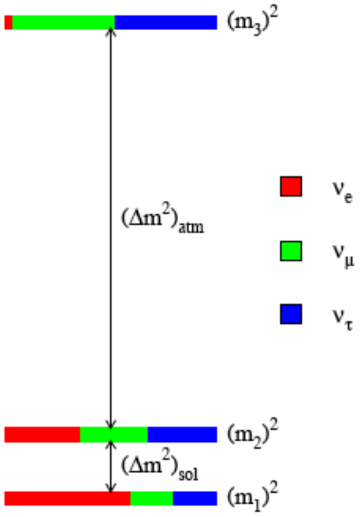
We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

Seeing CP violation is all about interference.



in a vacuum…

$$
\begin{aligned}
P = \quad & (\sin^2\theta_{23}\sin^2 2\theta_{13})\,(\sin^2\Delta_{31}) \\
& \mp \underline{\sin\delta}\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \underline{\cos\delta}\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& \qquad + (\cos^2\theta_{23}\sin^2 2\theta_{12})\,(\sin^2\Delta_{21}).
\end{aligned}
$$

We want to see if δ is nonzero

The δ-dependent terms arise from interference between the $\Delta m_{13}{}^2$ and $\Delta m_{12}{}^2$ oscillations

Our equation flips sign between

$\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

in a vacuum…

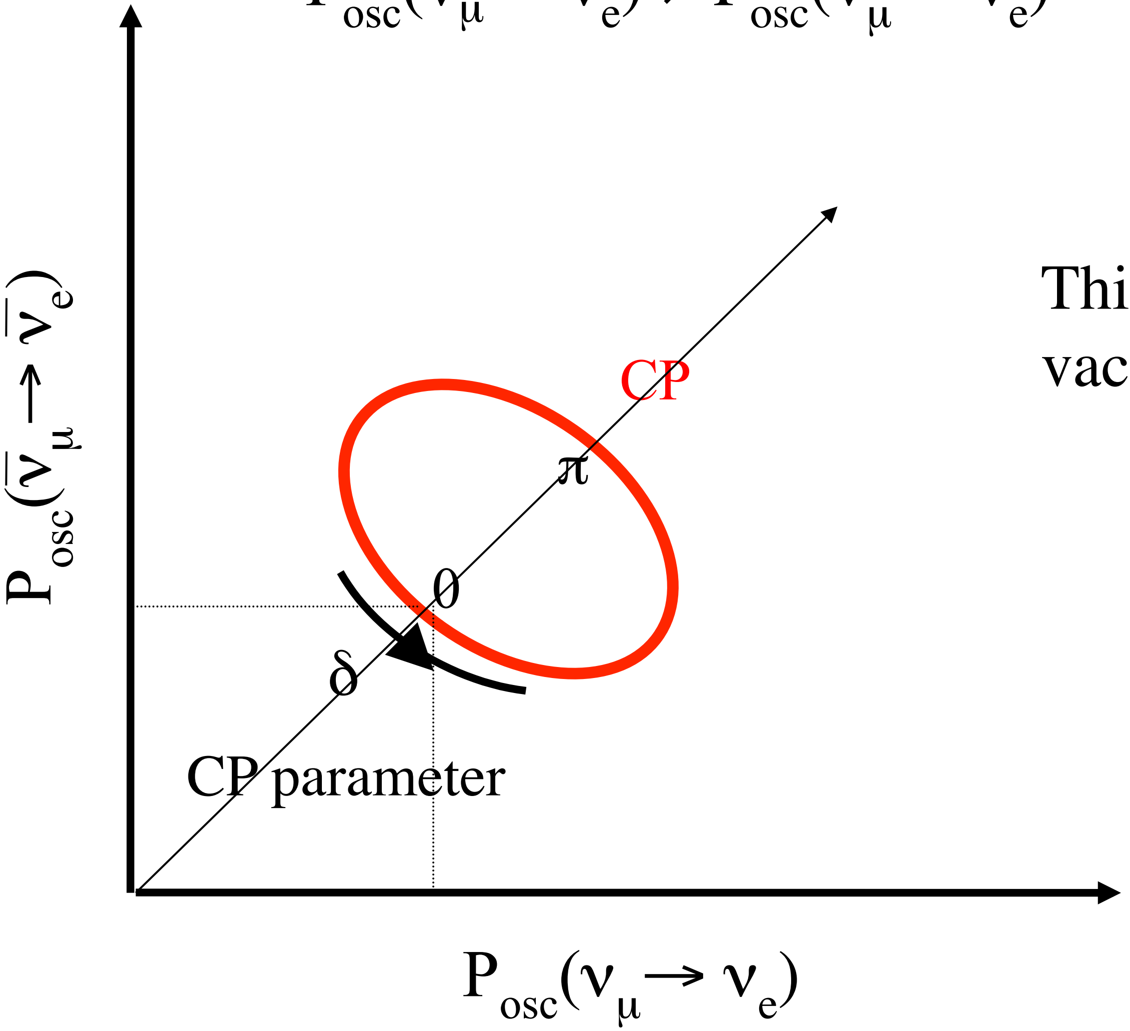
$$\begin{aligned} P = \; & (\sin^2\theta_{23}\sin^2 2\theta_{13})\,(\sin^2\Delta_{31}) \\ & \mp \underline{\sin\delta}\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin^2\Delta_{31}\sin\Delta_{21}) \\ & + \underline{\cos\delta}\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\ & + (\cos^2\theta_{23}\sin^2 2\theta_{12})\,(\sin^2\Delta_{21}). \end{aligned}$$

what we want to measure

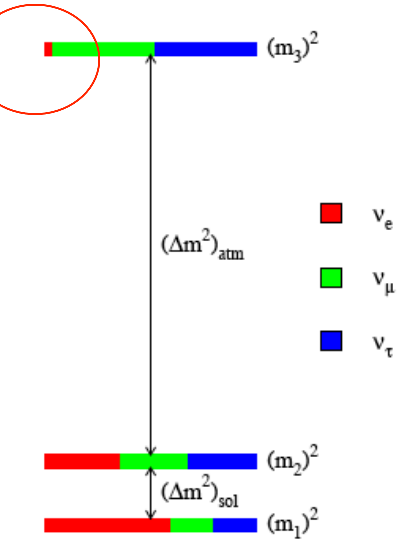
The matter and antimatter oscillation probabilities will be different!

The classic idea for how to see CP violation:

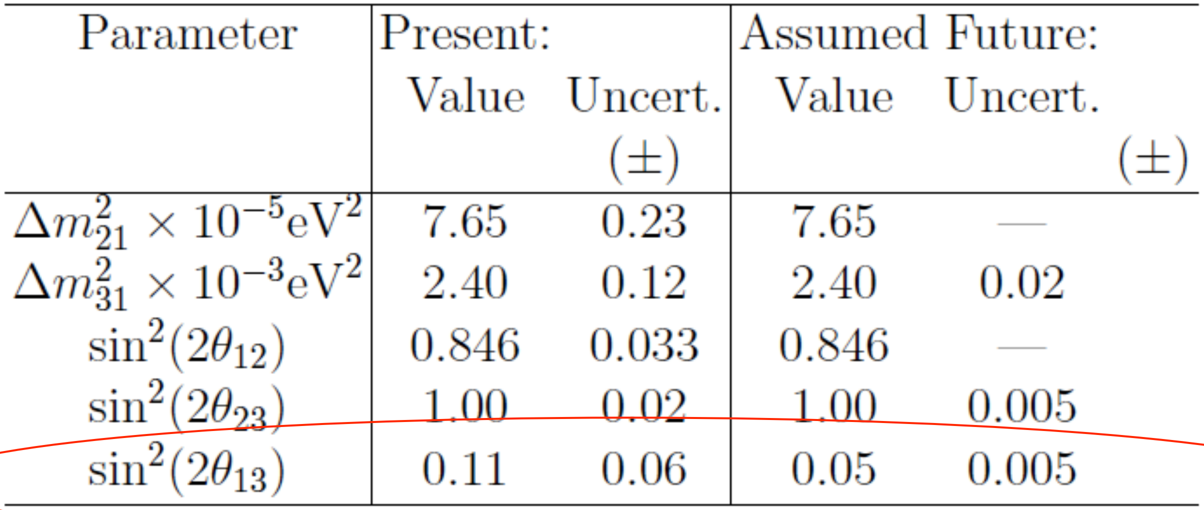
$$P_{osc}(\nu_\mu \rightarrow \nu_e) \neq P_{osc}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



This is in a
vacuum (or air).



Most parameters are well known…

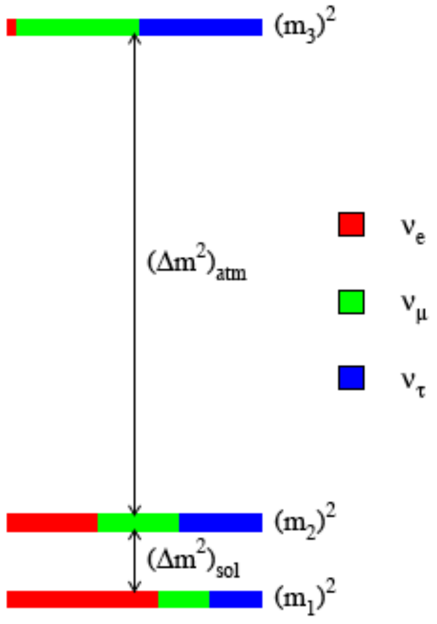


Parameter	Present: Value	Uncert. (±)	Assumed Future: Value	Uncert. (±)
$\Delta m^2_{21} \times 10^{-5}\mathrm{eV}^2$	7.65	0.23	7.65	—
$\Delta m^2_{31} \times 10^{-3}\mathrm{eV}^2$	2.40	0.12	2.40	0.02
$\sin^2(2\theta_{12})$	0.846	0.033	0.846	—
$\sin^2(2\theta_{23})$	1.00	0.02	1.00	0.005
$\sin^2(2\theta_{13})$	0.11	0.06	0.05	0.005

Except for that pesky θ_{13}!

We will end up having to quote our sensitivity as allowed regions in both θ_{13} and δ

This design requires a long baseline!



normal hierarchy

The Probability for Oscillations...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

P is maximized when $\Delta m^2(L/E) \sim 1$

The atmospheric $\Delta m^2 \sim 0.003\ \mathrm{eV}^2$

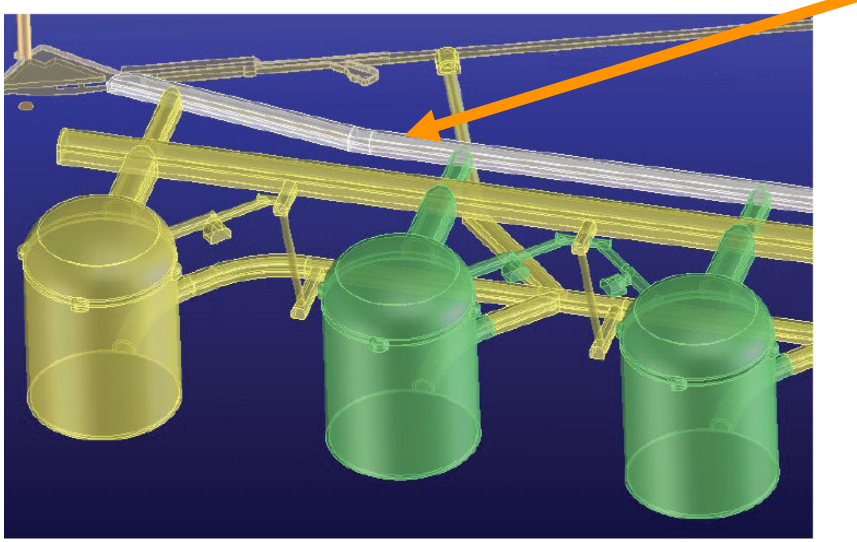
If E ~ 3 GeV

Then L = 1000 km !!!

E.g., LBNE -- starting in 2021

Beam from Fermilab

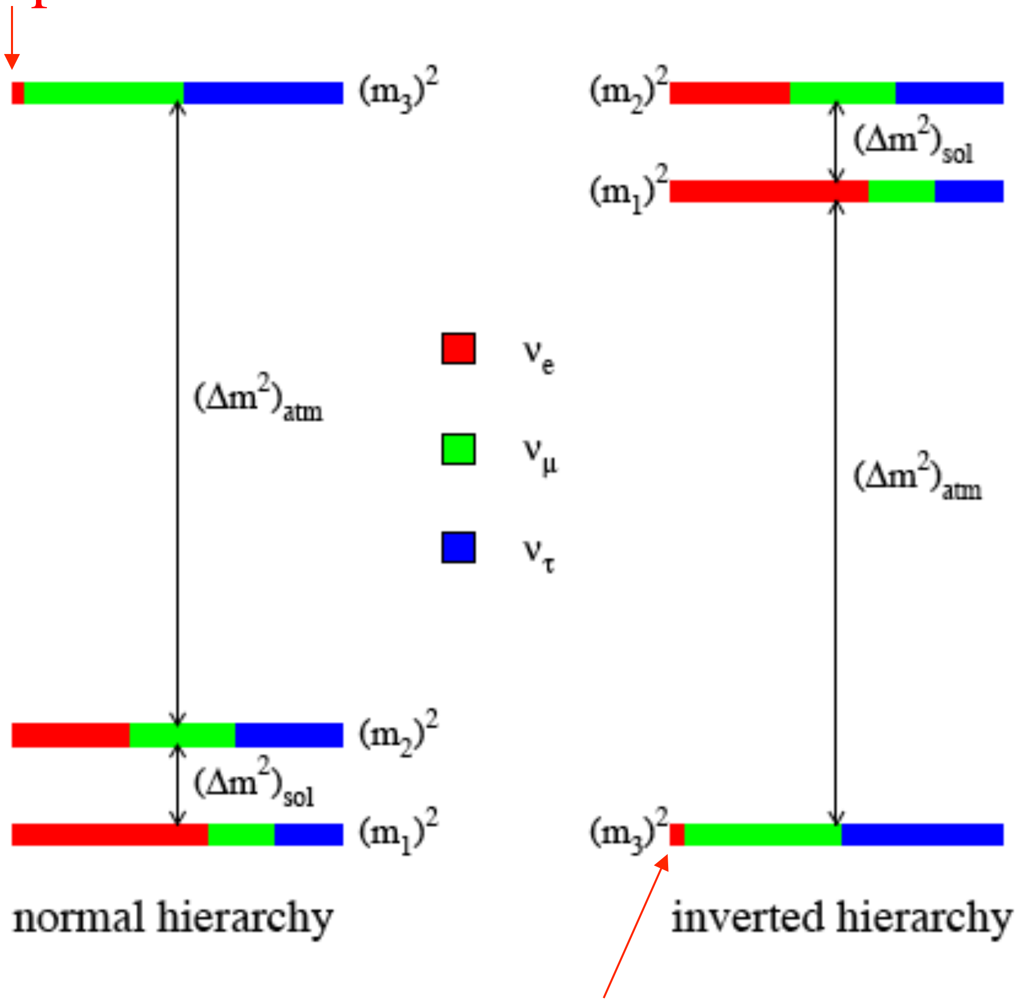
Shoots to detectors in South Dakota
1300 km



And there is **lots and lots**
of matter along a 1300 km path!

also true for LAGUNA and HyperK designs

Mystery 3:
Is the small ν_e content up here?



or down here?

i.e. What is the "mass hierarchy"?

Is it "opposite" to the quark sector?
(WHY???)

This affects the rates of

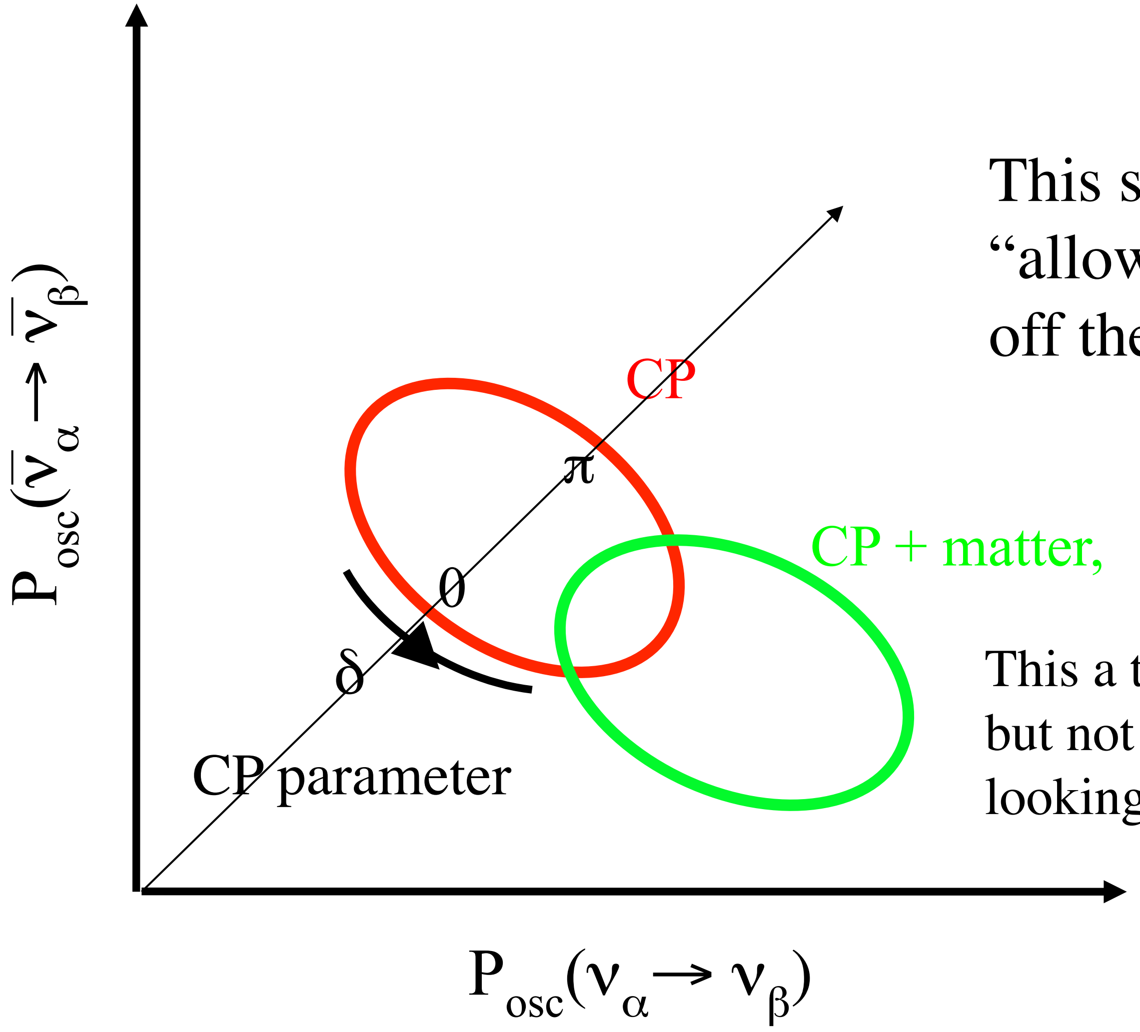
$$\nu_\mu \rightarrow \nu_e$$

Versus

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

The ground is made of matter (electrons)
not antimatter (positrons)

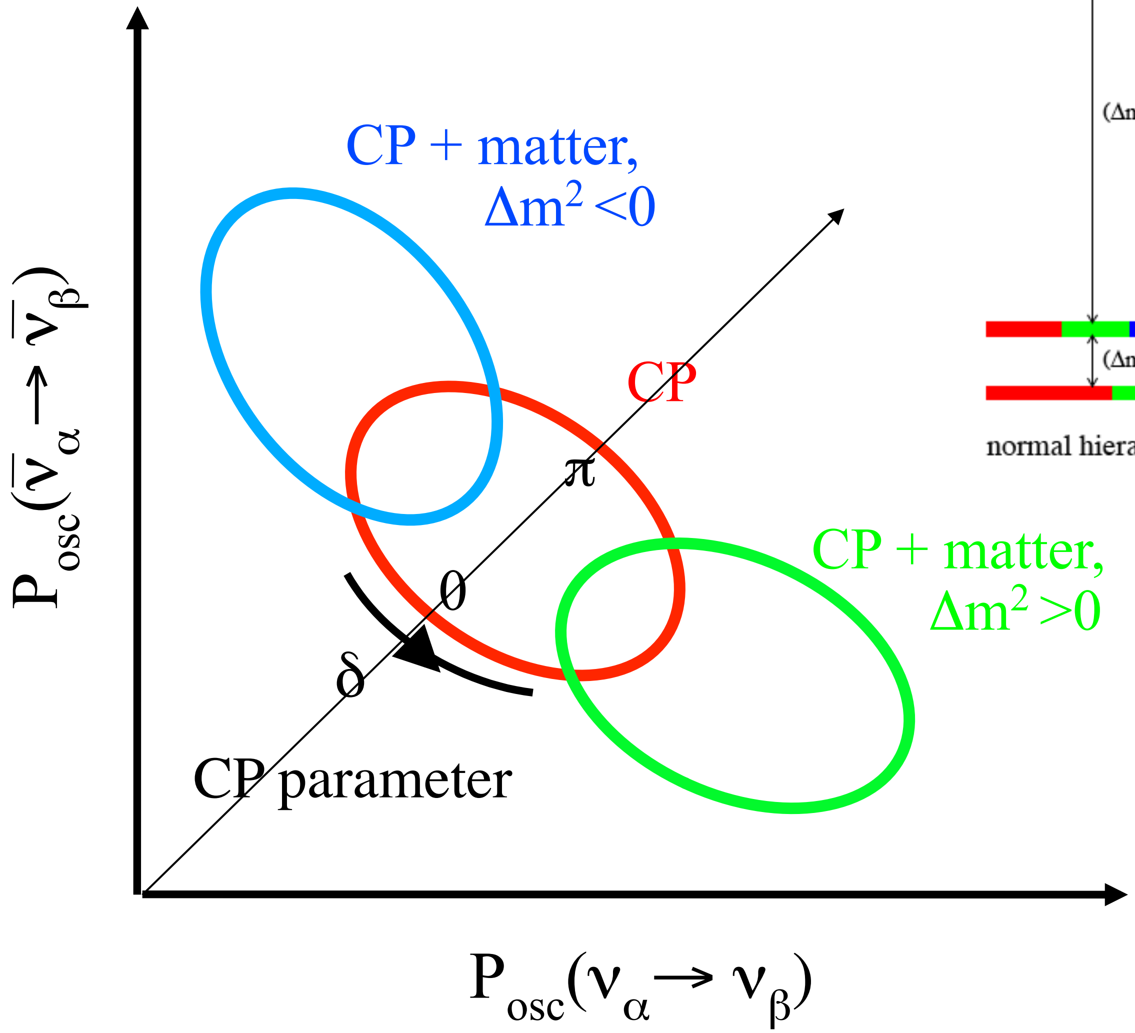
Forward scattering affects neutrinos differently than antineutrinos.

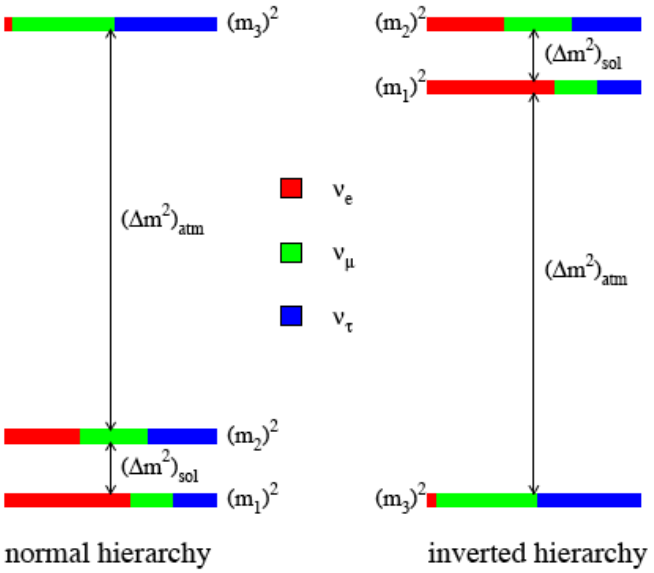


This slides the
“allowed ring”
off the diagonal

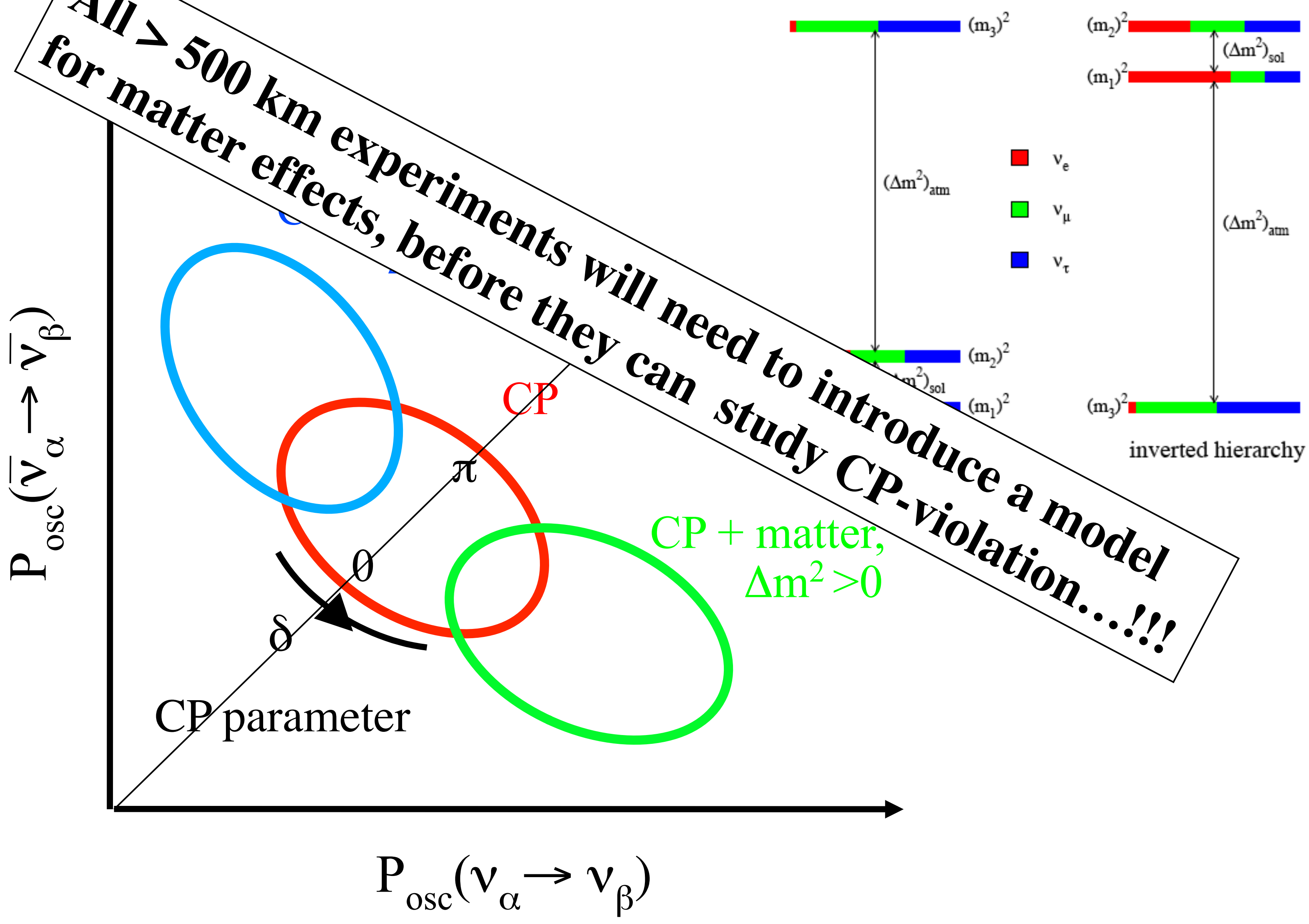
This a type of CP violation,
but not what we are
looking for!

We actually don’t know which direction…

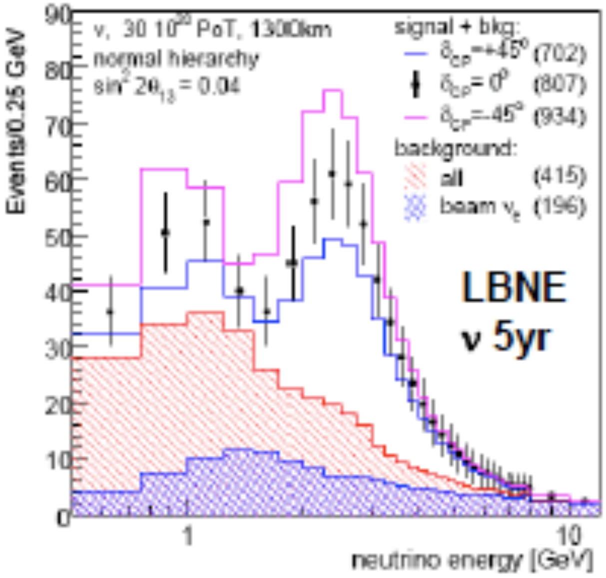


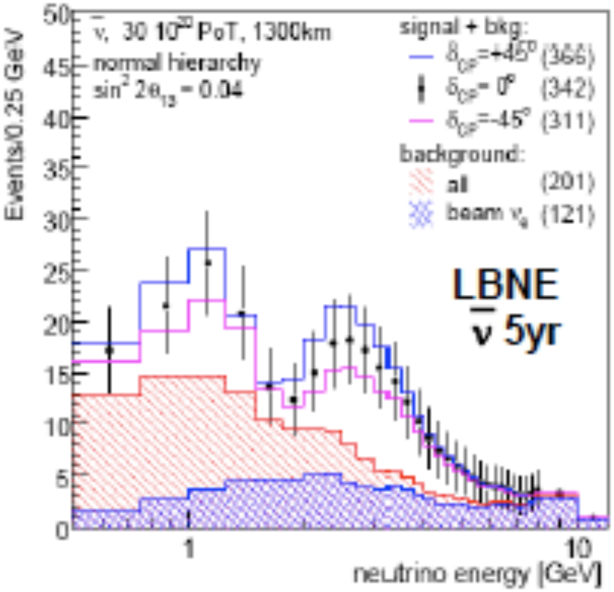


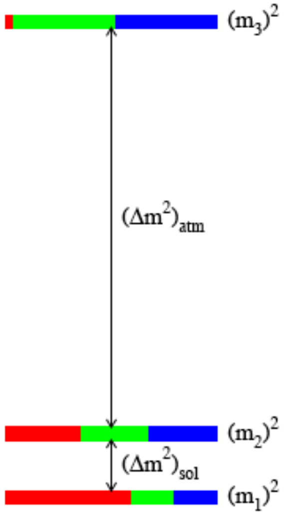
We actually don't know which direction…



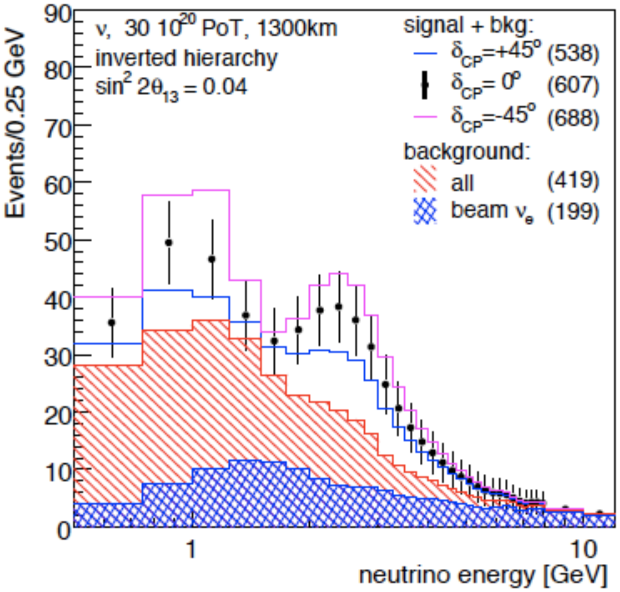
All > 500 km experiments will need to introduce a model for matter effects, before they can study CP-violation…!!!

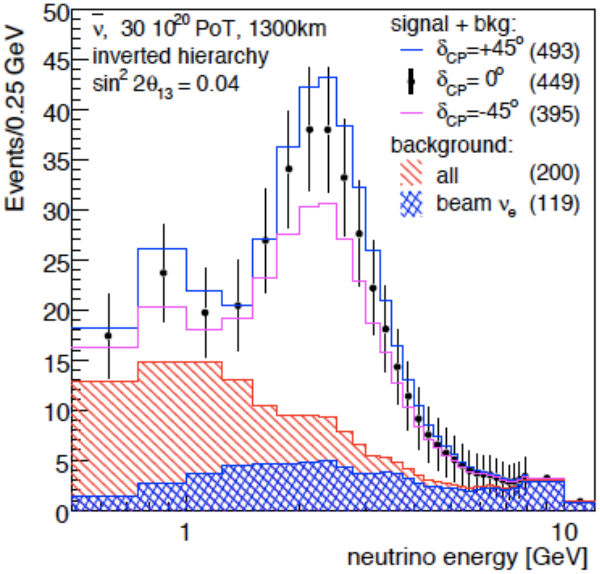


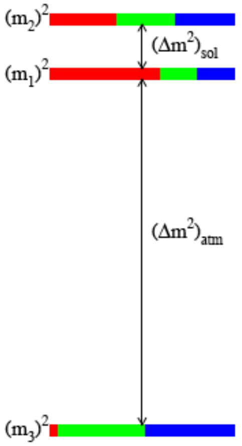




normal hierarchy



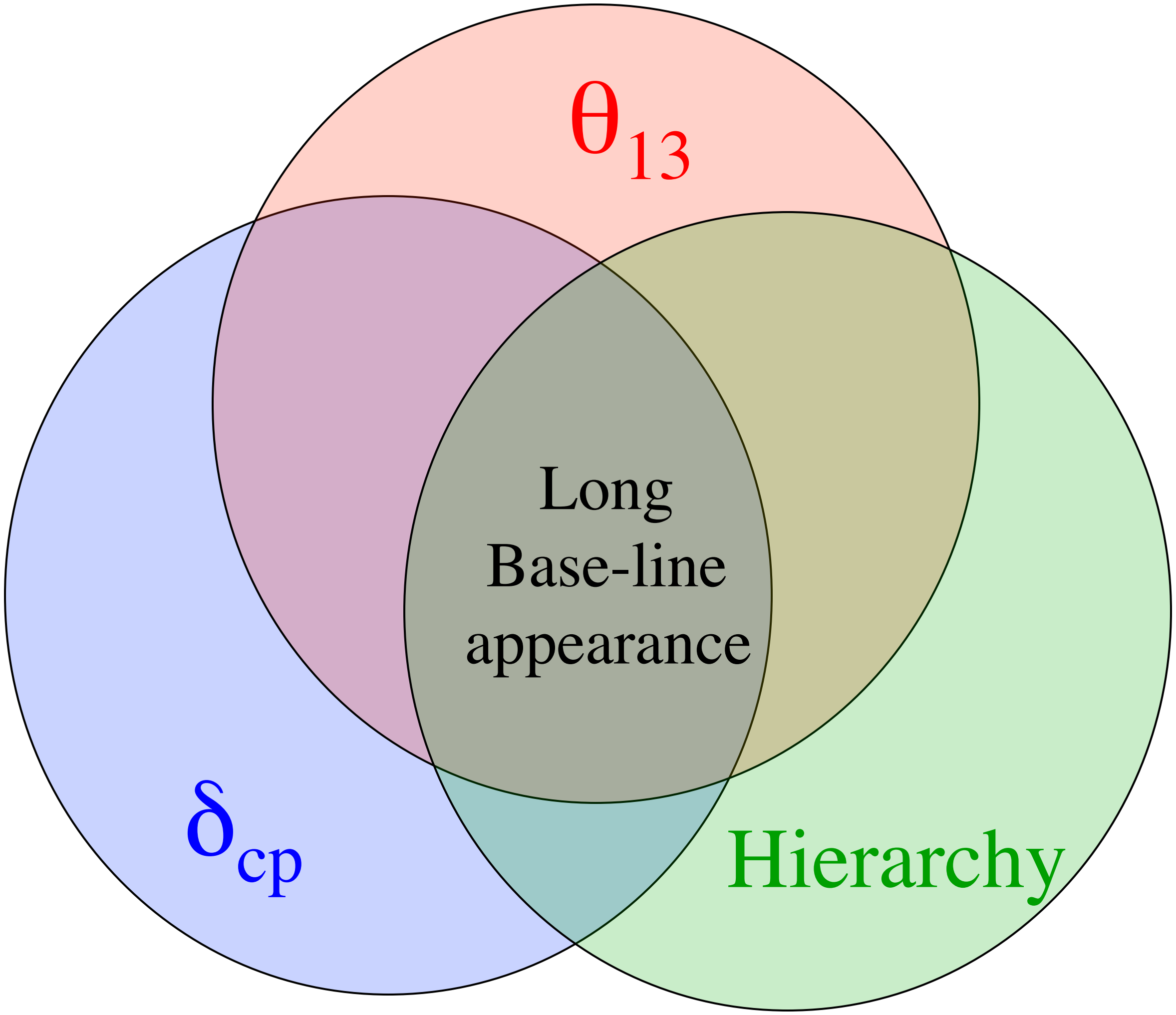




inverted hierarchy

So now matters become very convoluted.

If I ask: How well can I unravel these mysteries?



But don’t forget the reactors!

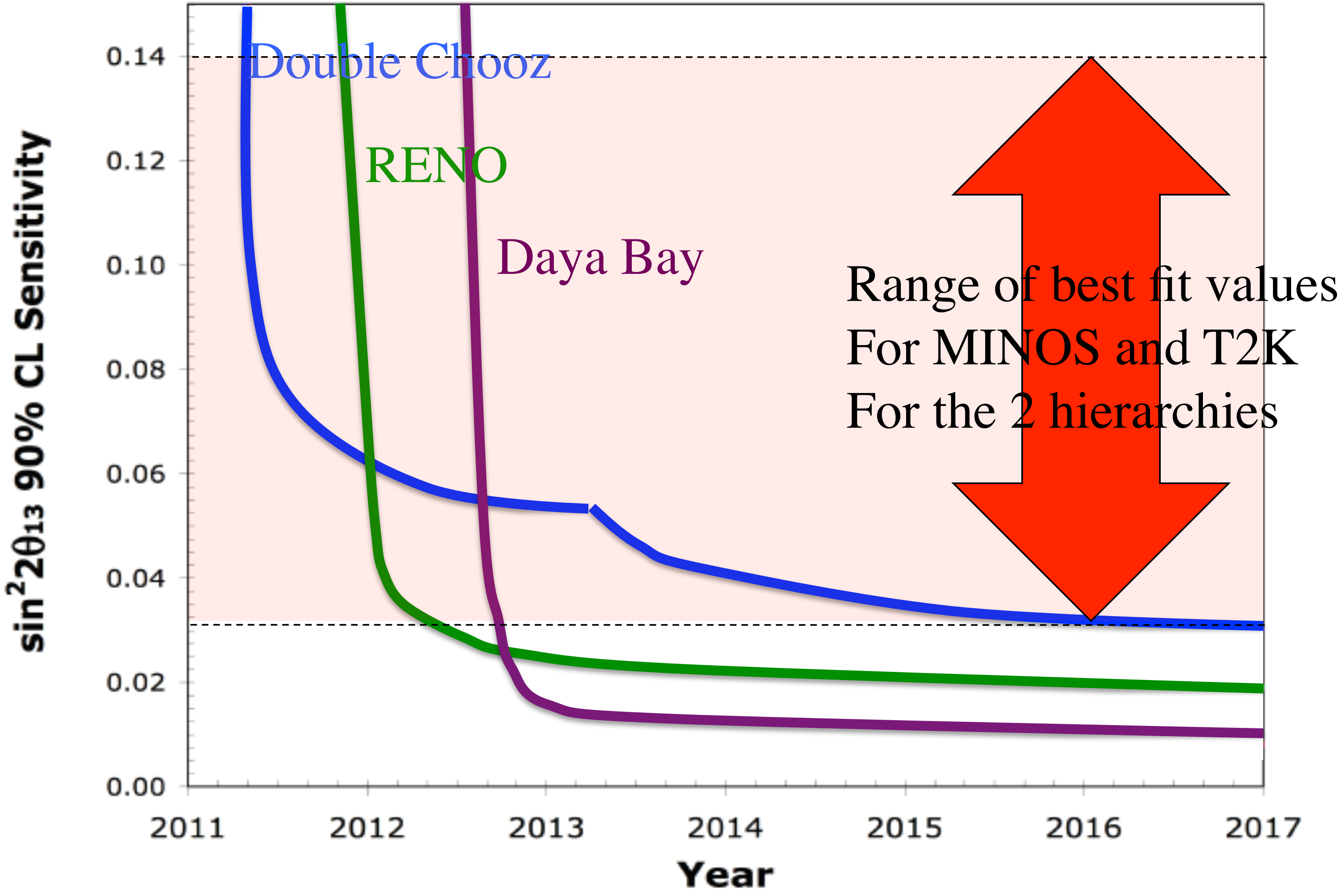
They can work on one and only one mystery

θ_{13}

$$P = 1 - \sin^2 2\theta_{13} \sin^2(1.27\ \Delta m^2\ L/E)$$

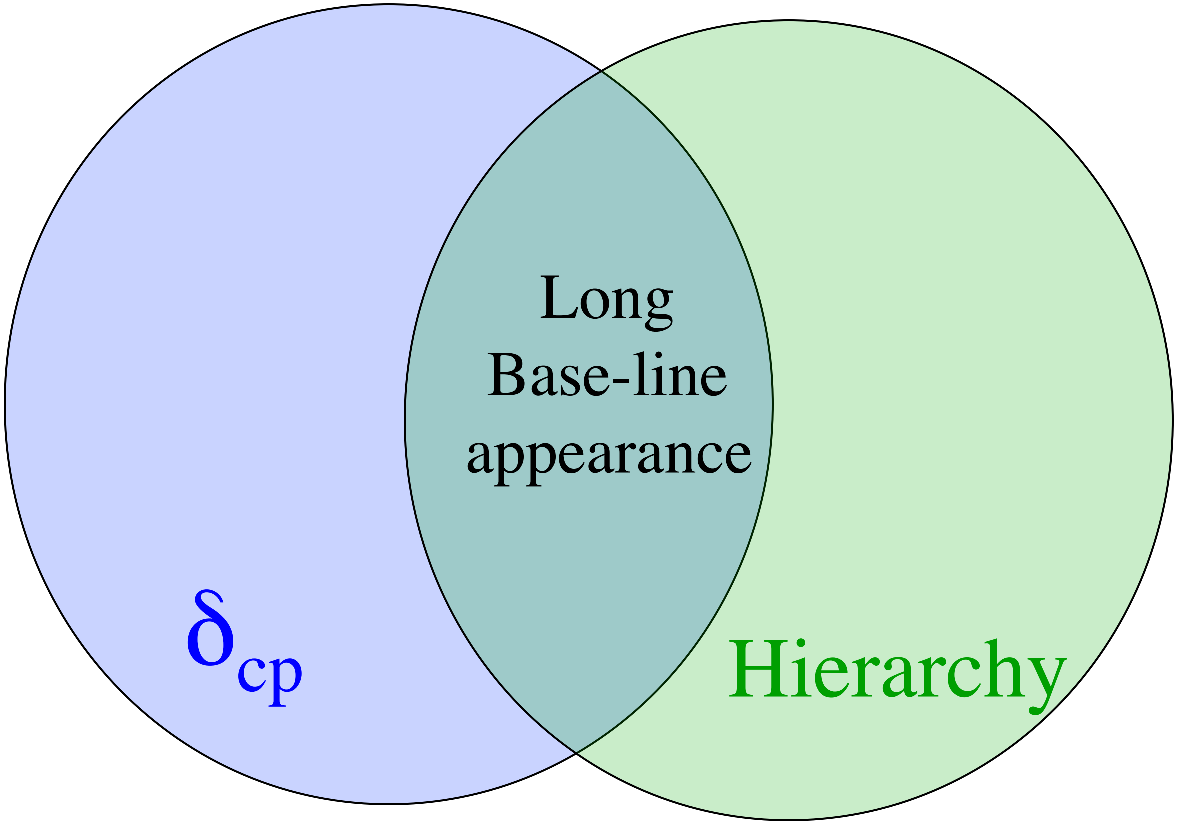
Reactor
Disappearance
Searches

And it seems that the reactors are looking at just the right place!
New from appearance experiments this summer!



Range of best fit values
For MINOS and T2K
For the 2 hierarchies

This still leaves us with:

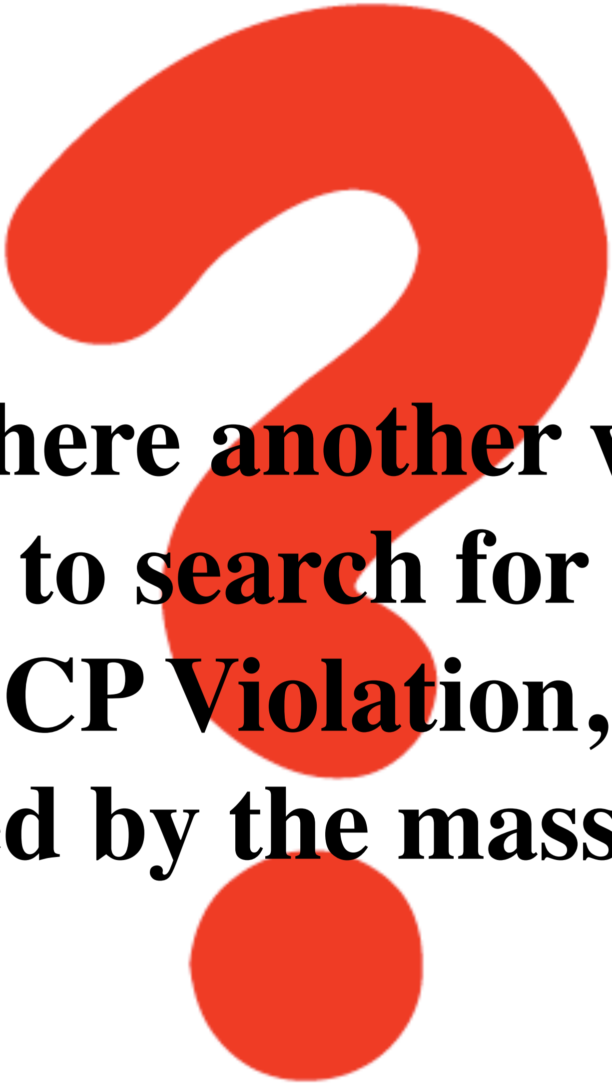


Long Base-line appearance

δ_{cp}

Hierarchy

And this is still messy



**Is there another way
to search for
CP Violation,
Not confused by the mass hierarchy?**

DAEδALUS

Decay
At rest
Experiment
for δ_{cp} studies
At the
Laboratory for
Underground
Science

- New ν source for an ultralarge detector
  - Enhanced neutrino oscillation program
  - New experiments possible

- Complementary to the long baseline proposals
  - Comparable measurements for osc parameters
  - Much improved measurements by combining DAEδALUS and long-baseline!

The plan: Use $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$
and exploit the L/E dependence in absolute rates

in a vacuum…

$$
\begin{aligned}
P = \; & (\sin^2\theta_{23}\sin^2 2\theta_{13})\,(\sin^2\Delta_{31}) \\
& \mp \underline{\sin\delta}\;(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \underline{\cos\delta}\;(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + (\cos^2\theta_{23}\sin^2 2\theta_{12})\,(\sin^2\Delta_{21}).
\end{aligned}
$$

We want to see
if δ is nonzero

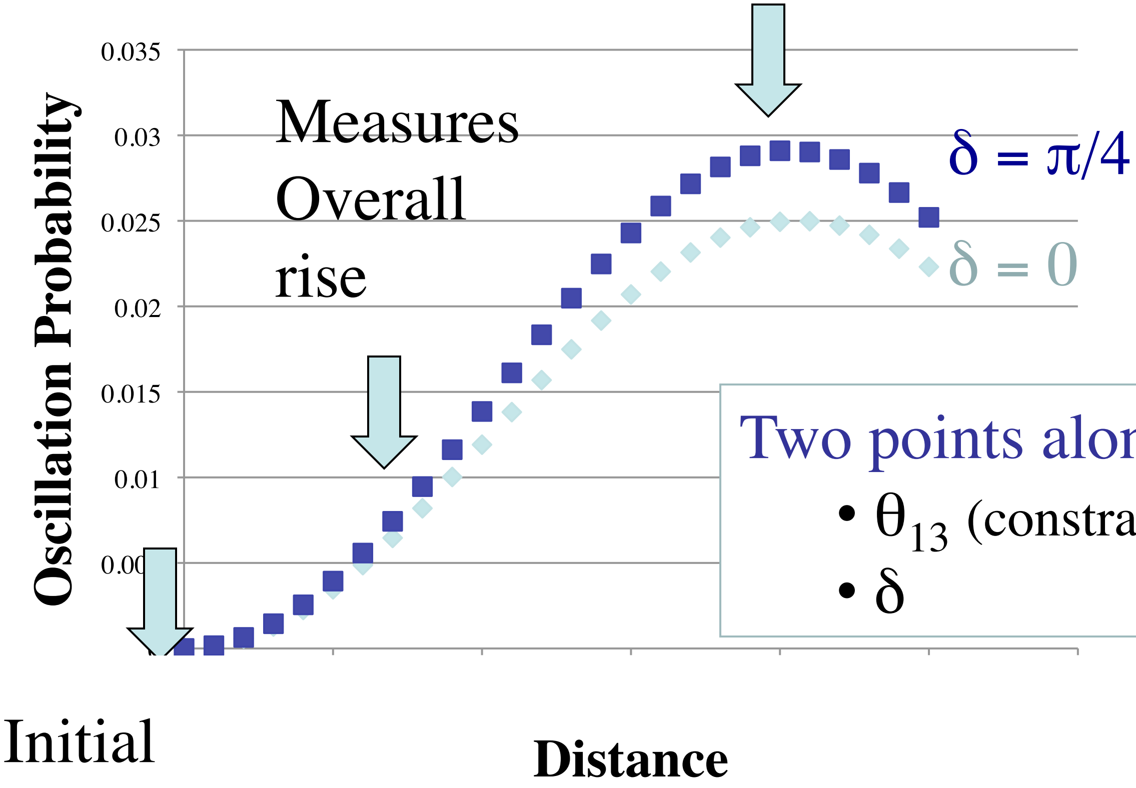
terms depending on
mixing angles

terms depending on
mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

The terms that depend on δ change the oscillation wave L dependence

Measures the maximum



Measures Overall rise

Two points along L can untangle

- θ_{13} (constrained by reactor)
- δ

Initial constraint

At low energy and short distances,
Modifications to this vacuum equation
By the mass hierarchy are very small

$$\begin{aligned} P = \quad & (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31}) \\ & \mp \underline{\sin\delta}\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21}) \\ & + \underline{\cos\delta}\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\ & \quad + (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}). \end{aligned}$$

We want to see
if δ is nonzero

terms depending on
mixing angles

terms depending on
mass splittings

$$\boxed{\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu}$$

I can change L and E,
But maintain L/E
And access the same oscillations as long baseline!

So we need:

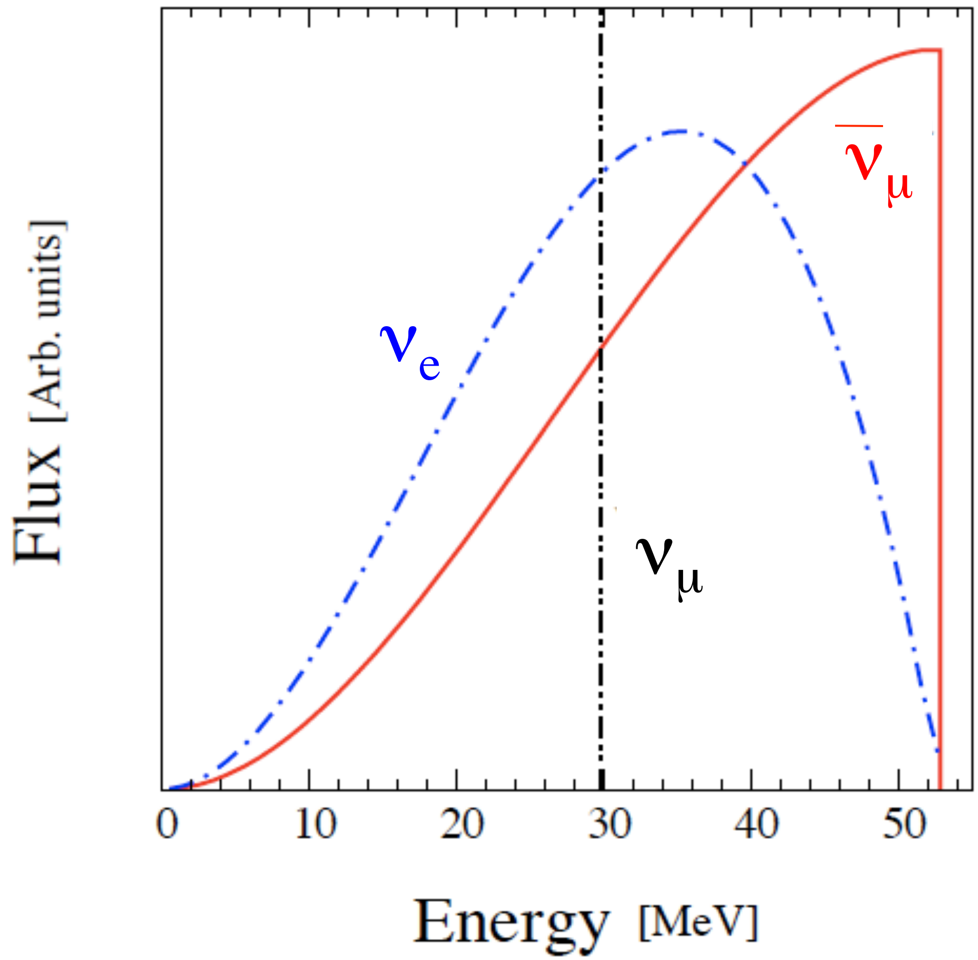
A multiple baseline
(at least 3 points),
Short baseline,
Low energy,
Experiment
To isolate

δ_{cp}

A really nice
low-energy beam

A π^+ decay at rest beam:

$$p+C \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e,$$



Shape driven by nature!

Only the normalization
varies from beam to beam

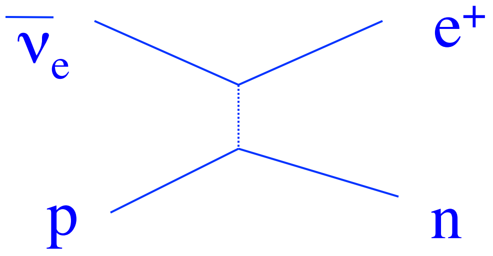
No intrinsic $\bar{\nu}_e$

Perfect for a
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
search

How do you observe ~50 MeV $\bar{\nu}_e$ events?

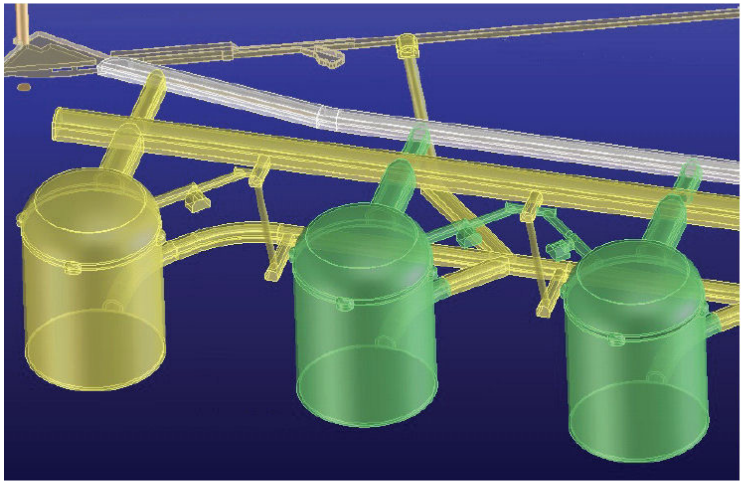
The signal:

inverse beta decay, IBD



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

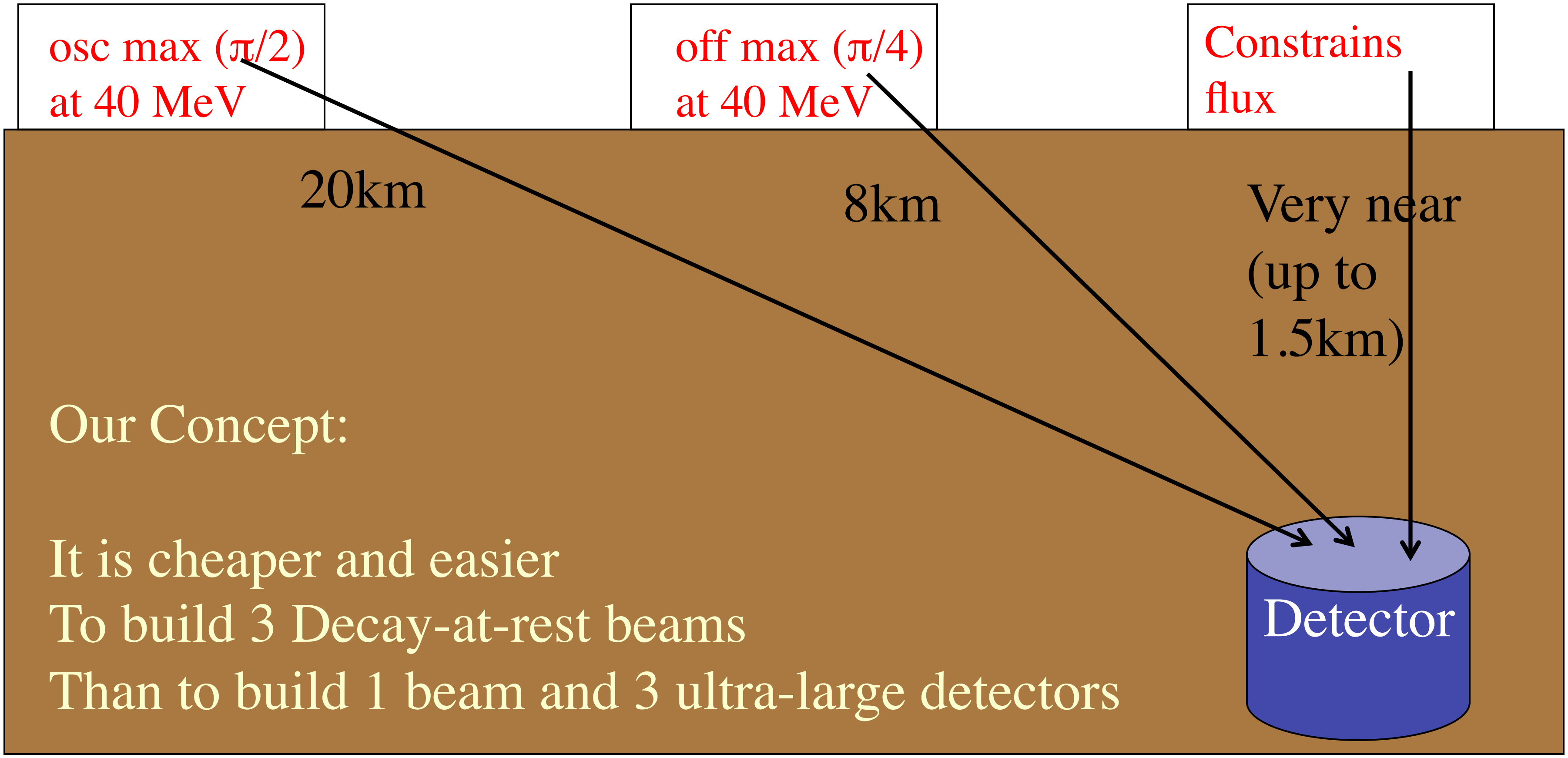
You need a lot of **free protons**!



Use the same ultra-large detector system as the long baseline

Water – MEMPHYS, LBNE

Oil -- LENA



osc max (π/2)
at 40 MeV

off max (π/4)
at 40 MeV

Constrains
flux

20km

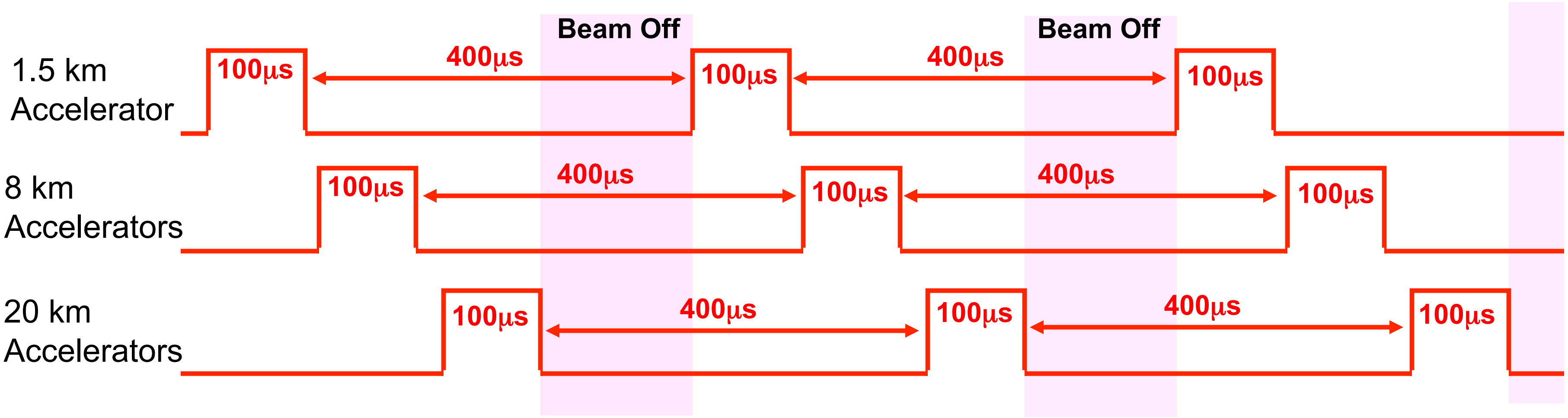
8km

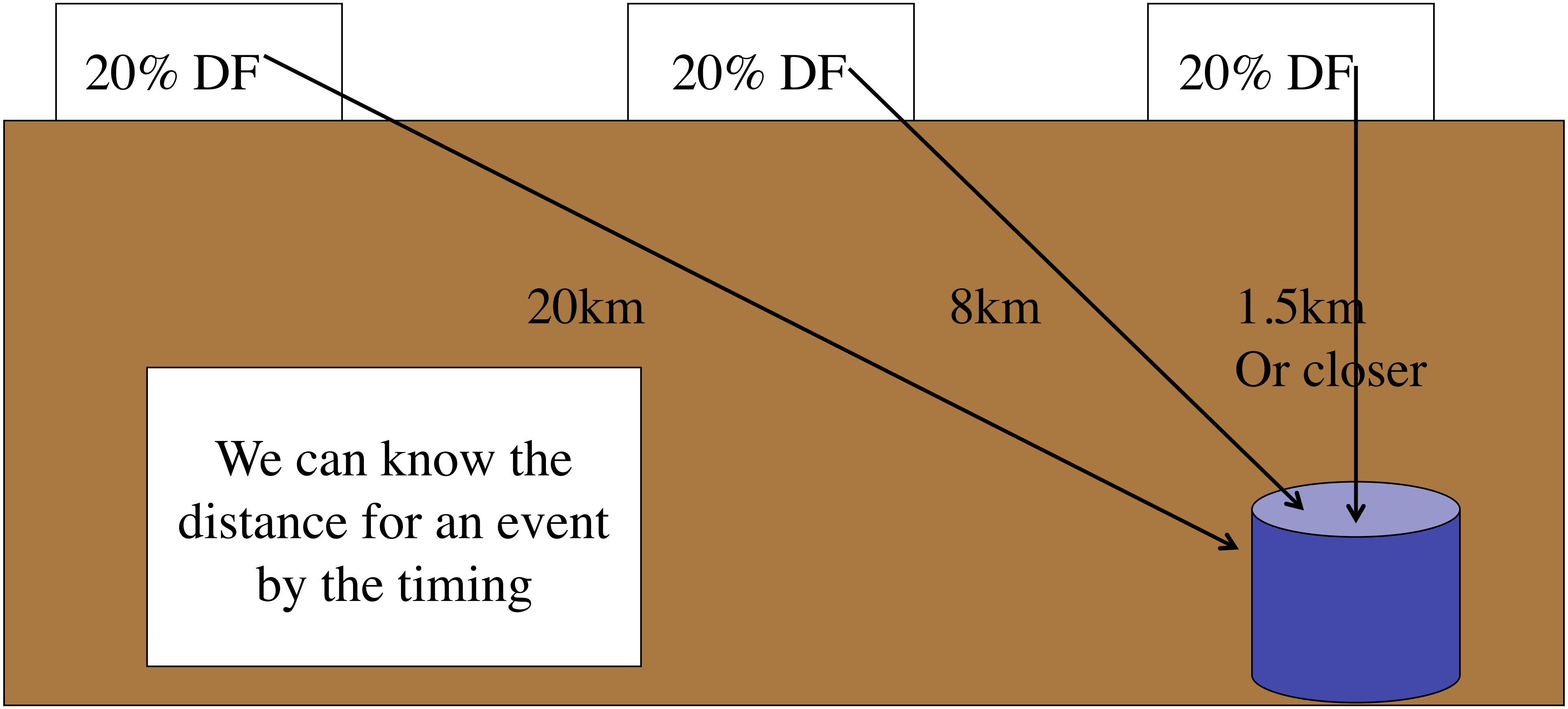
Very near
(up to
1.5km)

Our Concept:

It is cheaper and easier
To build 3 Decay-at-rest beams
Than to build 1 beam and 3 ultra-large detectors

Detector





We can know the distance for an event by the timing

Luckily, there are other people who want low-energy,
High-power proton sources!

Accelerator driven systems for thorium reactors

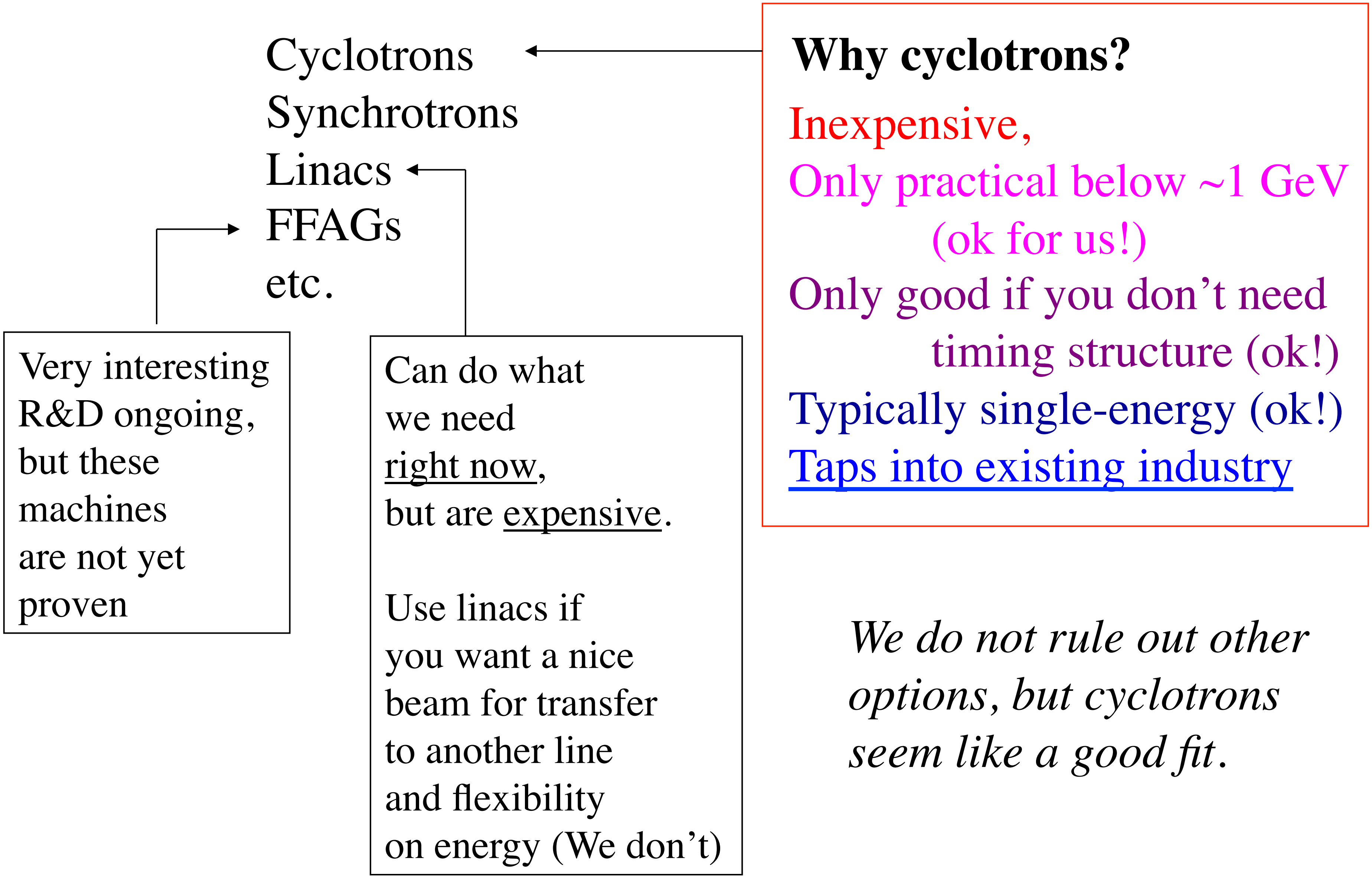
ThEC
THORIUM ENERGY
CONFERENCE 2011

Columbia University,
10-12 October 2011

Like the accelerators that we need
(and unlike Project X, SNS, etc)

- ~800 MeV protons only
  Single energy, no upgrade path
- No fancy beam structure
- No stringent emittance requirements

Among all of the types of accelerators out there…



Cyclotrons
Synchrotrons
Linacs
FFAGs
etc.

Very interesting R&D ongoing, but these machines are not yet proven

Can do what we need <u>right now</u>, but are <u>expensive</u>.

Use linacs if you want a nice beam for transfer to another line and flexibility on energy (We don't)

Why cyclotrons?

Inexpensive,
Only practical below ~1 GeV
(ok for us!)
Only good if you don't need
timing structure (ok!)
Typically single-energy (ok!)
<u>Taps into existing industry</u>

We do not rule out other options, but cyclotrons seem like a good fit.

Approaches using cyclotrons:

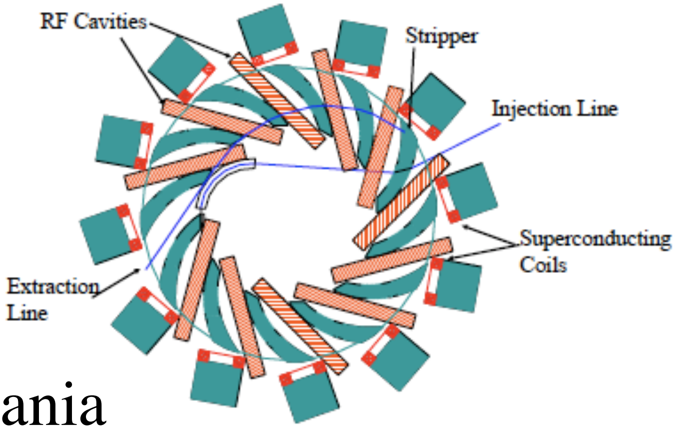
The compact cyclotron with self-extraction

under development for DTRA at MIT

An H2+ accelerator

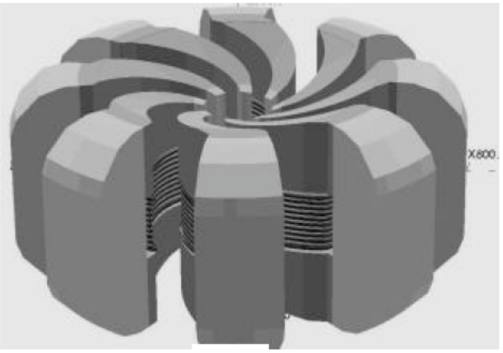
for ADS applications

Under dev. by INFN, Catania



The stacked cyclotron:

7 cyclotrons in one flux return



Under dev. for ADS at TAMU

Measurement strategy:

Using **near accelerator**
measure **absolute flux normalization** with ν-e events to ~1%,
Also, measure the ν_eO event rate.

At far and mid accelerator,
Compare predicted to measured ν_eO event rates
to get the **relative flux normalizations between 3 accelerators**

In all three accelerators,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with free parameters: **θ_{13} and δ**

Non-beam backgrounds
Depends on the detector

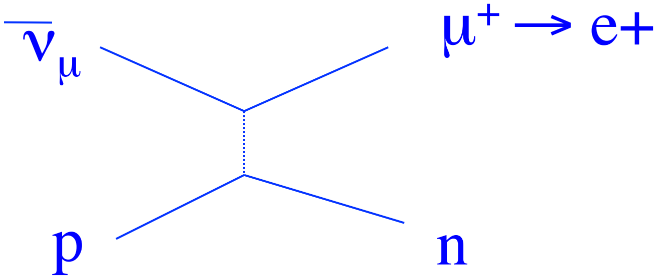
In water Cerenkov Detectors:

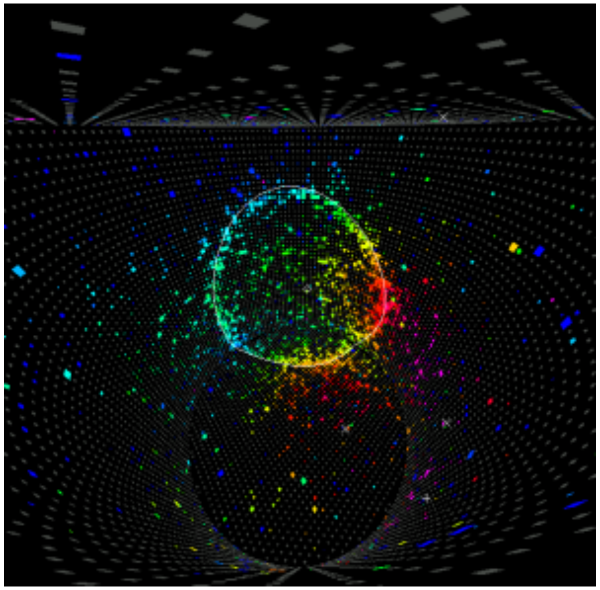
Atmospheric $\bar{\nu}_\mu$ “Invisible muons”:

$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ where

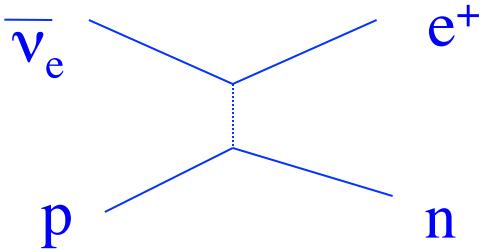
μ^+ is below Cherenkov threshold,

stops and decays.





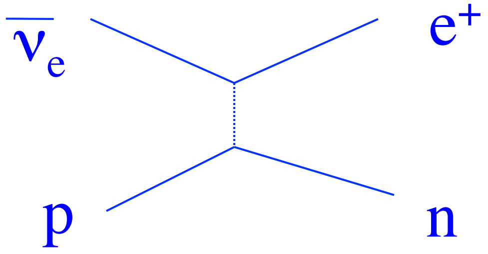
Looks just like



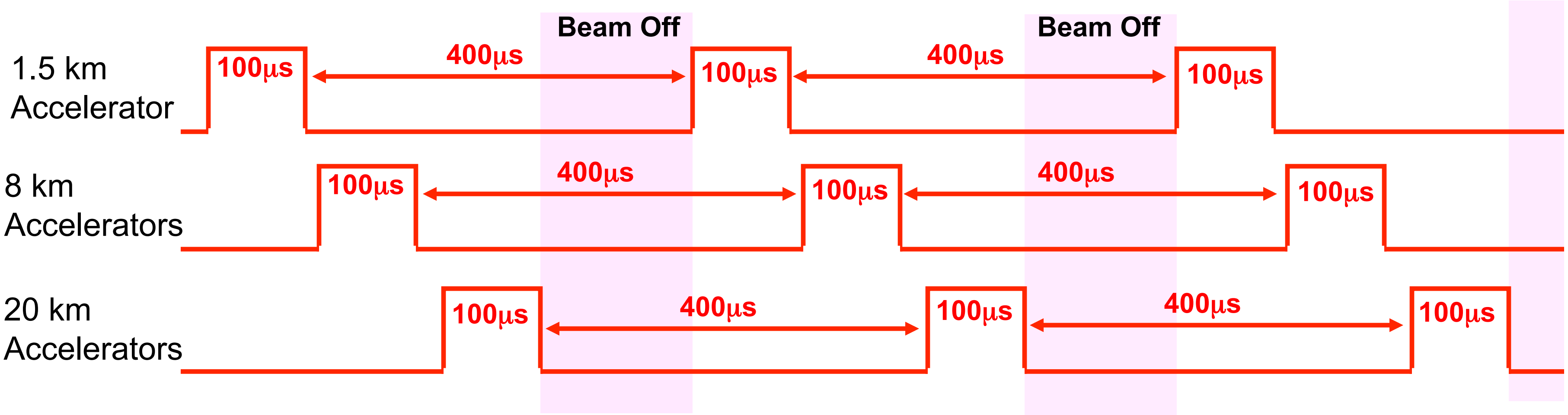
Not a background in scintillator!

Non-beam backgrounds, cont'd

- Atmospheric $\overline{\nu}_e$ IBD events:
  $\overline{\nu}_e + p \rightarrow e^+ + n$
- Diffuse supernova neutrinos



Measure all of these during the beam off periods:



Beam-related Background

- Intrinsic $\overline{\nu}_e$ in beam

  From $\pi^- \rightarrow \mu^-$ events which failed to capture in the beam stop

  $\sim 4\times10^{-4}$ of ν_e rate (low)

- Beam ν_e in coincidence with random neutron capture signal
  Estimated to be very small from Super-K rates

- ν_e-Oxygen CC scatters producing an electron+ n signal
  Subsequent n from nuclear de-excitation should be very small.

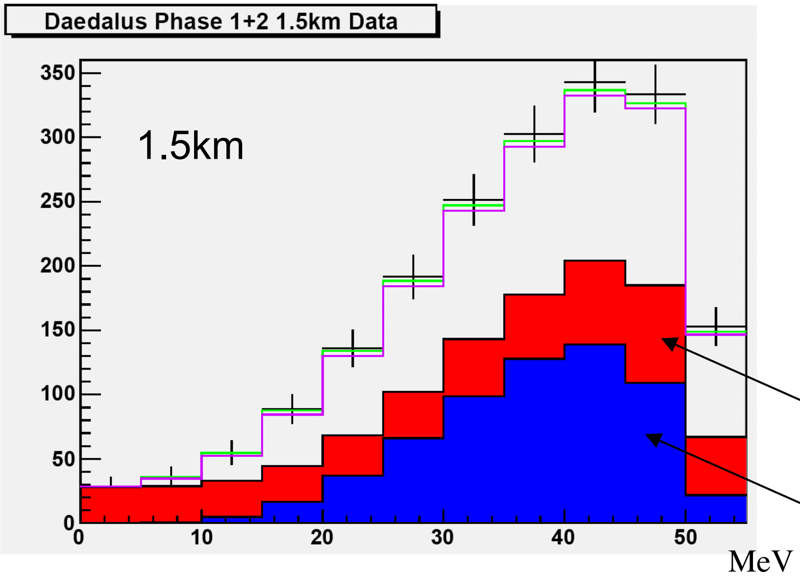
All fall as $1/r^2$ from the 3 accelerators,
near accelerator provides a measurement

To discuss how well we can do, I need to pick a model…

- Water Cerenkov
- “Homestake Accelerator Arrangement” -- 1.5, 8 and 20 km
- Gd doping of water so the neutron can be observed
- 300 kt (we are stats limited, so you can scale)

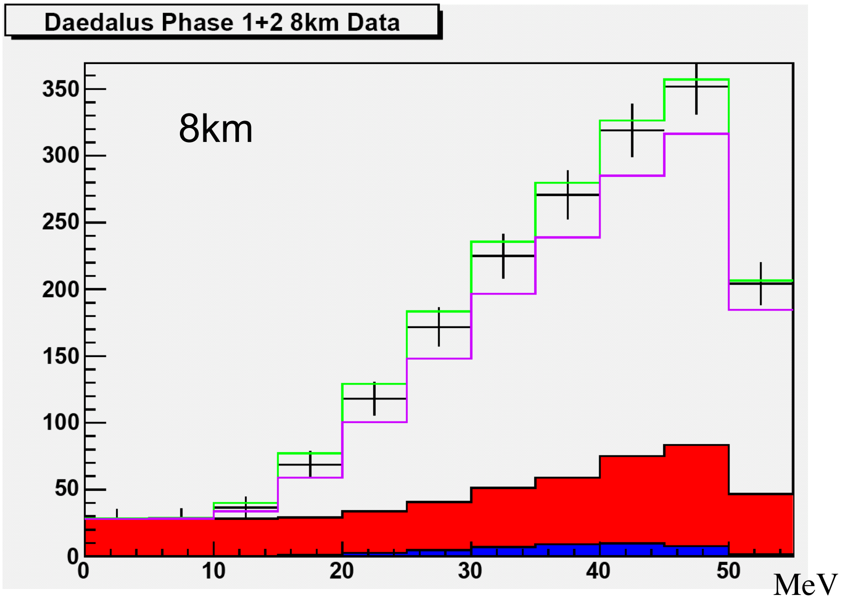
Daedalus Event Energy Distributions (Signal & Background)

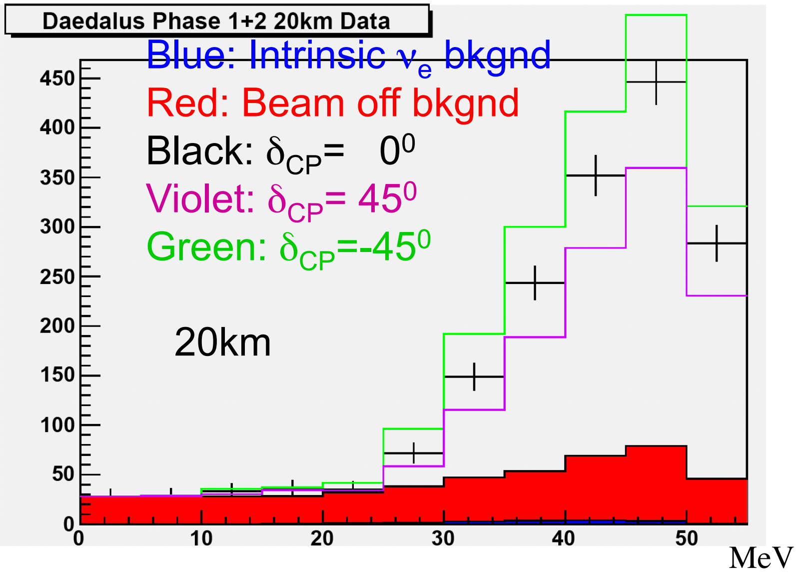
$(\sin^2 2\theta_{13} = 0.04)$



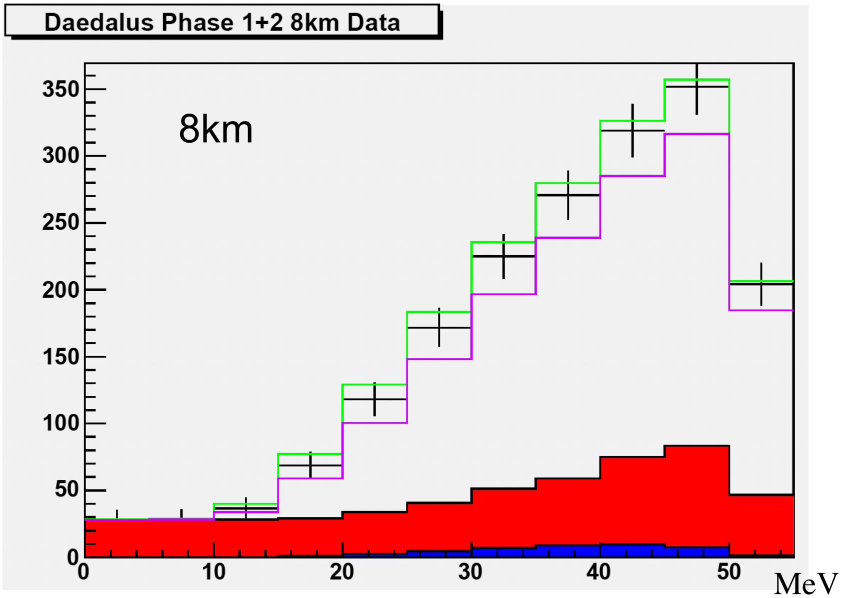
beam off

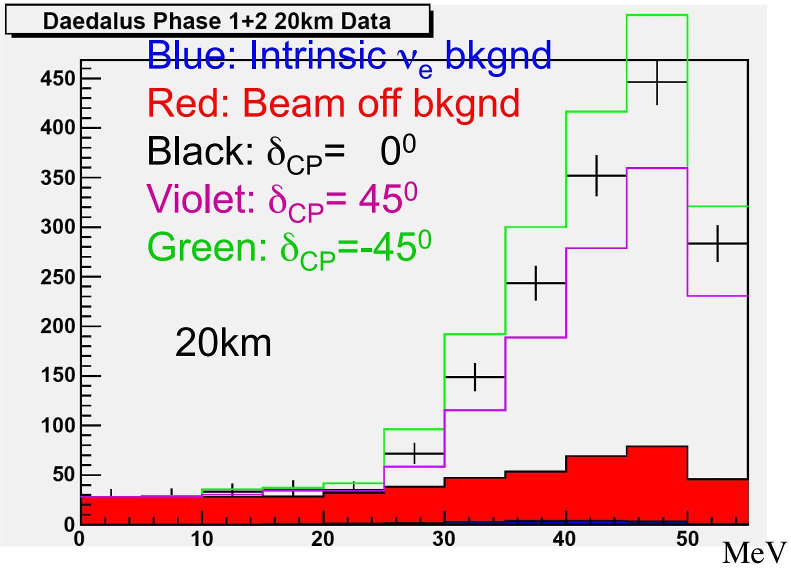
beam on



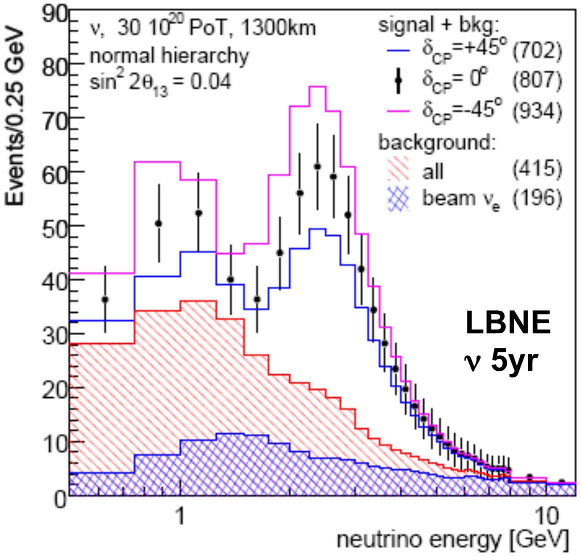


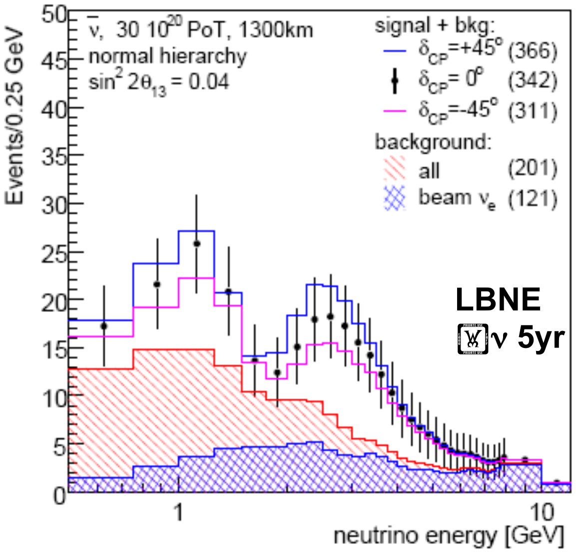
Compare signal to-background



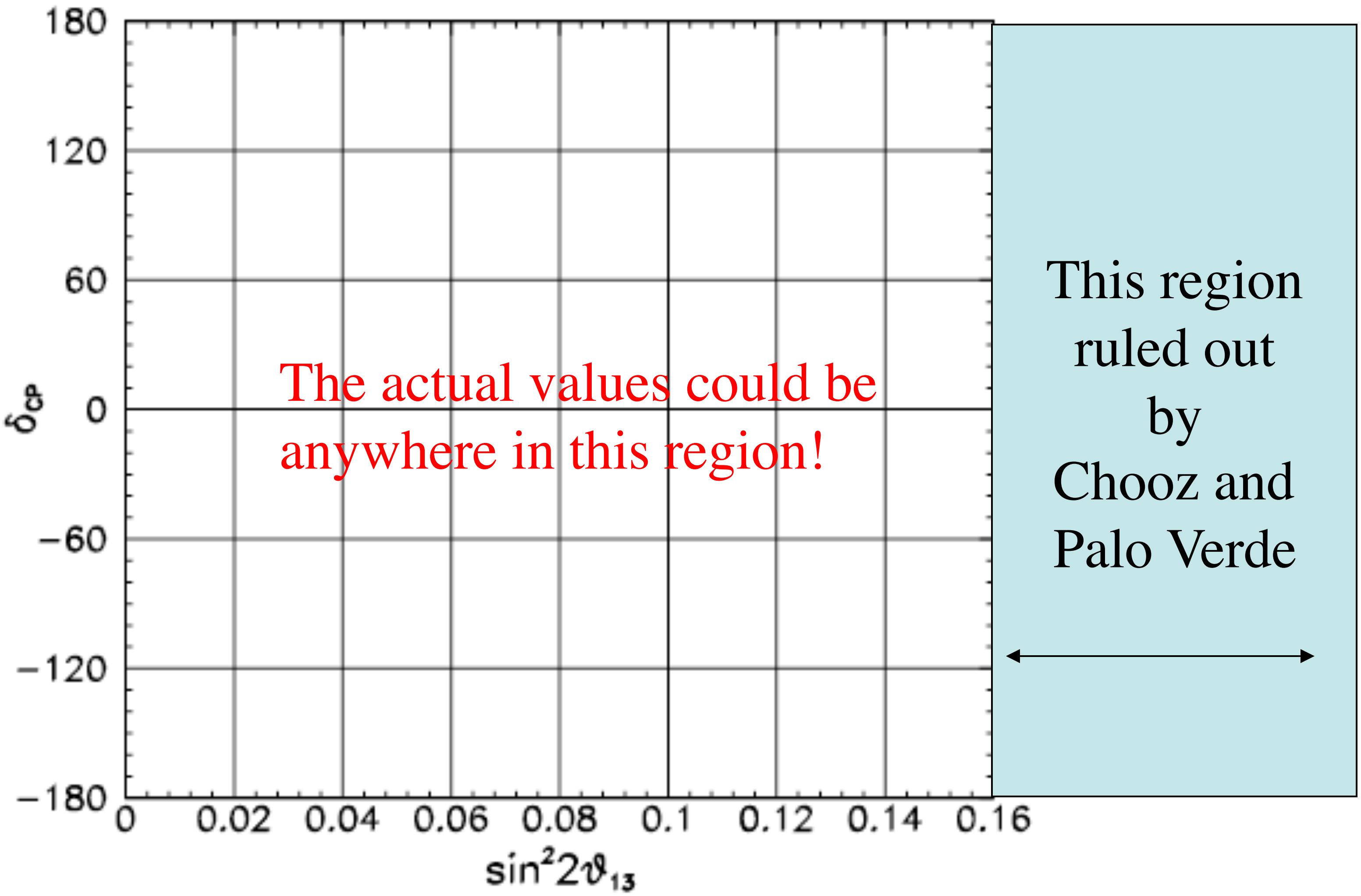


With LBNE…





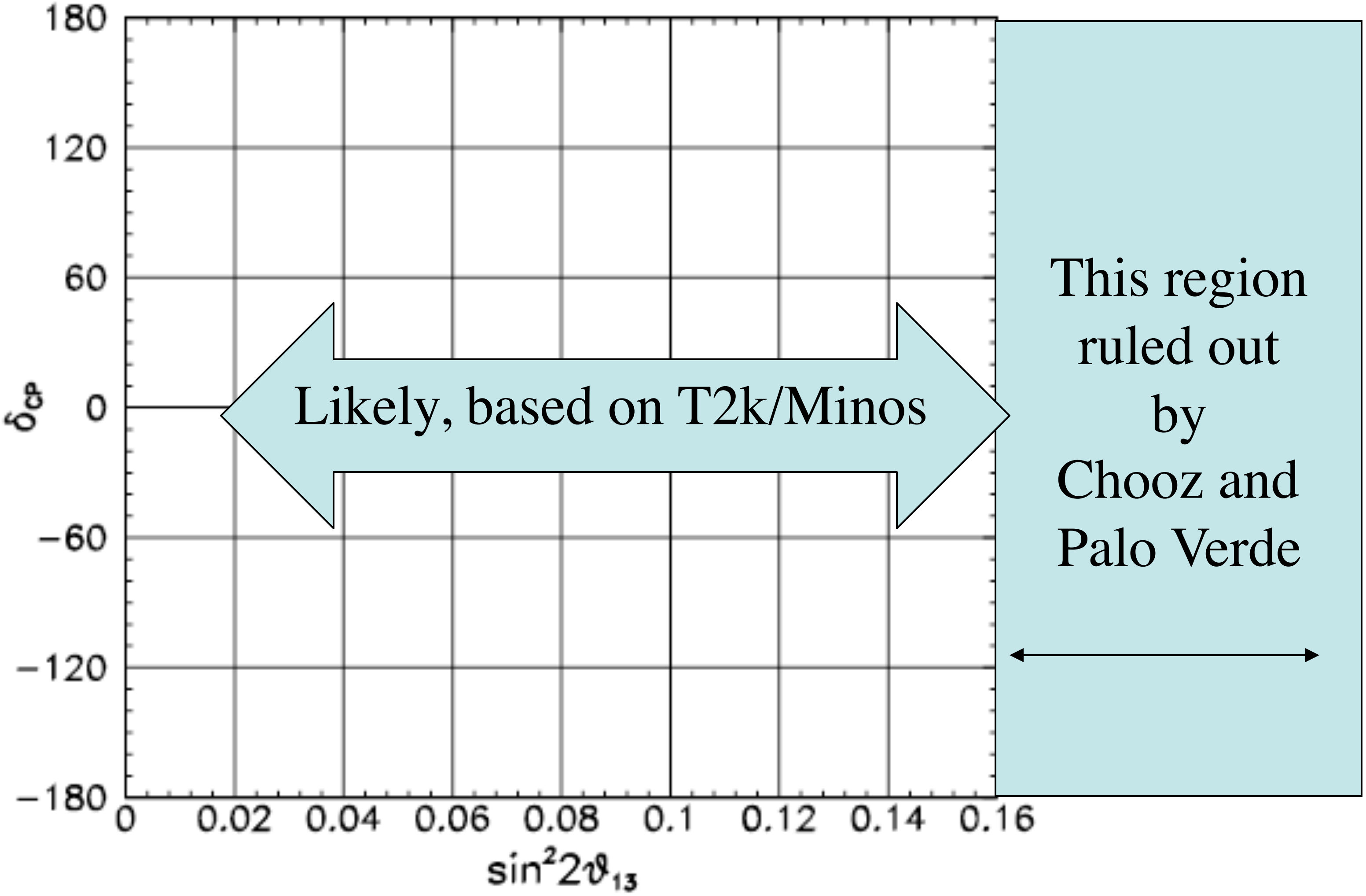
So what will we learn about δ vs θ_{13} from DAEδALUS??



The actual values could be anywhere in this region!

This region ruled out by Chooz and Palo Verde

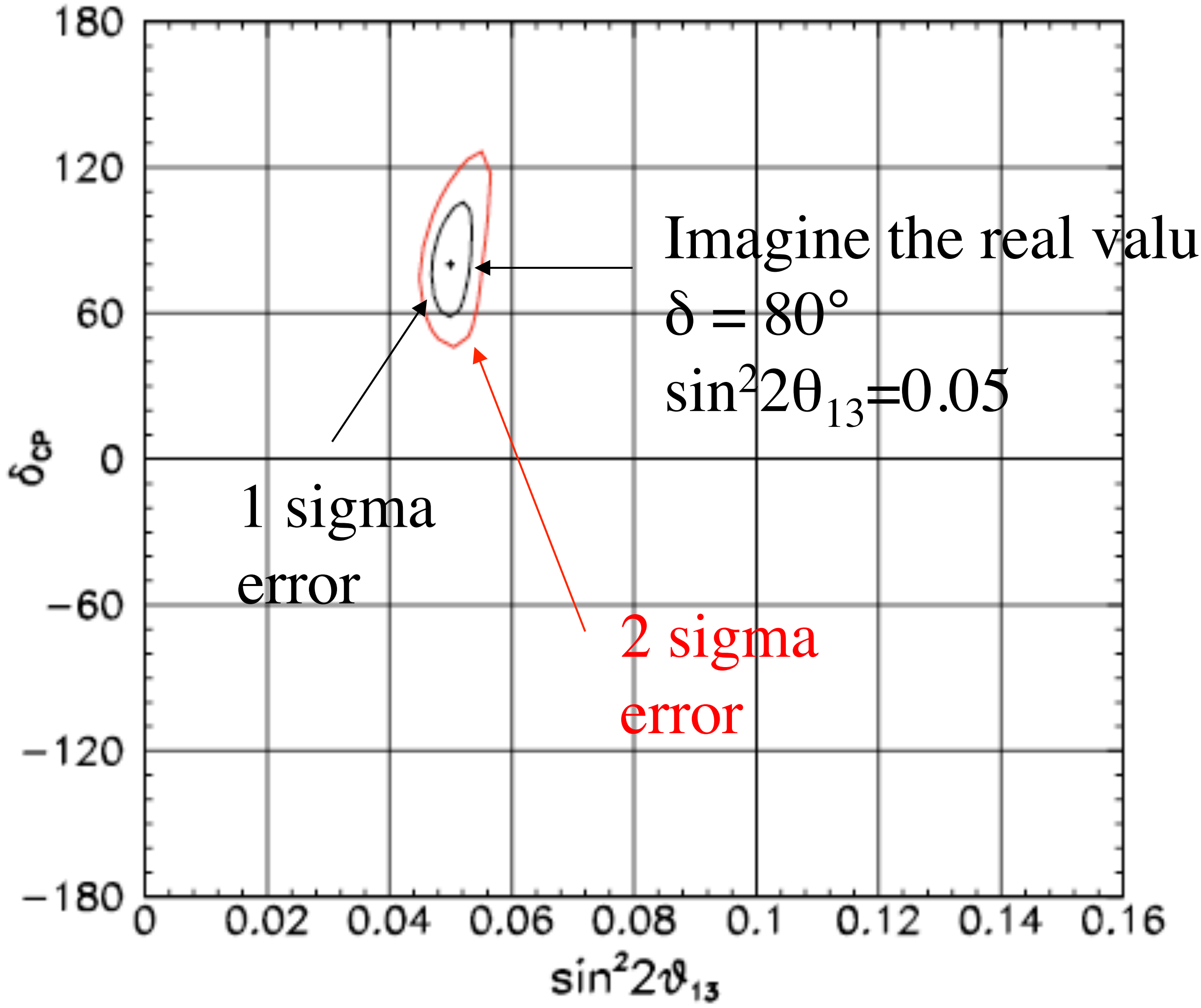
So what will we learn about δ vs θ_{13} from DAEδALUS??



Likely, based on T2k/Minos

This region ruled out by Chooz and Palo Verde

If we succeeded in observing a signal,
what would this plot look like?

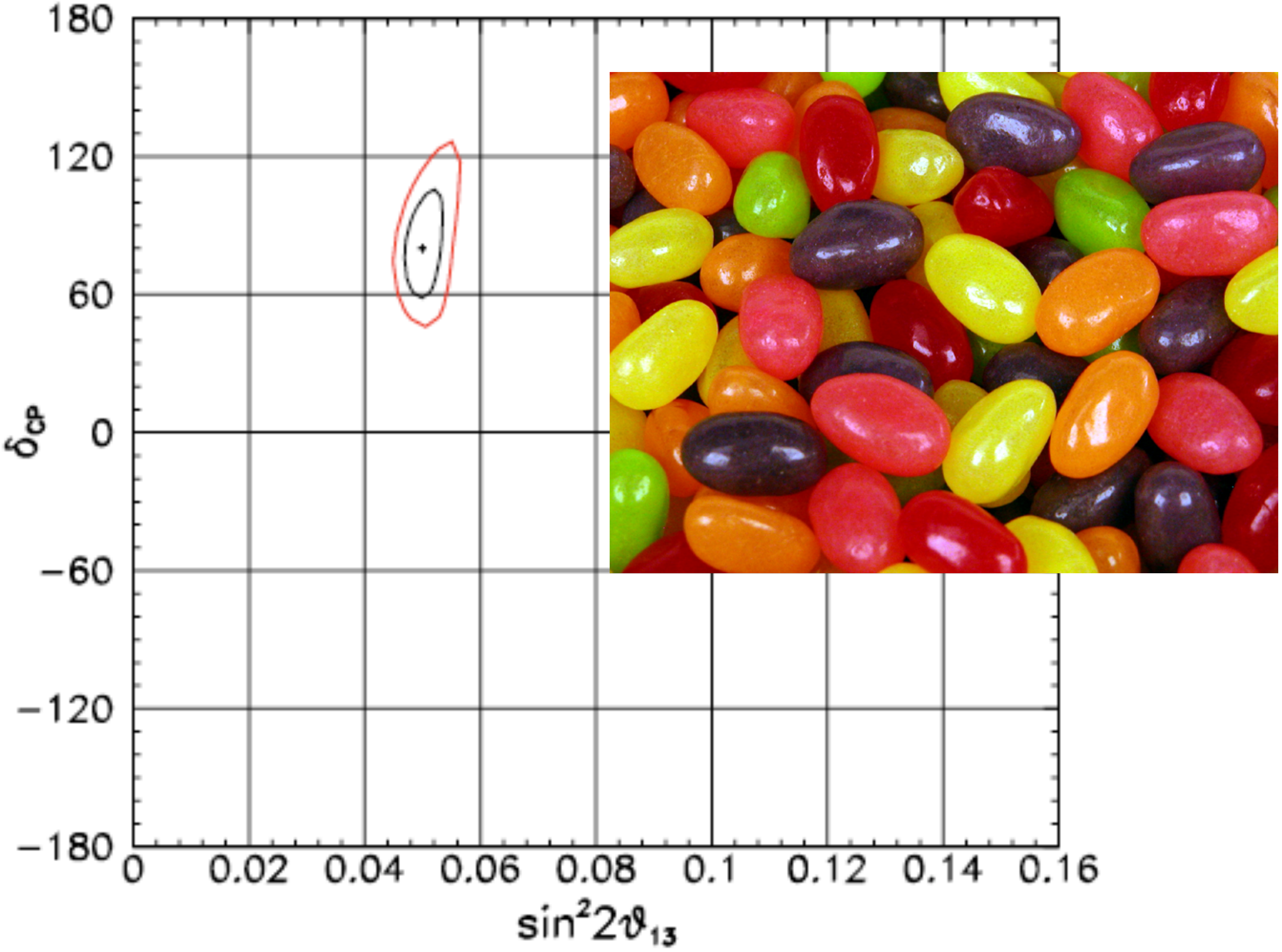


Imagine the real values are:
$\delta = 80°$
$\sin^2 2\theta_{13} = 0.05$

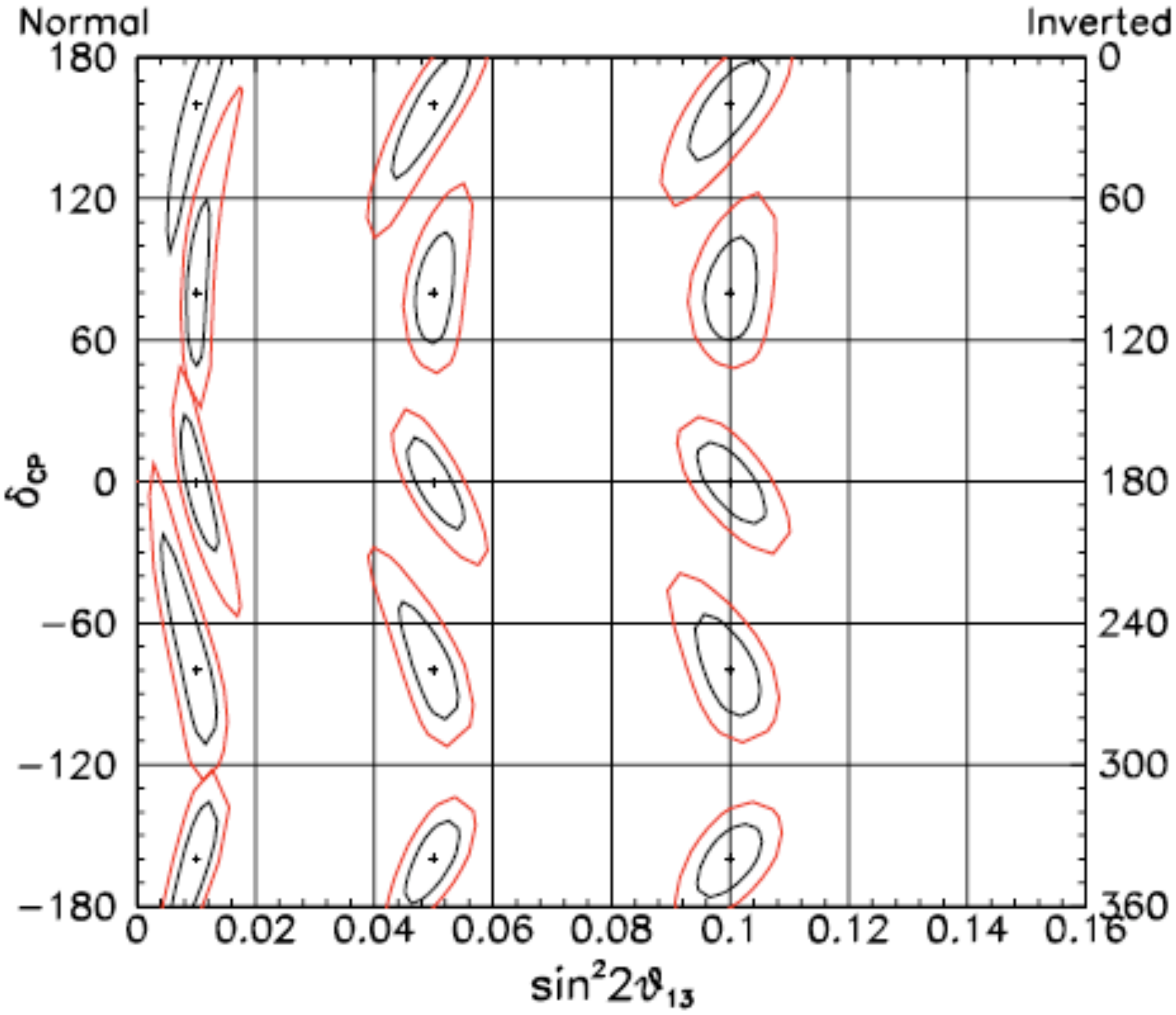
1 sigma error

2 sigma error

You get a “jelly bean”



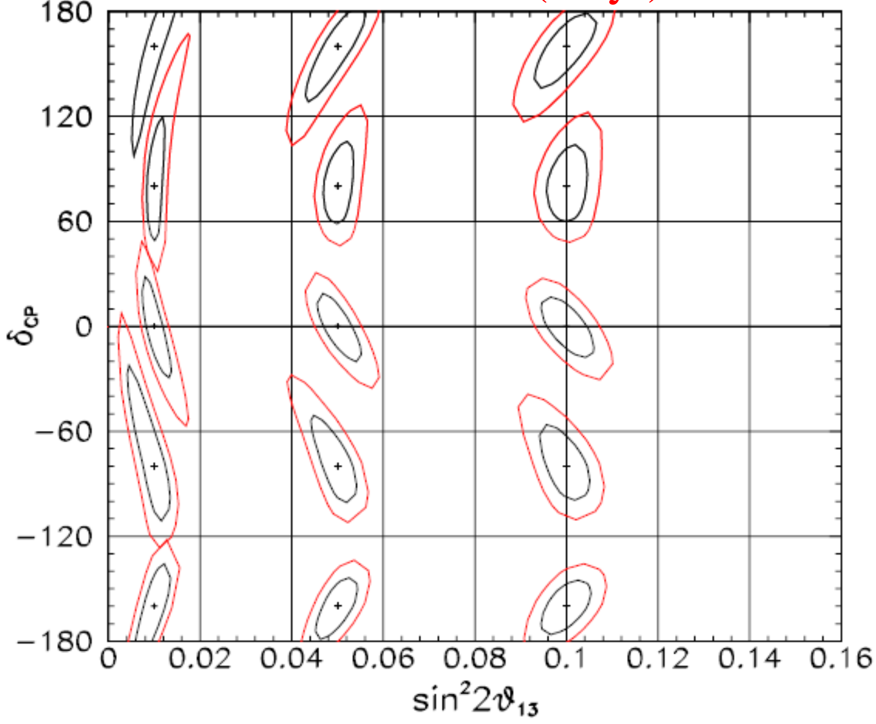
How well do we do on a “jelly bean” plot?



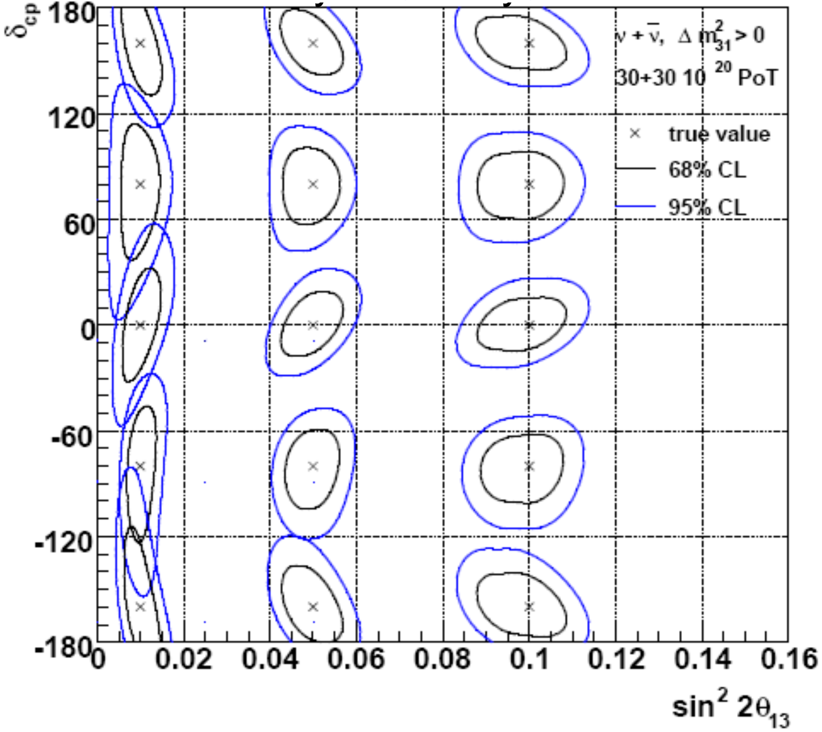
We can clearly
observe
CP violation!

By construction our capability is equal to LBNE,
With same sized detector
But our measurement has completely different issues!

DAEδALUS (10 yr)



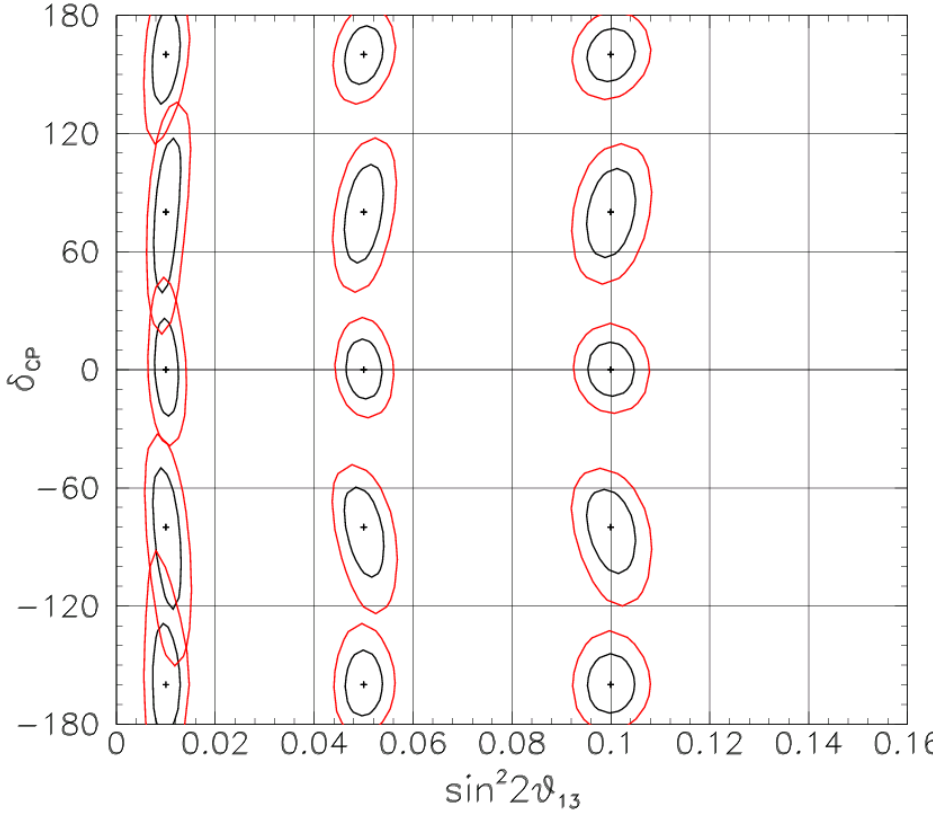
LBNE (5yr ν, 5yr $\overline{\nu}$)



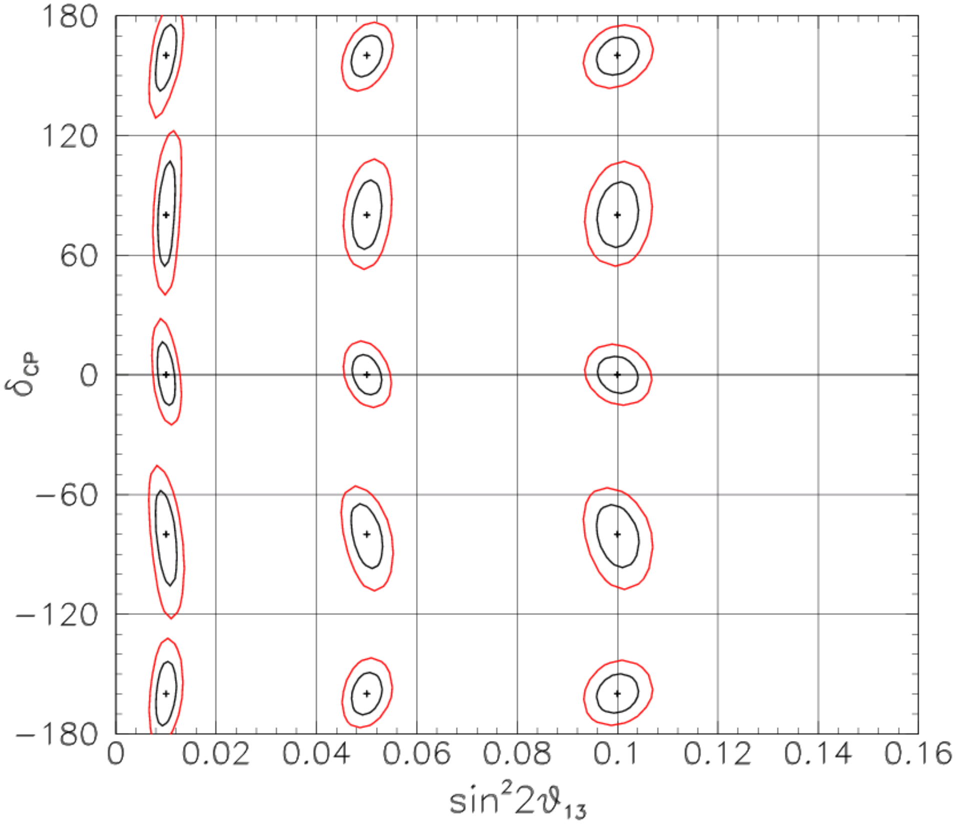
Normal Hierarchy

What the Combined Experiments can do!

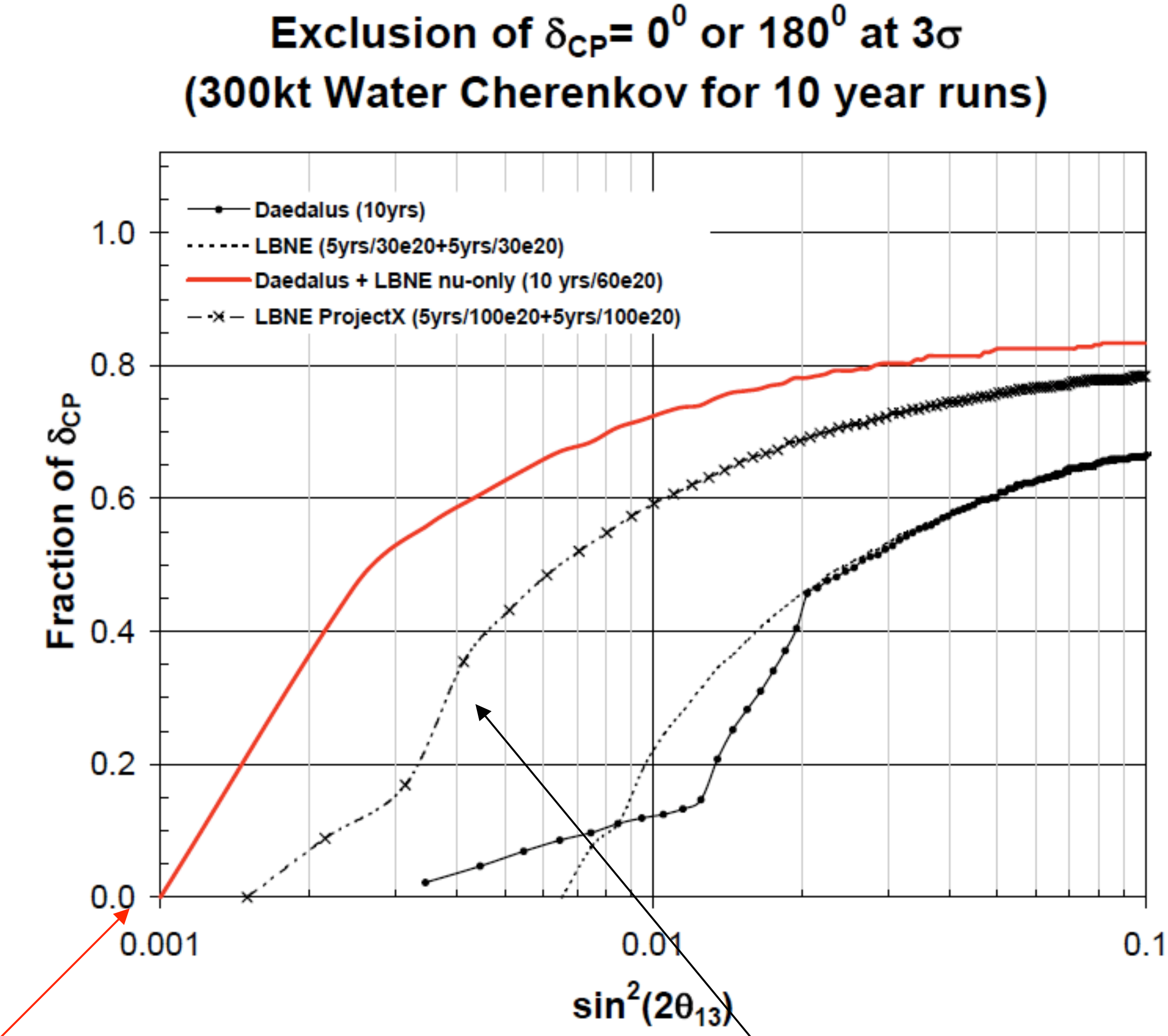
5yr Combined Running



10yr Combined Running



The fraction of “δ-space” where a measurement will be >3σ



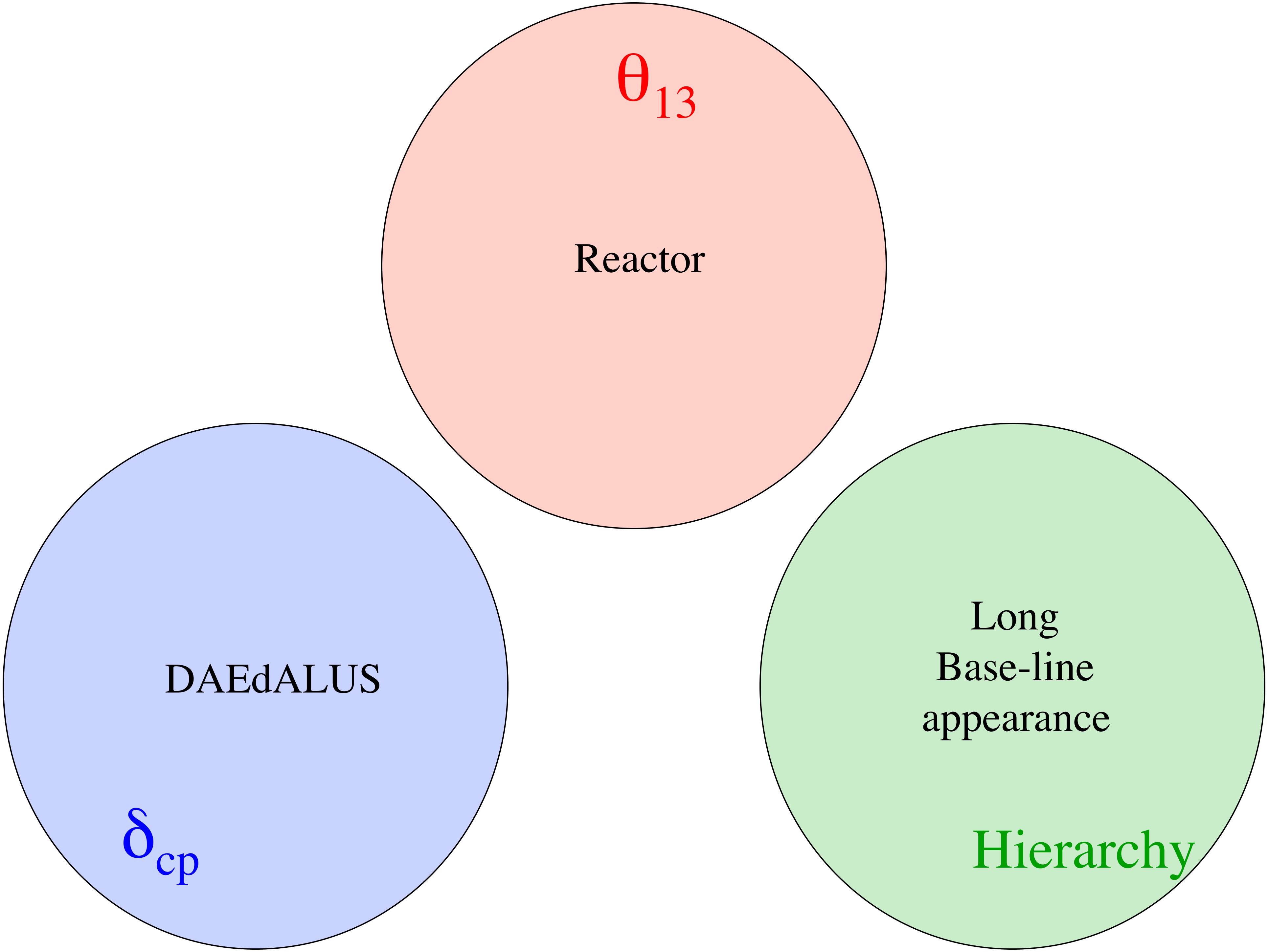
Better than a Project X (“superbeam”) experiment!

I have used a US-based example,
but this can be done anywhere you have

1. A detector with a lot of free protons (~100s of ktons).
   A scintillator detector should work too.
   → This is enough to match the conventional beam designs

2. A conventional beam at a reasonable distance.
   → This allows you to probe beyond the sensitivity of
   superbeams!

There is a big wide world of opportunities
for this design!

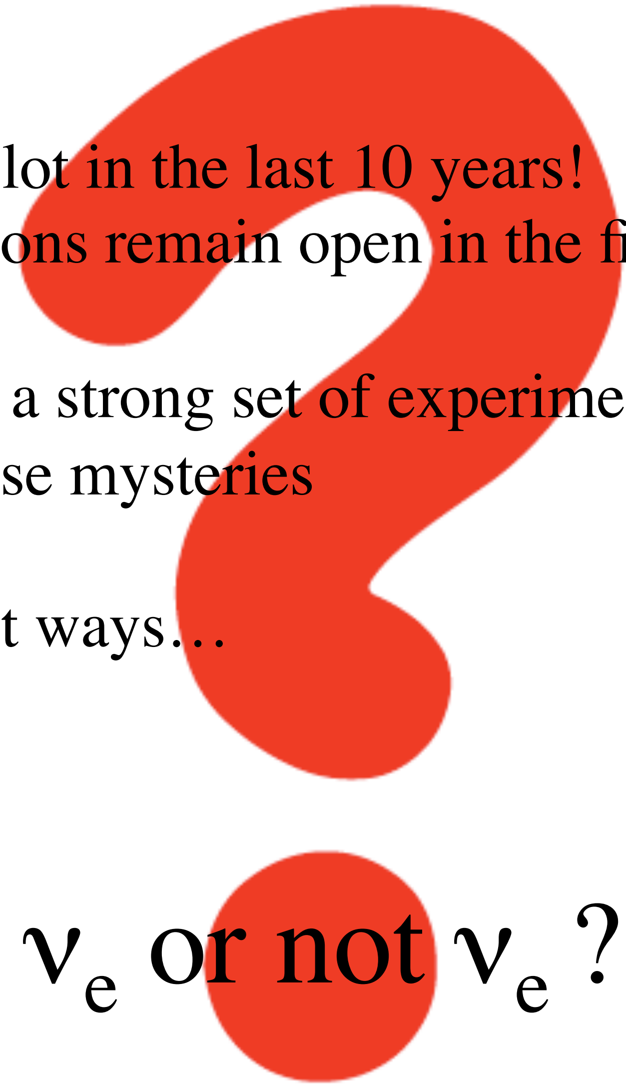

θ_{13}
Reactor
DAEdALUS
δ_{cp}
Long Base-line appearance
Hierarchy

Conclusions:

We have learned a lot in the last 10 years!
But exciting questions remain open in the field of oscillations.

We are developing a strong set of experiments to
go after these mysteries

Asking, in different ways…



ν_e or not ν_e ?

… I hope DAEδALUS will be one of them!