The plan:

Neutrinos Now... Today

Neutrinos Next:

Neutrinos and the New Paradigm Today

Neutrinos and the Unexpected Tomorrow

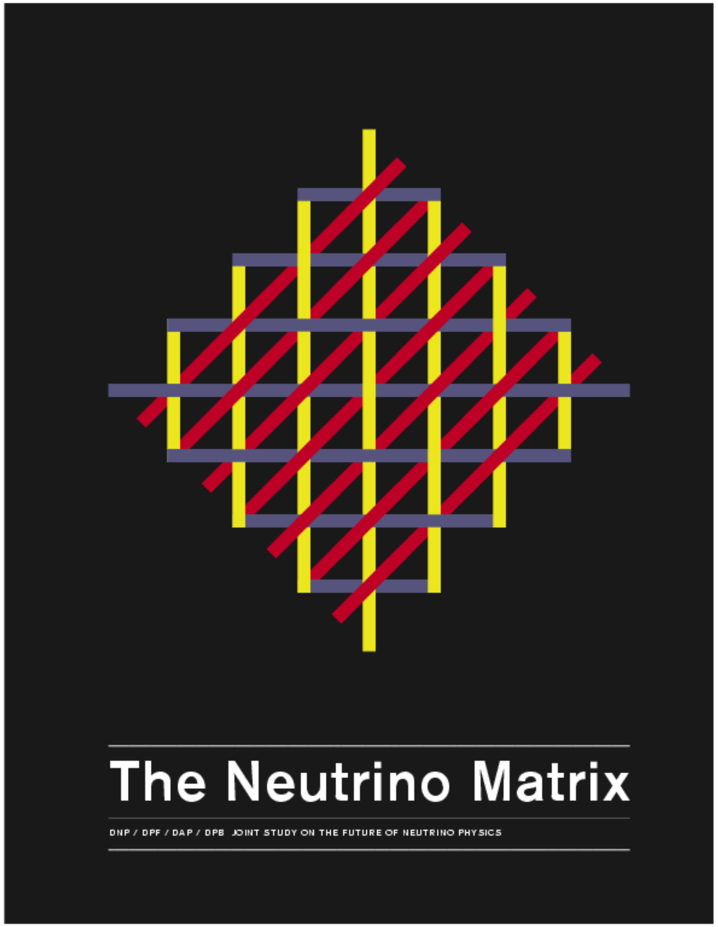
Neutrinos and the Cosmos Tomorrow

Neutrino Opportunities Tomorrow

“Neutrinos Next” will follow

The APS-sponsored
Multidivisional study on...
The Future of Neutrino Physics

Working Groups:
Solar & Atmospheric Neutrinos
Reactor Neutrinos
Super Beams
Neutrino Factory & Beta Beams
Neutrinoless Double Beta Decay
Astrophysics & Cosmology



http://www.aps.org/neutrinos

Disclaimers:

These lectures are on understanding neutrinos,
as opposed to using neutrinos to understand other physics.

I define a “neutrino experiment” as an experiment that
is relevant to understanding neutrinos

There are many experiments...
There are many experimental questions...
These are “Janet’s Picks”

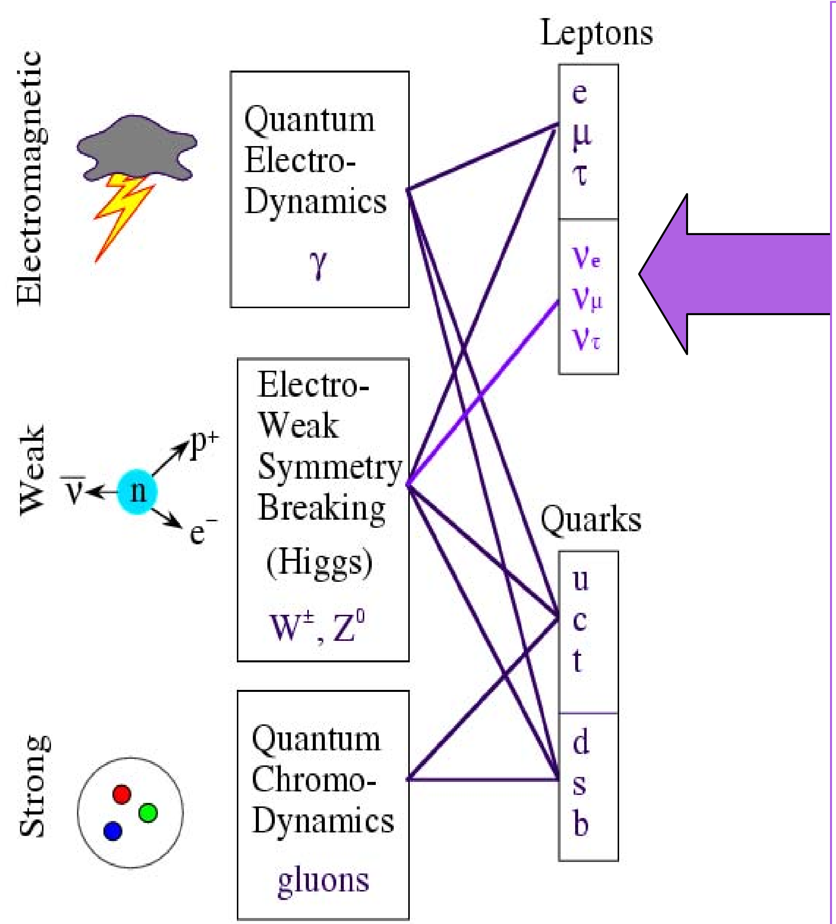
I identify statements that are “Janet’s Opinions”

I am focussing mainly on now and the future...

Neutrinos Now:

Setting up the Experimental Questions

SM Neutrinos in a nutshell..



- Only interact via the "weak force"
- Interact thru W and Z bosons exchange is (V-A)
  - Neutrinos are left-handed (Antineutrinos are right-handed)
- Neutrinos are massless
- Neutrinos have three flavors
  - Electron $\nu_e \rightarrow e$
  - Muon $\nu_\mu \rightarrow \mu$
  - Tau $\nu_\tau \rightarrow \tau$

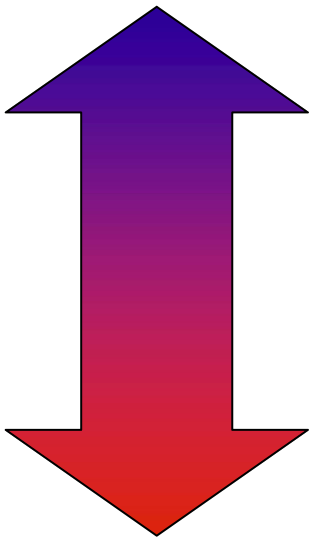
The interaction depends upon the ν energy...

The main sources

Useful interactions

Reactors,
The Sun

Few MeV



Multi-GeV+

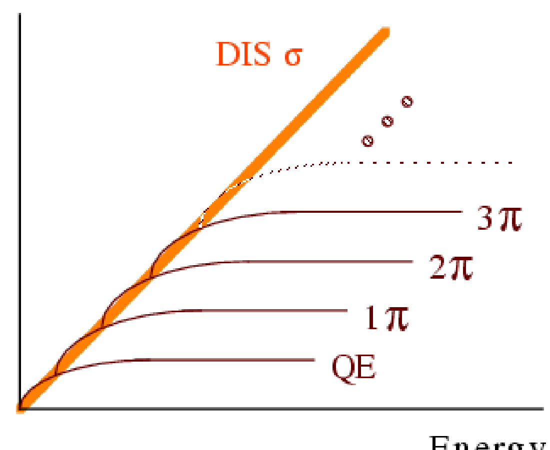
Cosmic rays,
accelerators

Elastic (esp. νe → νe)

Quasielastic (νN → ℓN')

Single Pion Production
(resonant & coherent)

Deep Inelastic Scattering

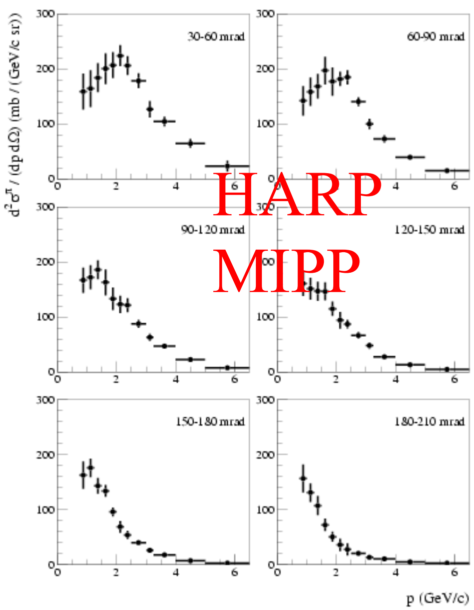


Janet's opinion:

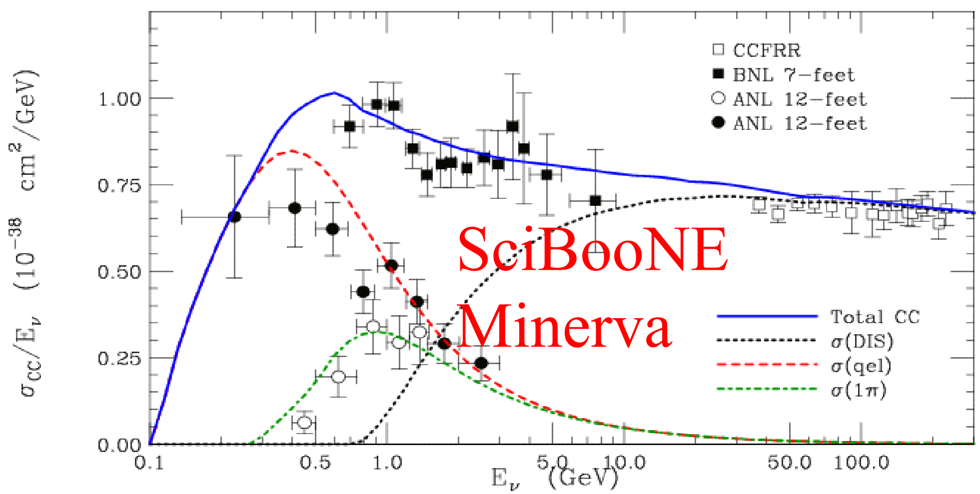
Nearly all "new physics" searches experiments require accurate knowledge of the beam and cross section.

Otherwise you end up with effects like the Hera "high Q^2 events"

In neutrino physics, these are experiments like:



HARP
MIPP



SciBooNE
Minerva

These types of experiments need your support

Why study neutrinos?

Theory-based Reasons

Even within the Standard Model,
Neutrinos are <u>not</u> "standard"!

Because of their unique properties,
BSM effects may show up in neutrino interactions

Experimentally-based Reasons

The Standard Model characteristics show 5σ disagreement with data.

The “non-standardness” of the SM neutrino...

- The only fermion that does not carry electric charge
- The only fermion that is only left handed
- The only fermion which is massless

The “non-standardness” of the SM neutrino...

- The only fermion that does not carry electric charge
- The only fermion that is only left handed
- The only fermion which is massless

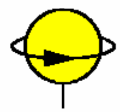
These two are related...

A quick reminder about parity violation...

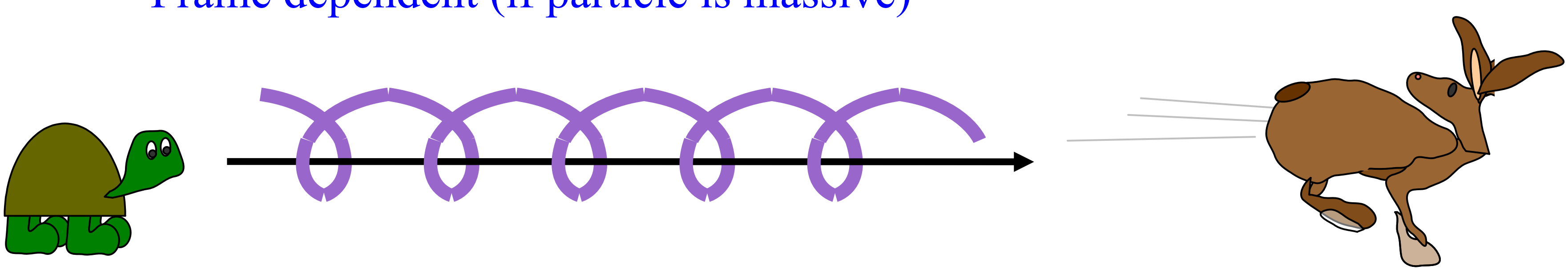
All spin 1/2 particles have "helicity"

The projection of spin along the particle's direction

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

right-helicity  left-helicity 

Frame dependent (if particle is massive)

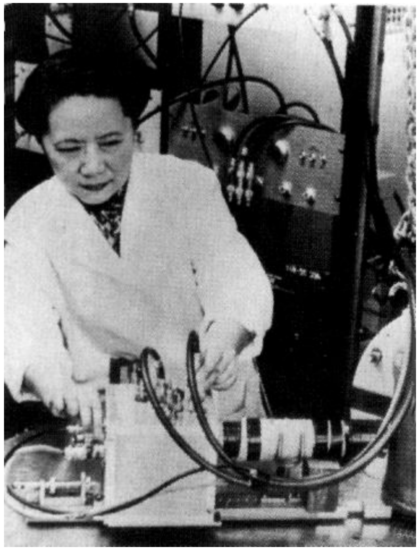


Handedness (or chirality) is the Lorentz-invariant counterpart

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

All particles except neutrinos come in LH & RH
Neutrinos are only observed as LH (and antineutrinos RH)

Neutrinos have a specific "handedness"



50th anniversary of
CS Wu's experiment
is next December!

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:

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

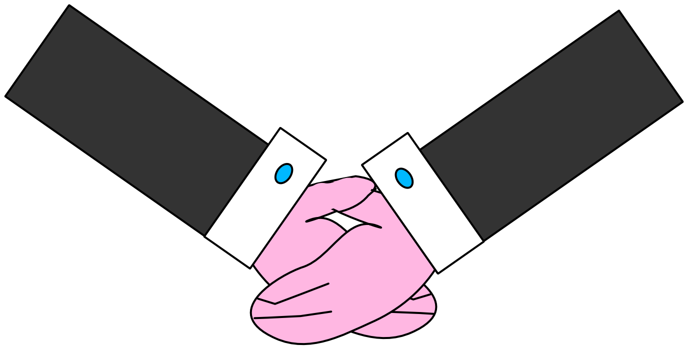
If you want to build parity violation into "the law"
you have to keep this term out of the Lagrangian...
a simple solution is: m=0

The SM neutrino may be sensitive to BSM effects...

- Not "obscured" by the "strongest" interactions...
  strong and electromagnetic.

- singlet partners can be motivated if
  handedness is intrinsic to the EW Bosons.

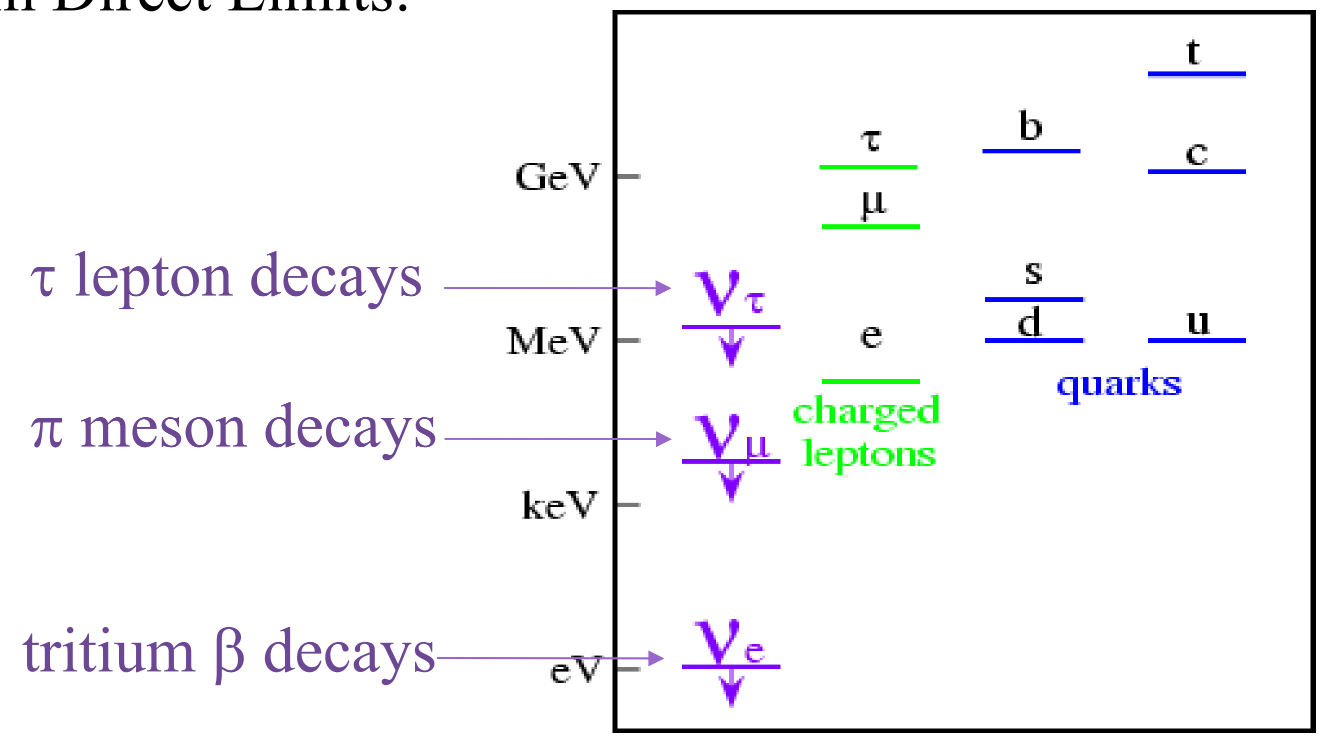
"The W only shakes
with the left hand"



The neutrino mass model is simply wrong...

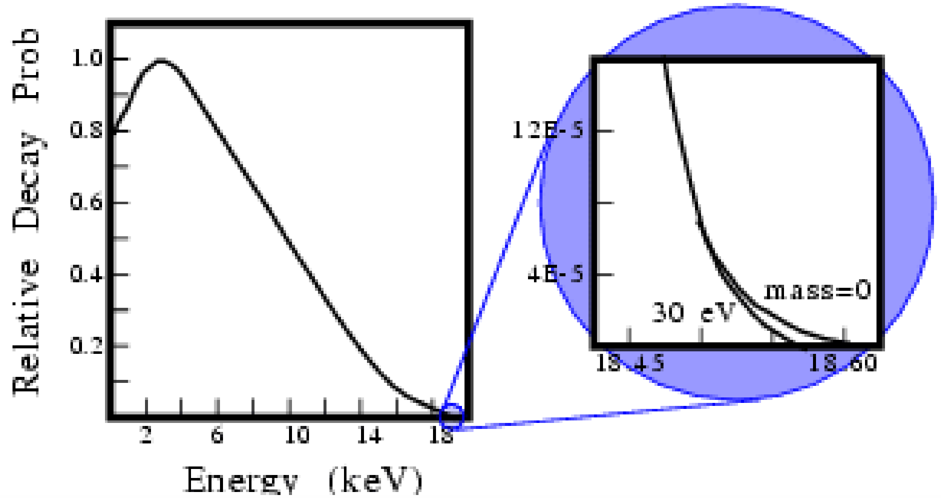
- Direct mass measurements are consistent with zero
- But we observe neutrino oscillations
- And flavor transitions in the Sun

From Direct Limits:



If neutrinos have Dirac masses,
it is small relative to the charged partners...
why?

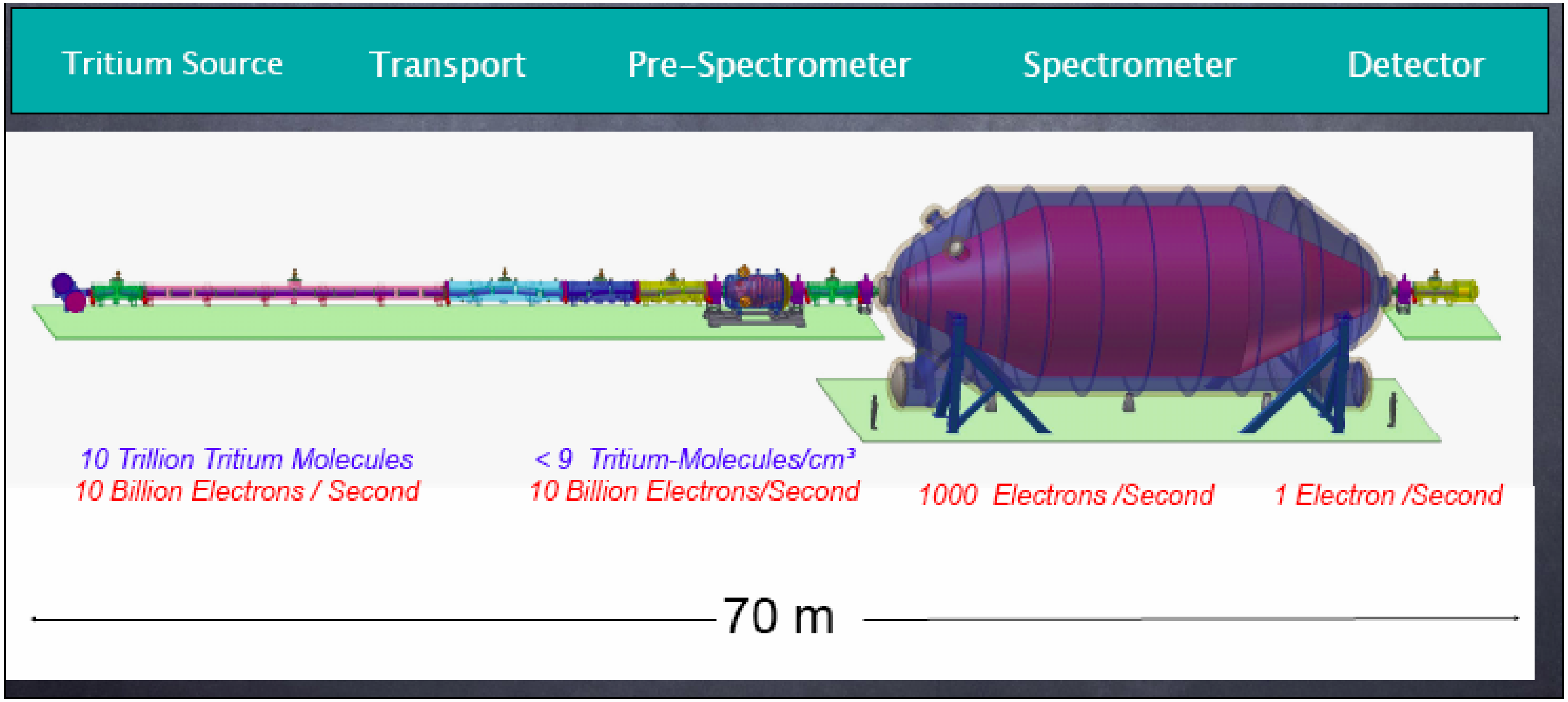
ν_e mass from Tritium



- Measurements of m^2 are systematically negative:

Experiment	measured mass squared (eV^2)	limit (eV), 95% C.L.	Year
Mainz	-0.6± 2.2± 2.1	2.2	2004
Mainz	-0.1± 3.8± 1.8	2.8	1998
Troitsk	-2.1 ± 3.7± 2.3	2.5	1998
Livermore	- 130± 20± 15	7.0	1995
China	- 31± 75± 48	12.4	1995
Zrich	-24± 48± 61	11.7	1992
Tokyo INS	- 65± 85± 65	13.1	1991
Los Alamos	- 147± 68± 41	9.3	1991

The future of this type of experiment is Katrin:

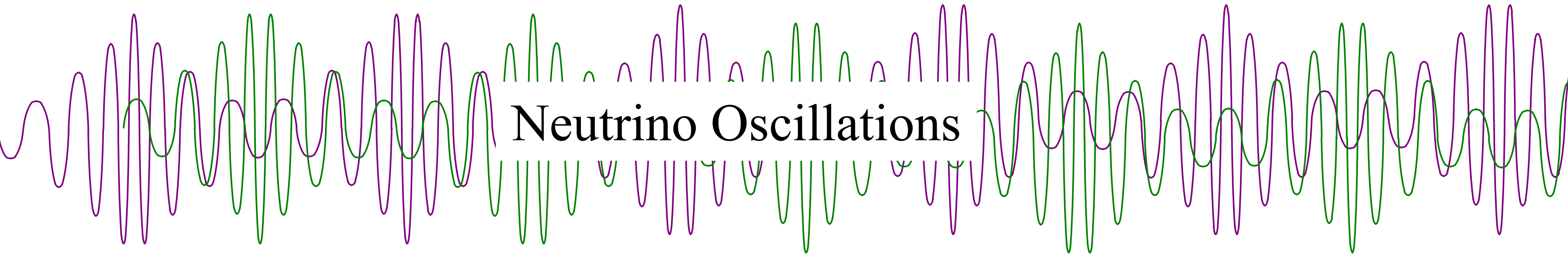


Probes to $m_\nu < 0.25$ eV @90% CL

- improved statistics (stronger source, longer running)
- improved resolution (electrostatic spectrometer with $\Delta E = 1$ eV)
- background reduction (materials choices, veto)

(Info on experiments in this talk taken from websites linked off http://neutrinooscillation.org/)

But in the meantime...



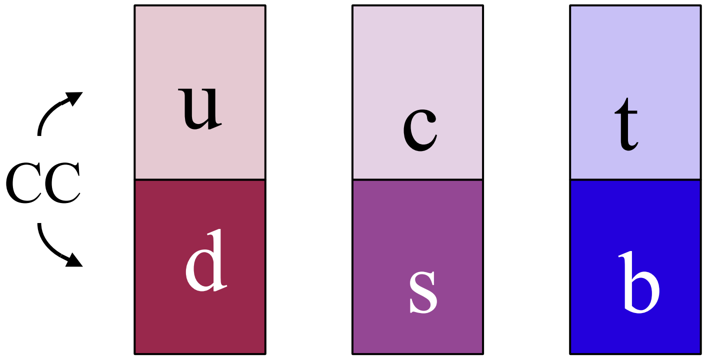
Which may result if we postulate:

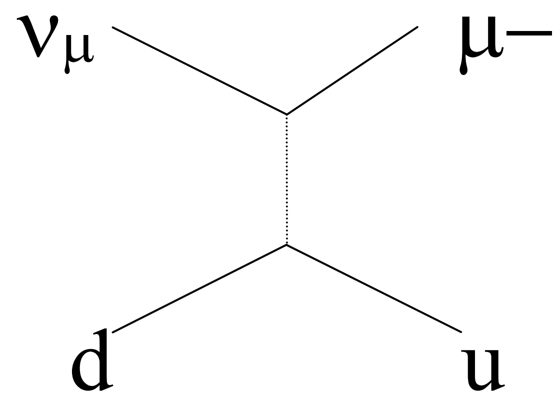
- Neutrinos have (different) mass

  $\Rightarrow \Delta m^2 = m_1^2 - m_2^2$

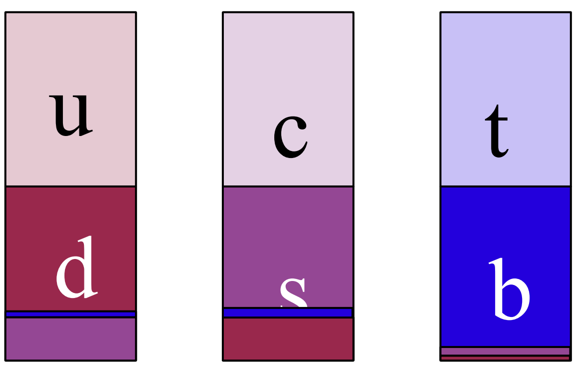
- The ***Weak Eigenstates*** are a mixture of ***Mass Eigenstates*** in analogy with the quark sector...

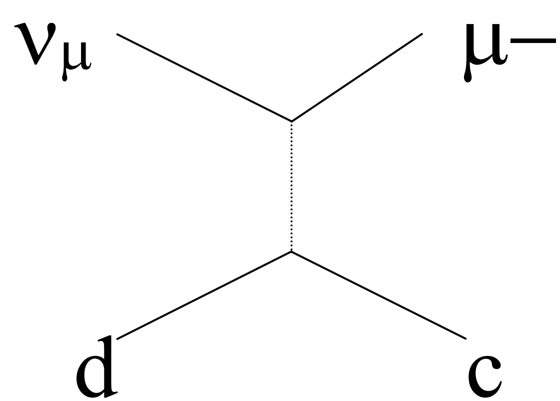
Quarks in theory....





Quarks in practice....





Assume mixing can also happen in the neutrino sector

Take the mixing matrix to be:

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

At production (t=0): $|\nu_\mu(0)\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$

At a later time, with $\hbar = c = 1$:

$$\begin{aligned} |\nu_\mu(t)\rangle &= -\sin\theta e^{-iE_1t}|\nu_1\rangle + \cos\theta e^{-iE_2t}|\nu_2\rangle \\ &= (\cos^2\theta e^{-iE_1t} + \sin^2\theta e^{-iE_2t})|\nu_\mu\rangle + \\ &\qquad \sin\theta\cos\theta(e^{-iE_2t} - e^{-iE_1t})|\nu_e\rangle \end{aligned}$$

And the probability is:

$$\begin{aligned} P_{osc} &= |\langle\nu_e|\nu_\mu(t)\rangle|^2 \\ &= \frac{1}{2}\sin^2 2\theta\,(1 - \cos\,(E_2 - E_1)\,t) \end{aligned}$$

Use $E_i = \sqrt{p^2 + m_i^2} \approx p + m_i^2/2p$ and $t/p = (tc)/(pc) = L/E$; then convert units by adding $1/\hbar c$:

$$\begin{aligned} P_{osc} &= \frac{1}{2}\sin^2 2\theta \left(1 - \cos\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)\right) \\ &= \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E) \end{aligned}$$

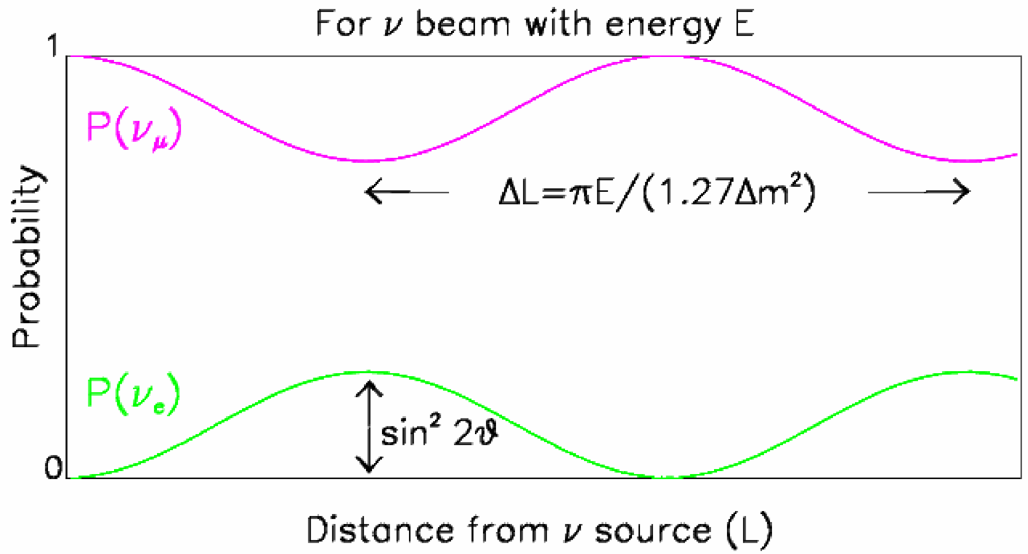
$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$

...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

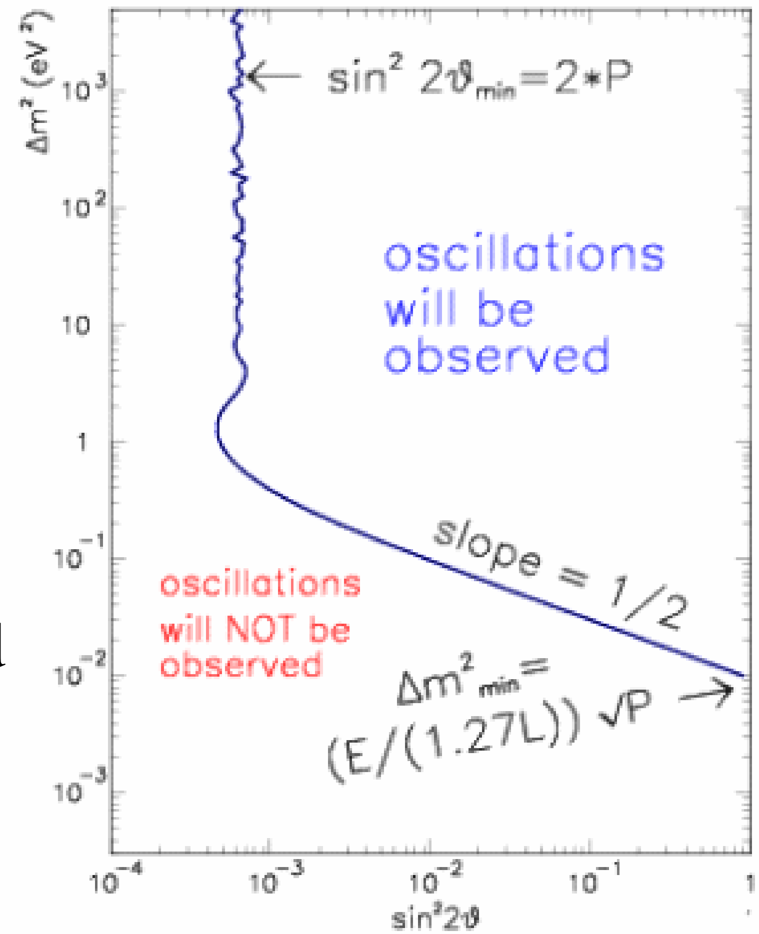
$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$

at high Δm^2,
$\langle \sin^2(1.27\Delta m^2 L/E)\rangle = 1/2$

1 measurement and 2 parameters...

Allowed regions will look like "blobs"

Exclusions by experiments with no signal are indicated by lines...



At low Δm^2 use the small angle approx.

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

How to design your experiment...

if Δm^2 is small, you need large L/E

if Δm^2 is large, you want relatively small L/E to have sensitivity to Δm^2

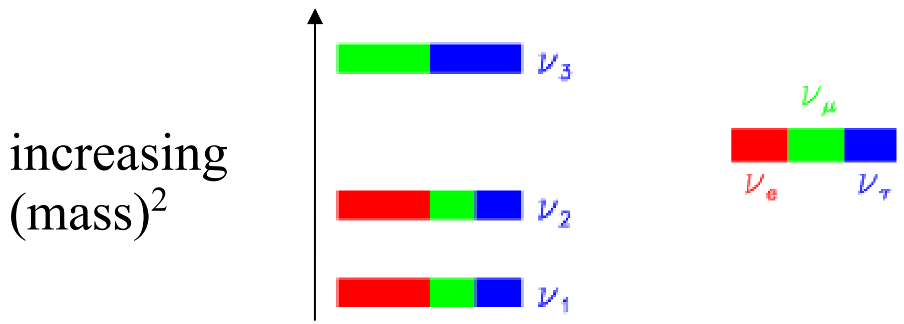
A value of $(\Delta m^2 L/E) \sim 1$ is preferable.

if θ is small, P is small & life is very hard

This is a simplistic view....

There are 3 neutrinos, so...

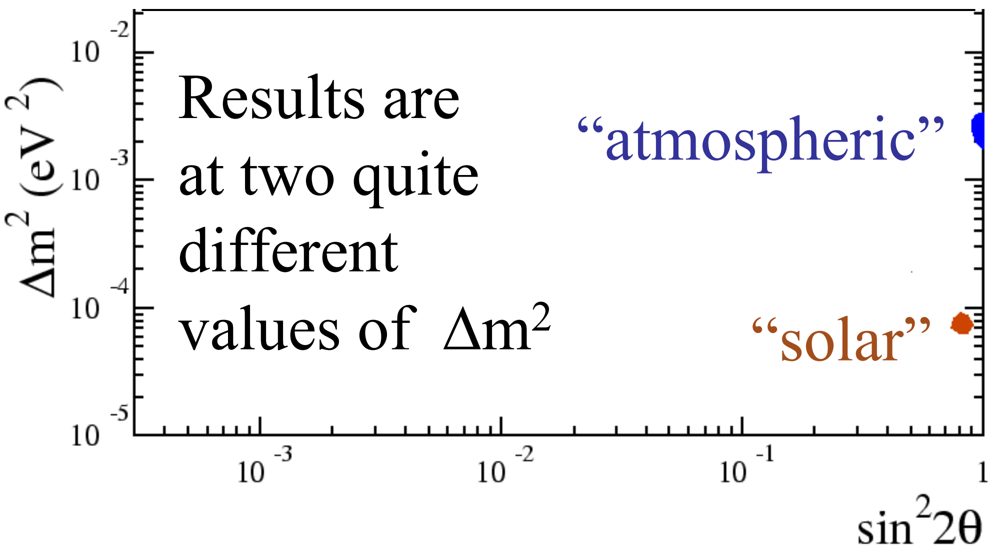
there are 3 mass states and 3 weak states
and three mixing angles θ_{12}, θ_{13} and θ_{23}



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

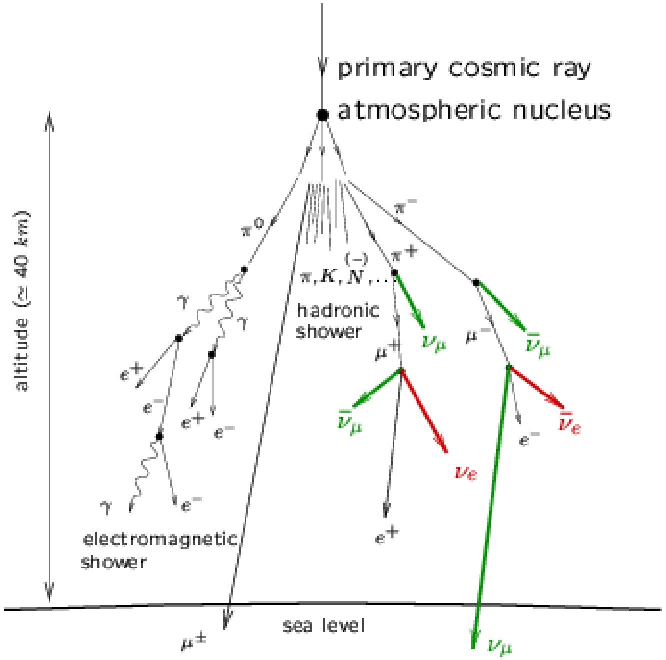
Evidence for neutrino oscillations is now very strong...

High significance experiments (many >5σ)
Experiments have differing systematics



“Atmospheric” >5σ Experiment: Super K

Also:
IMB,
Kamioka
MACRO



Below 1 GeV, simple counting gives 1:2 $\nu_e:\nu_\mu$

Above 1 GeV, ratio gradually goes to 1:1 because

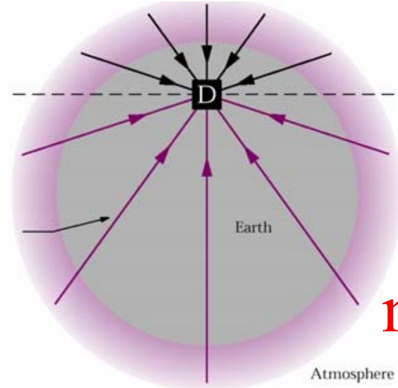
μ's do not have opportunity to decay

Average path length d of a 1 GeV muon:

$$\begin{cases} \gamma\beta \simeq \gamma = E/m \sim 10 \\ c\tau \sim 600\ m \end{cases} \Rightarrow d = \gamma\beta c\tau \sim 6\ km$$

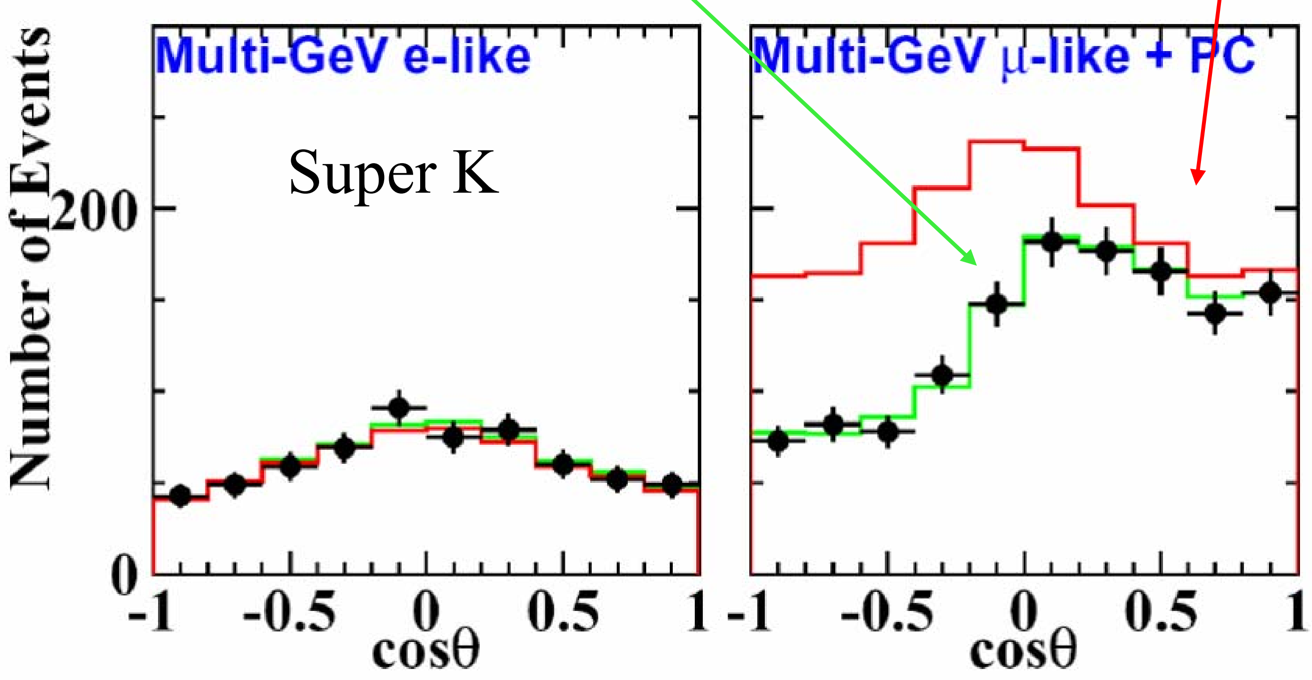
length dependence in ν_μ oscillation probability

consistent with ν_μ disappearance



no oscillations

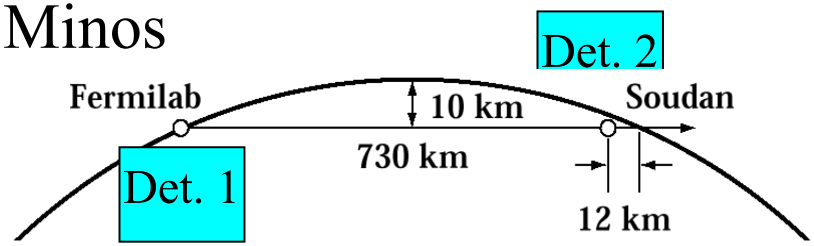
$\nu_\mu \rightarrow \nu_\tau$ oscillations



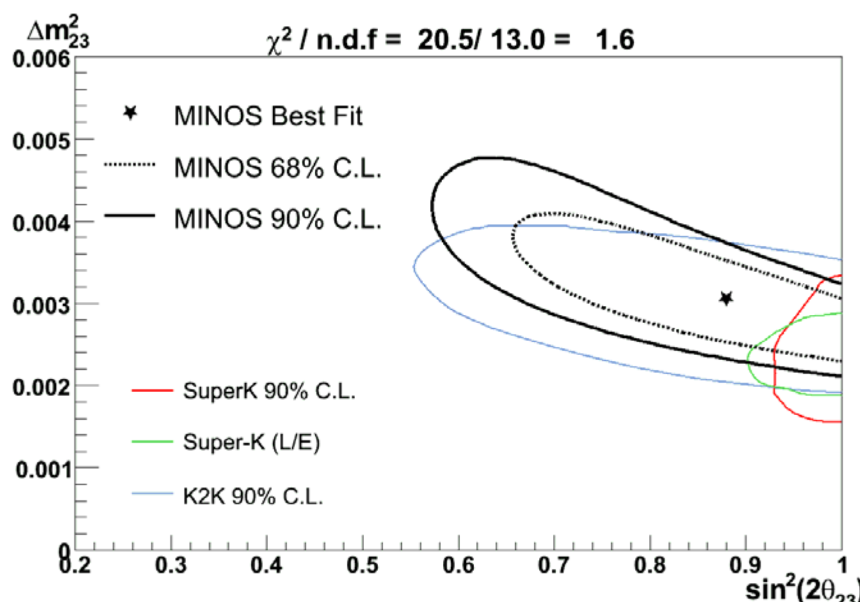
K2K and Minos are Long-baseline beam experiments running at L/E appropriate for $\Delta m^2 \sim 10^{-3}$

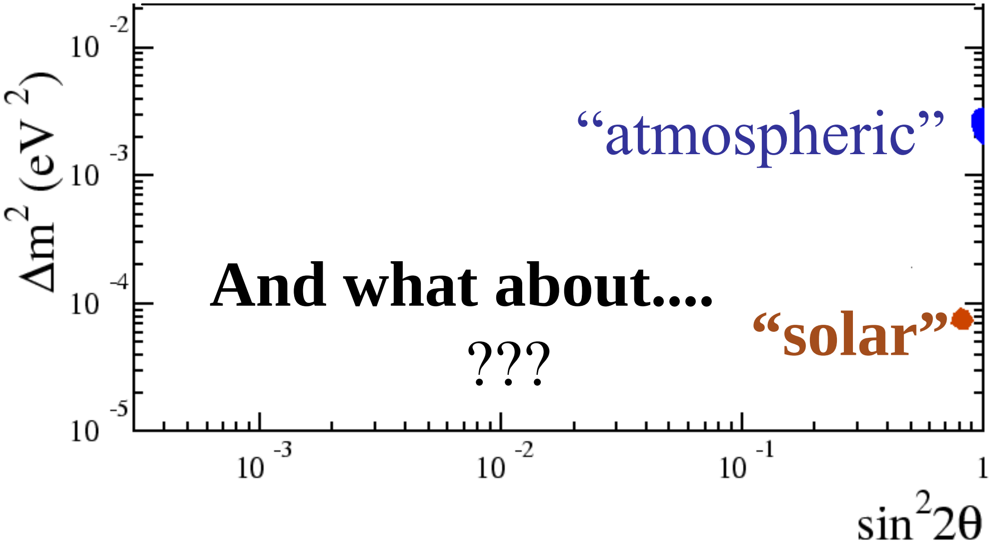
$E_\nu \sim 5$ GeV

Minos



Minos is just bringing out results now!





If what was happening with solar neutrinos was <u>pure neutrino oscillations</u>...

$L \sim 1.5 \times 10^{11}$ m
$E \sim 5$ MeV

To be sensitive to oscillations $(\Delta m^2 L/E) \sim 1$

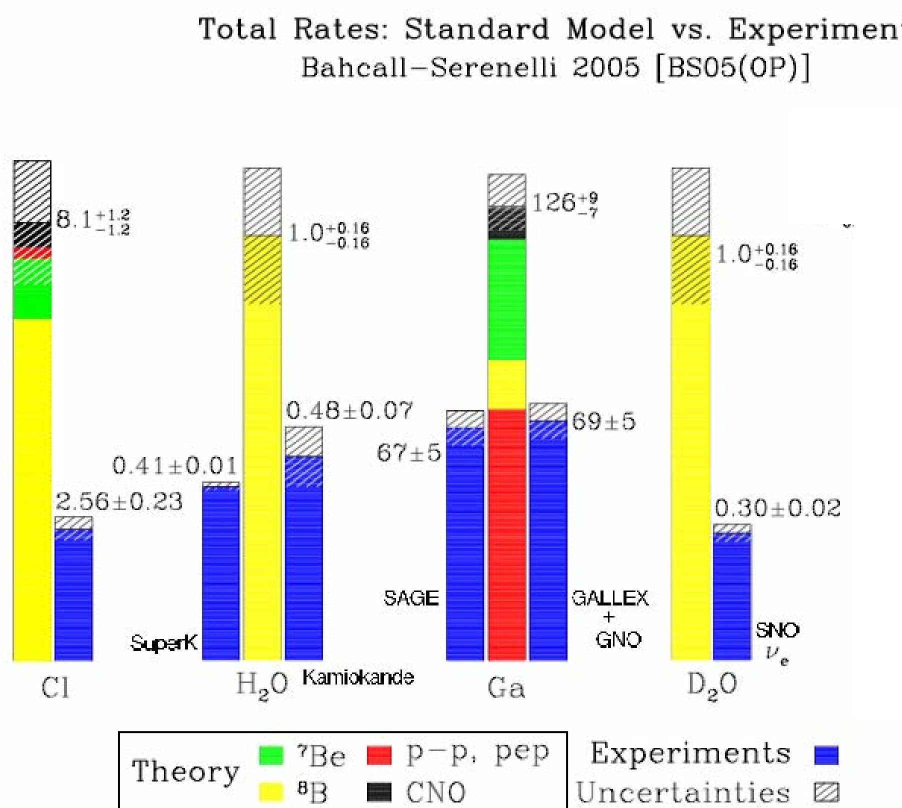
This would imply $\Delta m^2 \sim 3 \times 10^{-10}$ eV^2

But solar experiments **<u>do</u>** see flavor changing effects!

Suppression in the solar neutrino rate is now well established...

But it isn't pure oscillations!

These experiments are all sensitive to ν_e CC interactions

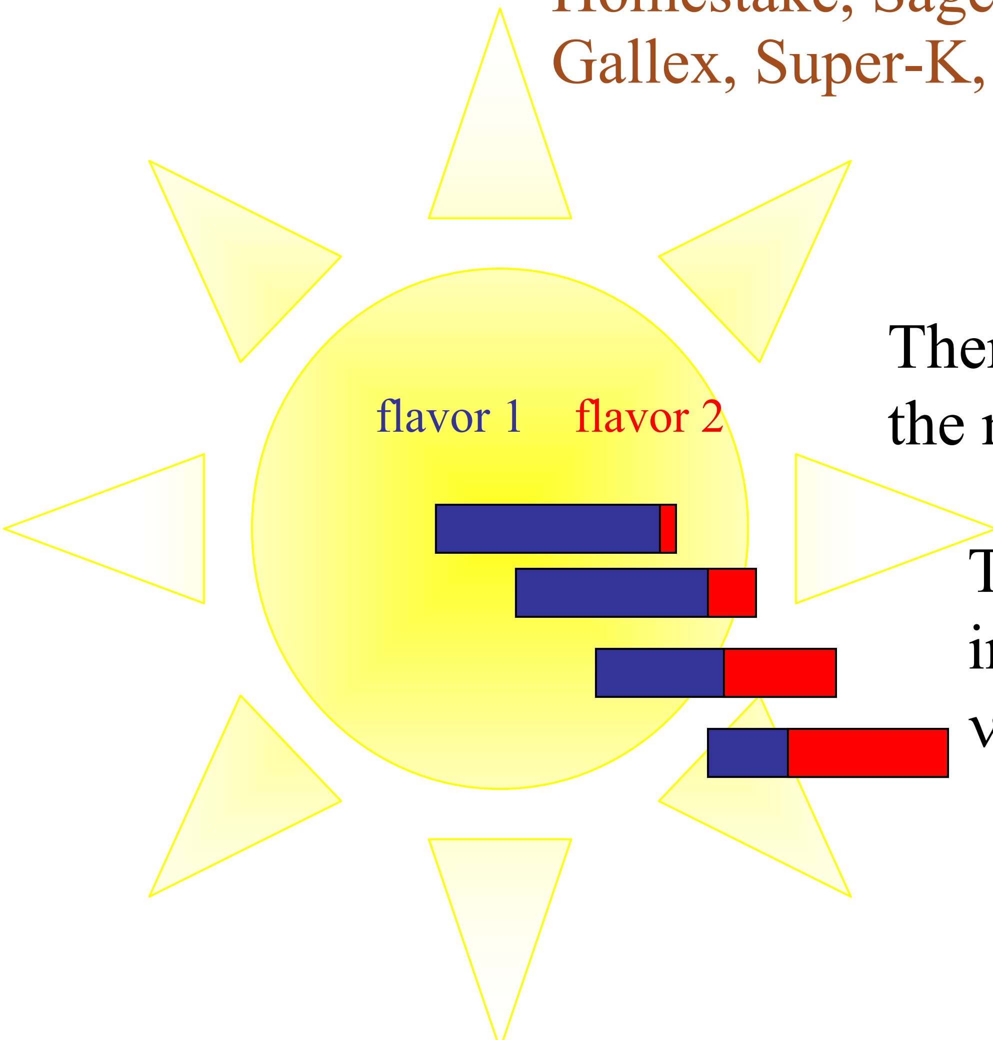


solar processes

Something extra is happening to neutrinos in the sun!
Matter effects....

Homestake, Sage, Gallex, Super-K, SNO

"The LMA MSW solution"

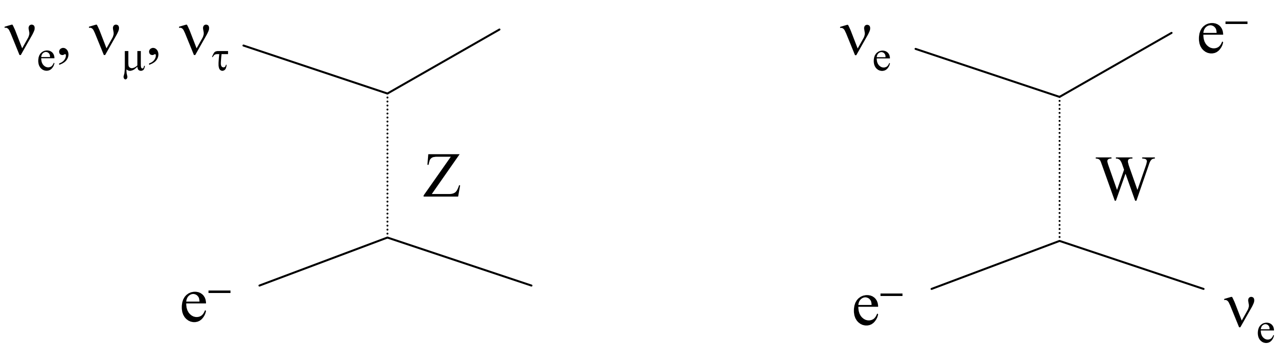


There is flavor evolution as the neutrinos traverse the sun.

The result is disappearance in detectors sensitive to only ν_e flavors...

Matter effects will occur
whenever one type of neutrino can interact in ways
the other “types in the mix” cannot...

In the case of ν_e’s in the plasma of the sun,
this is because the CC interaction
for μ and τ are kinematically suppressed...



How can we be sure the Solar suppression is due to neutrinos?
Maybe something is wrong with the solar model...

Sudbury Neutrino Observatory (SNO) can measure the solar flux regardless of the neutrino species:

$$\nu_{sol}\, d \rightarrow \nu\, n\, p \;\Rightarrow\; \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$

SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (4.94 \pm 0.21 \pm 0.36) \times 10^6/\text{cm}^2\text{sec}$

Theory: $\phi_{total} = (5.69 \pm 0.91) \times 10^6/\text{cm}^2\text{sec}$

Bahcall, Basu, Serenelli

You see disappearance in experiments sensitive to CC
But not in experiments sensitive to NC!

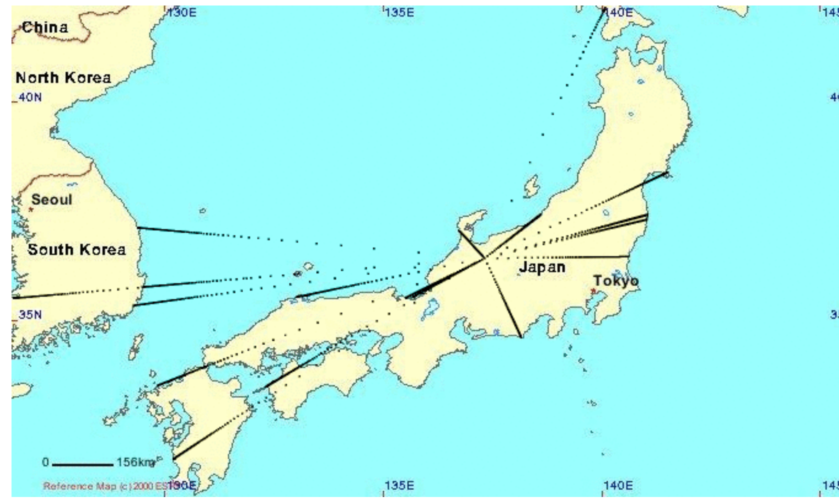
Ok, what's happening in the sun is not "pure oscillations,"
but if you go to the L/E on earth,
corresponding to the solar parameters
you ought to see oscillations...

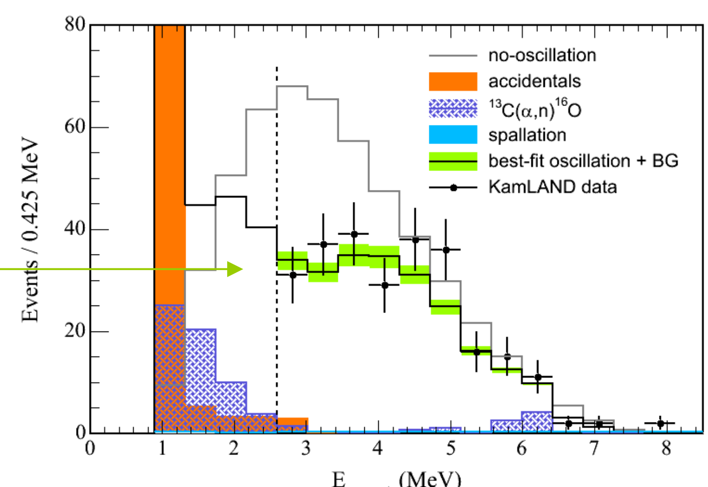
$\Delta m^2 \sim 10^{-5}$ eV^2, large mixing

You can see this if you have....
L~100 km
E~ 0.001 GeV

... The Kamland experiment

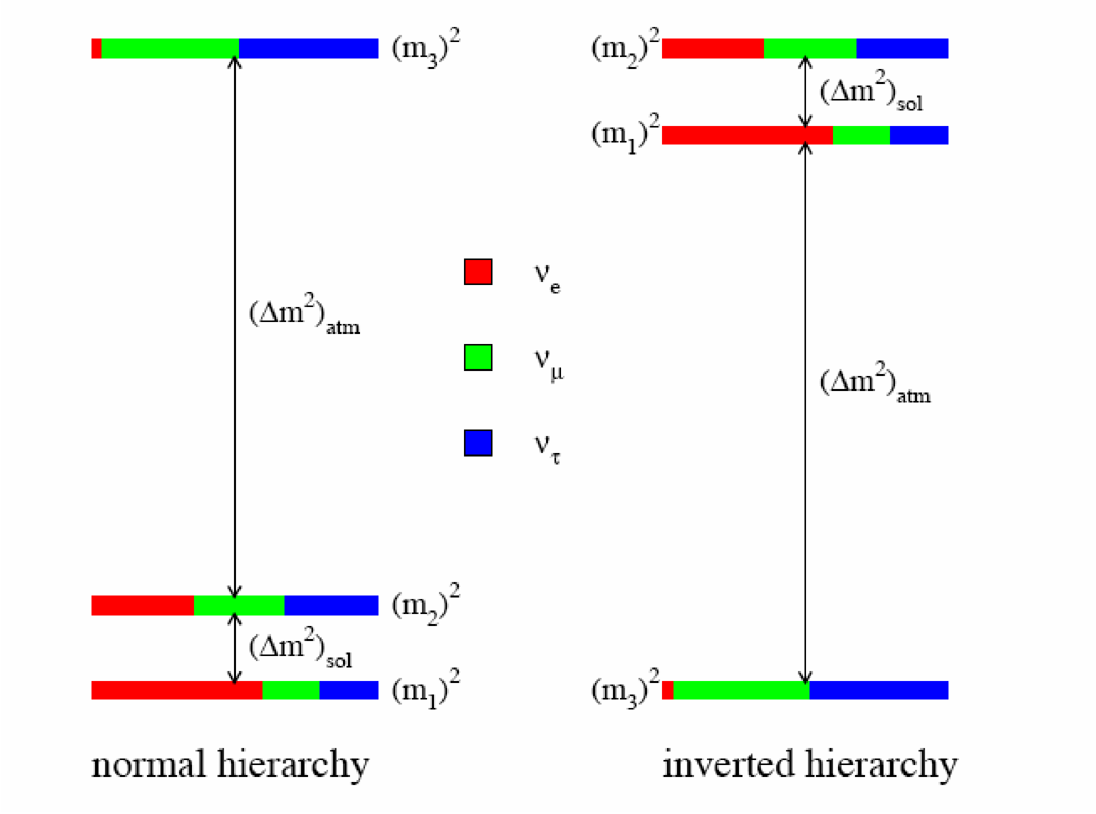
A clear signal at the solar parameters!





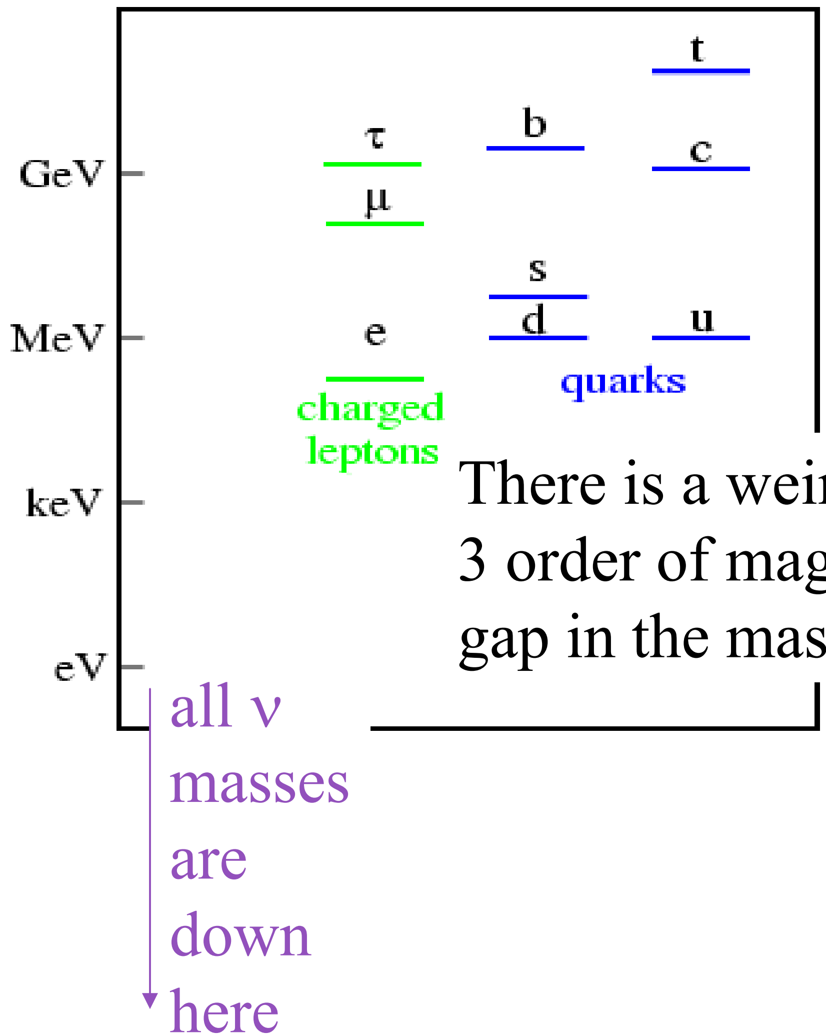
(There are other oscillation results, but let's stick at those which are 5σ for now...)

What can we conclude?
Two possible successful 3 neutrino mixing models:



The combination of the tritium and the oscillation experiments constrains all ν masses to be small

This plot should show ν_1, ν_2, and ν_3 not ν_e, ν_μ, and ν_τ



There is a weird 3 order of magnitude gap in the masses

These results confounded all theoretical expectations!
In the mid-1990's:

- Neutrinos don't have mass... **Wrong**
- But if they did, then **Wrong**
  natural scale for $\Delta m^2 \sim 10 - 100\ eV^2$
  since needed to explain dark matter
- Oscillation mixing angles must be small **Wrong**
  like the quark mixing angles
- Solar neutrino oscillations must be **Wrong**
  small mixing angle MSW solution
  because it is "elegant"
- Atmospheric neutrino anomaly must be **Wrong**
  other physics or experimental problem
  because it needs such a large mixing angle

Let’s face it...
Nature isn’t elegant...

Let’s face it...
Nature isn’t elegant...

... or maybe we just don’t have the
right taste!

Neutrinos and the “New Paradigm”:

The last of the mid-90’s ideals

The defining assumption: Neutrinos are Majorana Particles

ν and $\bar{\nu}$ are the two helicities of the same particle...

Why?

This would explain 100% parity violation OK!

"if it can happen it will happen" ummmm...

This makes neutrinos "even more different" then the other particles in the Standard Model

The result is new "mass-like" terms in the Lagrangian

- ▹ Dirac Mass terms like $m(\bar{\psi}_L \psi_R + ...)$
- ▹ and things which look like:
  $(M_L/2)(\bar{\psi}^c{}_L \psi_L) + (M_R/2)(\bar{\psi}^c{}_R \psi_R) + ...$
  "Majorana mass terms"

To improve notation, use:

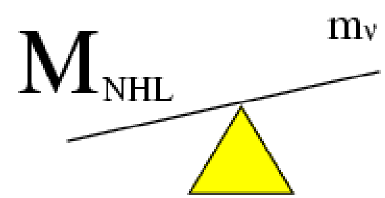
$$\phi = (\psi_L^c + \psi_L)/\sqrt{2} \text{ and } \Phi = (\psi_R^c + \psi_R)/\sqrt{2}$$

Which allows you to write the mass terms as

$$(\bar{\phi} \;\; \bar{\Phi}) \begin{pmatrix} M_L & m \\ m & M_R \end{pmatrix} \begin{pmatrix} \phi \\ \Phi \end{pmatrix}$$

Diagonalize this to get the physical mass states...

Now you can connect
to see-saw models,
that motivate mass matrices like...



$$\begin{pmatrix} 0 & m_\nu \\ m_\nu & M \end{pmatrix}$$

- $\mu_{light} \approx m_\nu^2/M$
- $\mu_{heavy} \approx M$

Three happy theoretical consequences:

1) You get a neutrino which is apparently very light,
even though m_ν ~ other lepton masses...
2) You get a natural connection to GUT models
3) There is a mechanism for leptogenesis

Experiments addressing this model:

1. Neutrinoless double beta decay

   The “clinching” signature for Majorana neutrinos

2. Precision measurements of the mixing angles

   “Selects” classes of models for the higher theory

3. Is there CP Violation?

   “A smoking gun” for Leptogenesis

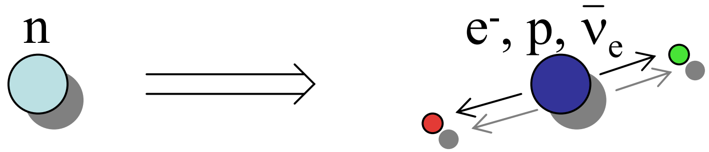
Experiments addressing this model:

1. Neutrinoless double beta decay

   The “clinching” signature for Majorana neutrinos

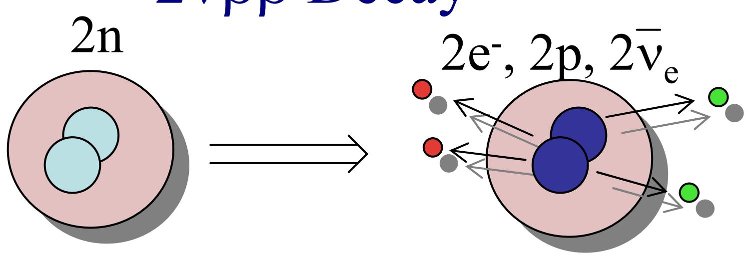
Double Beta Decay, 101

Single β Decay

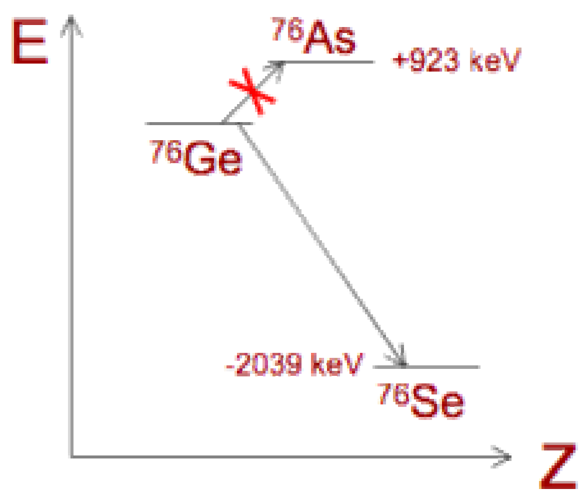


Half-life: About 10 minutes

2νββ Decay



Can occur if single β decay is energetically forbidden



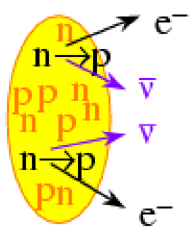
Half-life: $10^{18\text{-}24}$ years

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, ^{242}Pu

Neutrinoless Double Beta Decay

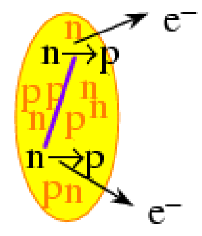
$$(Z,A) \rightarrow (Z+2,A) + (e\text{-}\ e\text{-}\ \cancel{\bar{\nu}_e\ \bar{\nu}_e})$$

Nuclei that do this...



2νββ

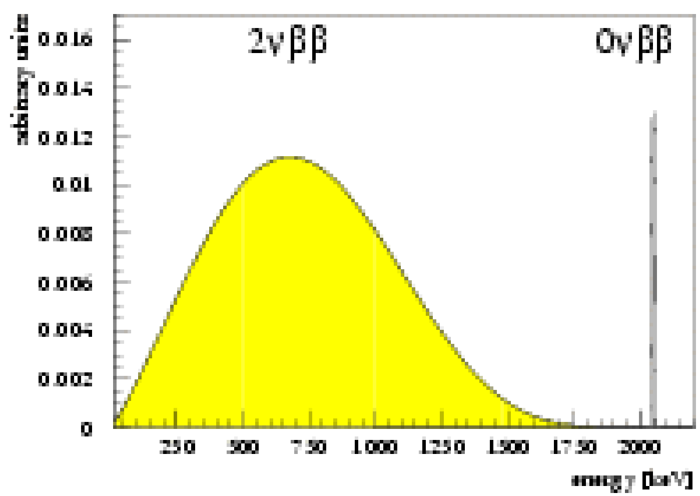
Can sometimes also do this



0νββ

IF neutrinos are their own antiparticles

The tell-tale signature is in the decay spectrum:



The lifetime for this process is given by:

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(E_o, Z)\left|M^{0\nu}\right|^2 \left|\langle m_{\nu,\beta\beta}\rangle\right|^2$$

The phase space factor (3×10^{-26}/y in Ge)

$$\left|M^{0\nu}\right|^2 = \left|M_{GT}^{0\nu} - \left(\frac{g_V}{g_A}\right)^2 M_F^{0\nu}\right|^2$$

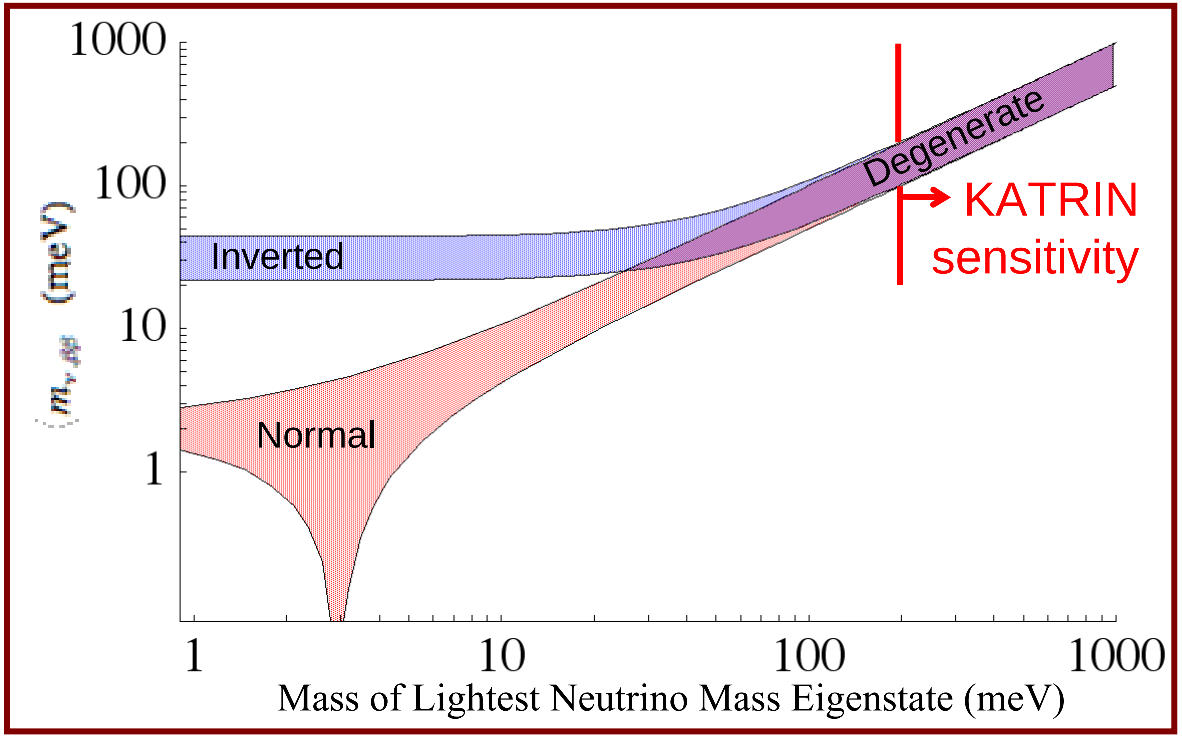
The nuclear matrix element, can be calculated at some level, can be measured from excited states of 2νββ

$$\left|\langle m_{\nu,\beta\beta}\rangle\right| = \left|\sum_i \lambda_i^{CP} m_i \left|U_{ei}^L\right|^2\right|$$

Weights the mass w/ the mixing (what's the contribution from the ν_e?)

$$\left|\left\langle m_{\nu,\beta\beta}\right\rangle\right| = \left|\sum_i \lambda_i^{CP} m_i \left|U_{ei}^L\right|^2\right|$$

This is a big deal for 0νββ experiments...



Bornschein, *Nucl. Phys. A* **752** (2005) 14c-23c.

Many experiments have not seen $0\nu\beta\beta$:

Most recently:

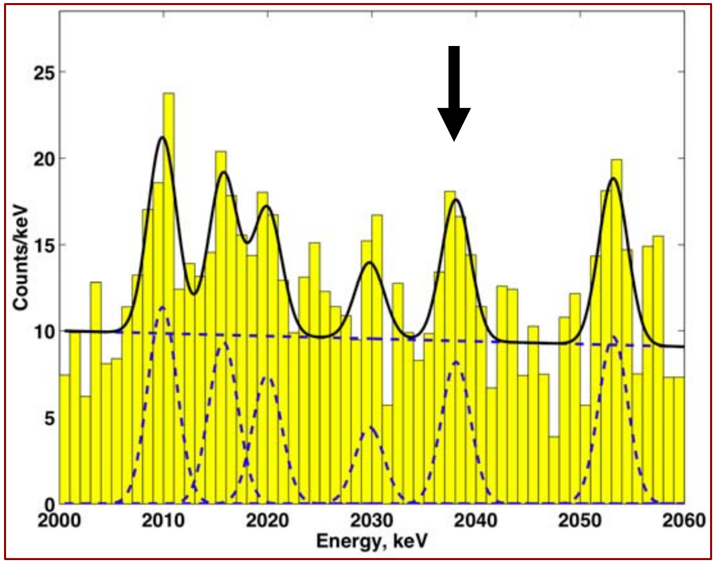
CUORICINO: $^{130}Te \geq 1.8\times10^{24}$ yr, *PRL* **95** 142501 (2005).

NEMO-3: $^{100}Mo \geq 3.5\times10^{23}$ yr, $^{82}Se \geq 1.9\times10^{23}$ yr, hep-ex/0412012.

One experiment claims a signal:

Klapdor-Kleingrothaus *et al.*,
hep-ph/0403018

Germanium
Half-life = 1.19×10^{25} years,
4.2σ result

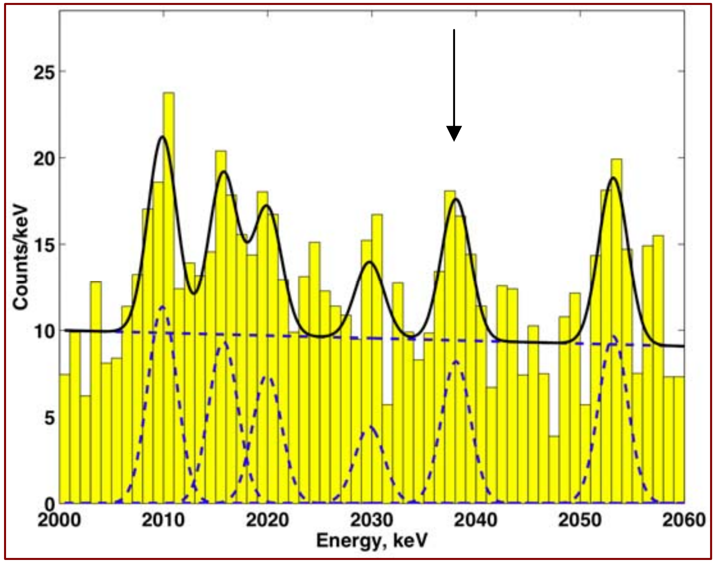


(Germanium is the only $0\nu\beta\beta$ "source" that is its own detector!)

Janet's opinions:

You know exactly where to look.
This is a blessing and a curse.

It is easy to make cuts that bias
the significance of the signal

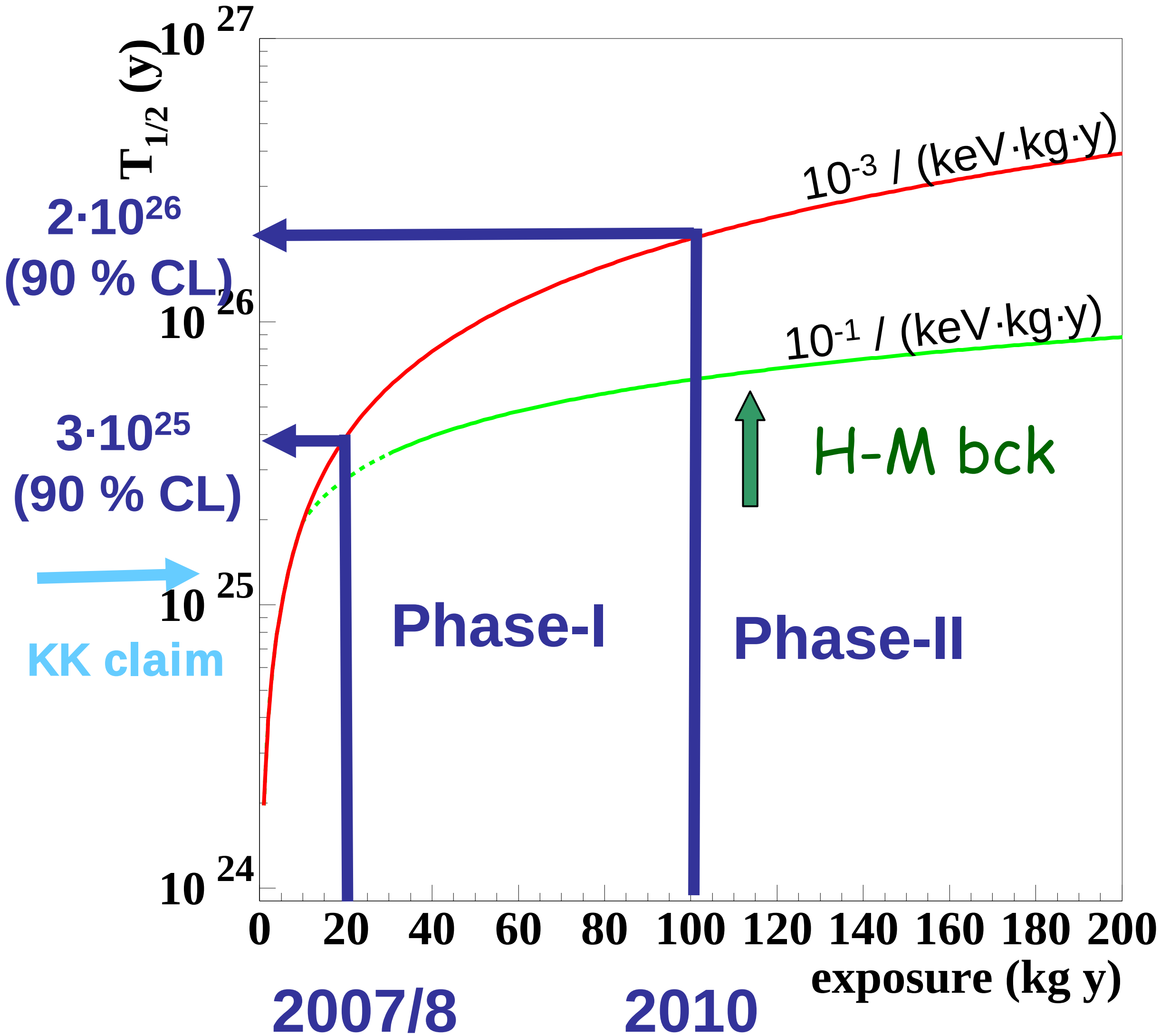


This is an experimental question...
And there are experiments planned to answer it.

GERDA and Majorana

Both use Germanium, like KK's experiment,
but with segmentation and other improvements

GERDA

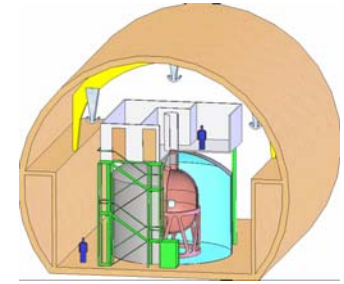


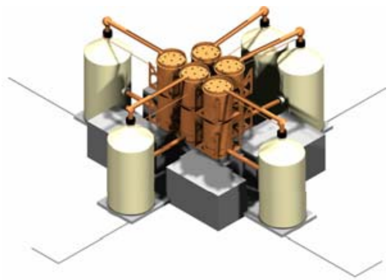
Phase I: existing detectors

Phase II: new detectors

Phase III: worldwide new collaboration O(ton) experiment → 10^{27} y.
Cooperation with Majorana

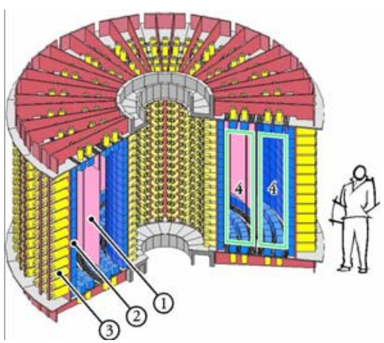
0νββ is a big industry for the future!

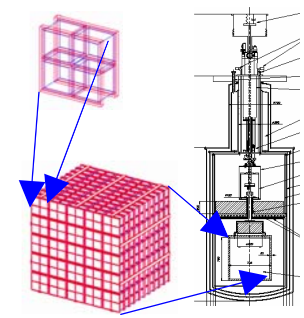




GERDA: Bare Ge crystals in LN

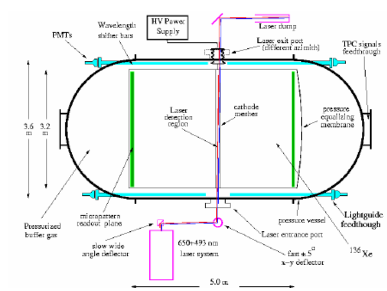
Majorana: Ge detector in a cryostat



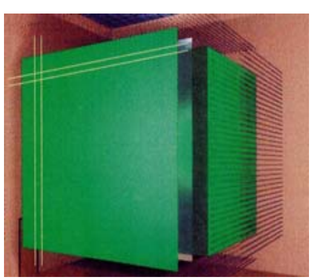


CUORE: TeO_2 crystal bolometer

SuperNemo: Many types of foils,
with tracking and scintillator



EXO: Liquid Xenon with Ba tagging



Moon: Mo foils sandwiched
between scintillator

Experiments addressing this model:

2. Precision measurements of the mixing angles

"Selects" classes of models for the higher theory

The MNS Matrix for neutrinos

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

Doesn’t look much like the CKM matrix for quarks...

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} 0.97 & 0.22 & 0.003 \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

At present-day energies

But *if* the values are related to the masses,
and the masses evolve with energy scale...
You can get quark-lepton “complementarity”

These theories generally want $\sin^2 2\theta_{13} \gtrsim 0.01$ and $\sin^2 2\theta_{23} < 1$

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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

Overview of expected values of $\sin^2 2\theta_{13}$

Model(s)	Refs.	$\sin^2 2\theta_{13}$
Minimal SO(10)	[22]	0.13
Orbifold SO(10)	[23]	0.04
SO(10) + Flavor symmetry	[24]	$1.2 \cdot 10^{-6}$
	[25]	$7.8 \cdot 10^{-4}$
	[26–28]	0.01 .. 0.04
	[29–31]	0.09 .. 0.18
SO(10) + Texture	[32]	$4 \cdot 10^{-4}$ .. 0.01
	[33]	0.04
$SU(2)_L \times SU(2)_R \times SU(4)_c$	[34]	0.09
Flavor symmetries	[35–37]	0
	[38–40]	$\lesssim 0.004$
	[41–43]	10^{-4} .. 0.02
	[40, 44–47]	0.04 .. 0.15
Textures	[48]	$4 \cdot 10^{-4}$ .. 0.01
	[49–52]	0.03 .. 0.15
3×2 see-saw	[53]	0.04
	[54] (n.h.)	0.02
	(i.h.)	$> 1.6 \cdot 10^{-4}$
Anarchy	[55]	> 0.04
Renormalization group enhancement	[56]	0.03 .. 0.04
M-Theory model	[57]	10^{-4}

Blue:
Wants a large value

Red:
Tolerates or favors small values

list is taken from hep-ex/0509019

In this section, I want to talk about

THIS

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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

In this section, I want to talk about

And then THIS

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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

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From Solar Neutrino Measurements

One mixing angle is not yet observed: θ_{13}

This governs the transition between ν_e and other species at the atmospheric Δm^2

A very clean measurement comes from ν_e flavor disappearance and a very clean $\bar{\nu}_e$ beam comes from a reactor

$$P_{reactor} \simeq \sin^2 2\theta_{13} \sin^2 \Delta + \alpha^2 \Delta^2 \cos^4 \theta_{13} \sin^2 2\theta_{12},$$

$$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{23}$$

$$\Delta \equiv \Delta m^2_{31} L / (4E_\nu).$$

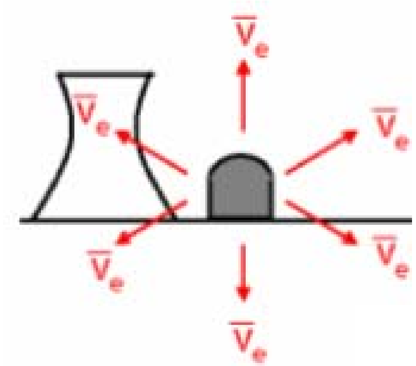
One mixing angle is not yet observed: θ_{13}

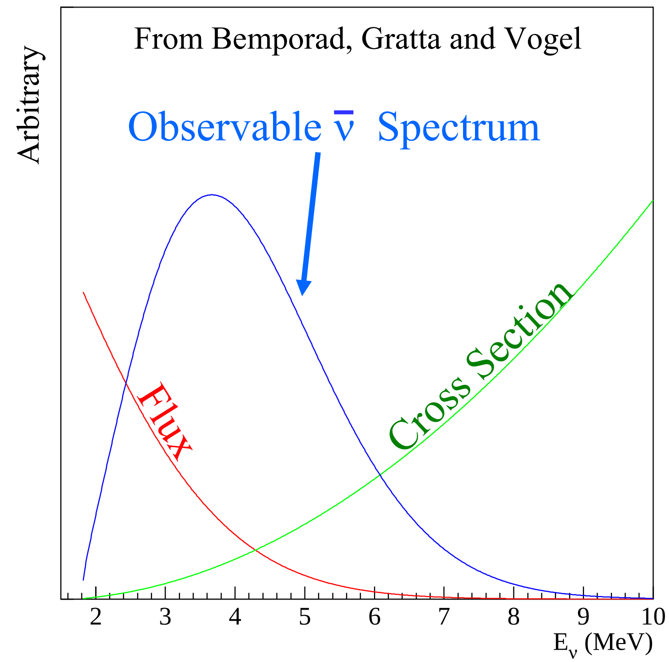
This governs the transition between ν_e and other species at the atmospheric Δm^2

There are 2 types of experiments used for these studies:

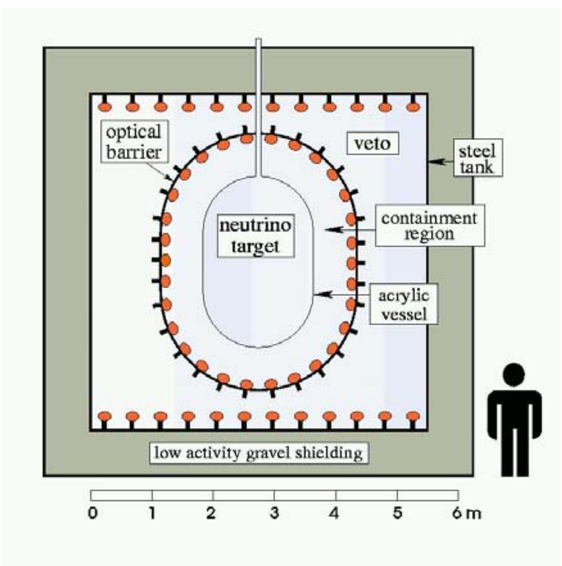
1. Reactor-based experiments
2. Long Baseline Experiments

Reactors: Disappearance ($\bar{\nu}_e \to \bar{\nu}_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2





for Δm^2 L/E ~ 1
you need L ~ 1000 m



A nice method for observing the $\bar{\nu}$:

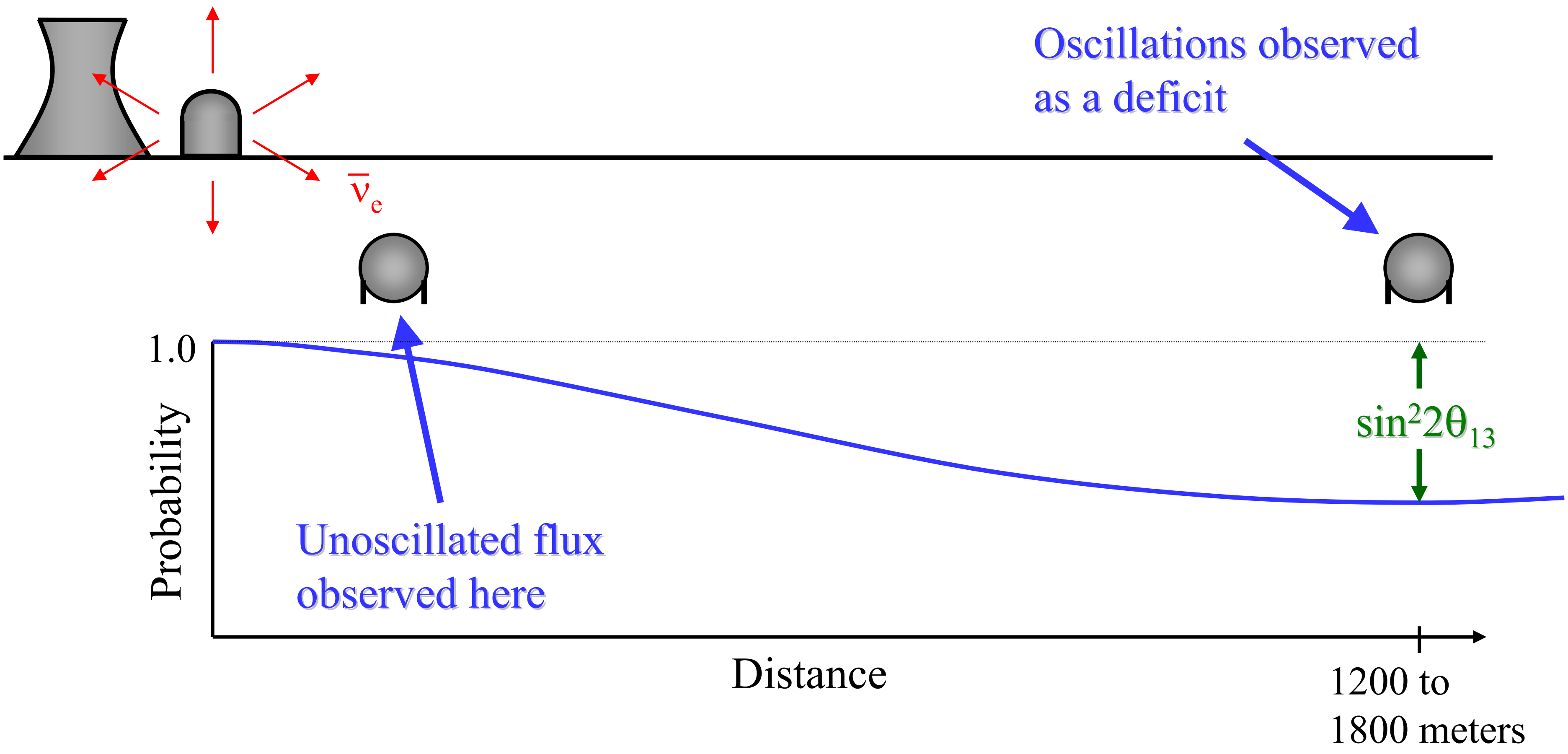
$\bar{\nu} + p \to e^+ + n$ (then n captures)

Use Gd-doped Scintillator oil detectors

Ways to improve:

- near and far detectors
- ability to switch detectors
- better shielding from cosmic rays

the art is in control of the systematics



Janet's opinion:

Knowing if $\sin^2 2\theta_{13}$>1% at 3σ is important physics

This is a very difficult measurement.

You simply cannot skimp on the systematic checks.

Reactor experiments have a bad reputation for false signals!

The one experiment that could reach this level, Braidwood,
was regarded by DOE as too expensive ($60M)

This leaves two other lesser reactor experiments:

- Double Chooz which reaches $\sin^2 2\theta_{13}$>2.5% at 90% CL

  (Purposely designed to cover ~1/3 of the models
  speedily and inexpensively: if "yes" get it quick!)

- Daya Bay, which may reach $\sin^2 2\theta_{13}$>0.9% at 90% CL

  (But has no demonstrated design for this goal yet)

So if we can't get at θ_{13} via reactors, what can we do?

It can be measured in accelerator-based $\nu_\mu \to \nu_e$ long-baseline experiments:

$$P_{long-baseline} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta$$
$$+ \alpha \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin^2\Delta$$
$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\Delta$$

$$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{23}$$
$$\Delta \equiv \Delta m^2_{31} L/(4E_\nu).$$

But the situation is clearly messy!

Remember: you are trying to measure P<0.01!

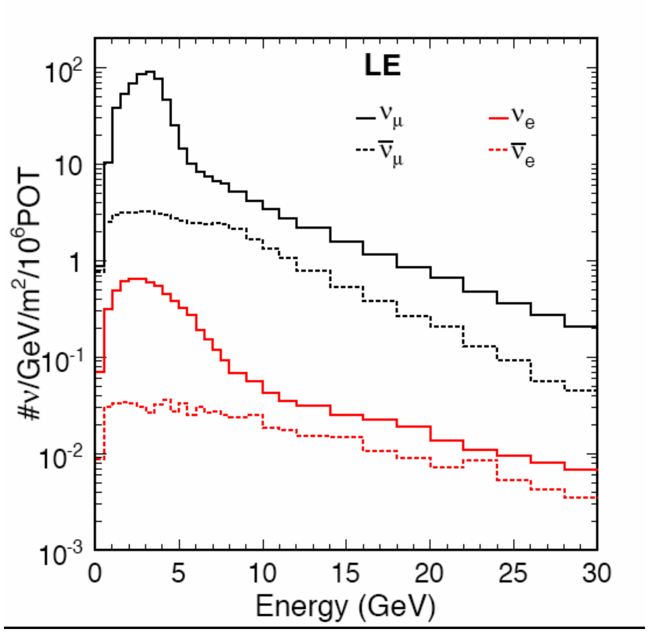
Problem 1: The typical wide-band LB beam...

Has a lot of ν_e contamination

Kaon decays

Muon decays

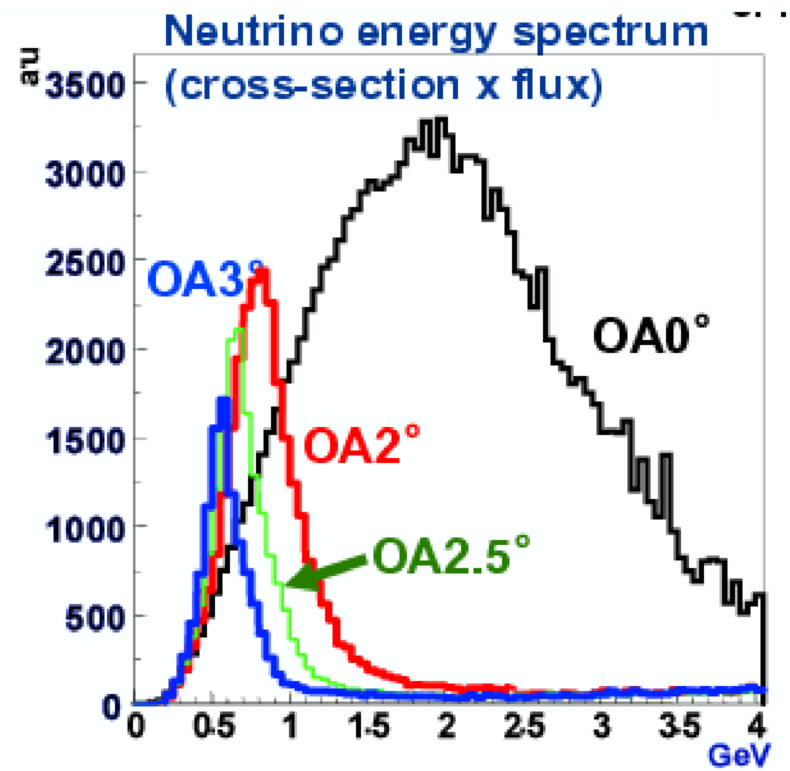
Has a high energy tail that leads to high rates of π^0 production $\Rightarrow$ mis-ids



Going “off axis” makes the ν_μ beam monoenergetic
-- easier to pick out signal from background --
but less intense!

Approved Dec, 2003
Expected to run: 2009

Plan is to use a 2.5° off-axis beam
& the existing Super K detector



Problem 2: Knowing θ_{23}...

Not squared.

$$P_{long-baseline} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta$$
$$+ \alpha \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin^2\Delta$$
$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2\Delta$$

angle not multiplied by two

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$$
$$\Delta \equiv \Delta m^2_{31} L/(4E_\nu).$$

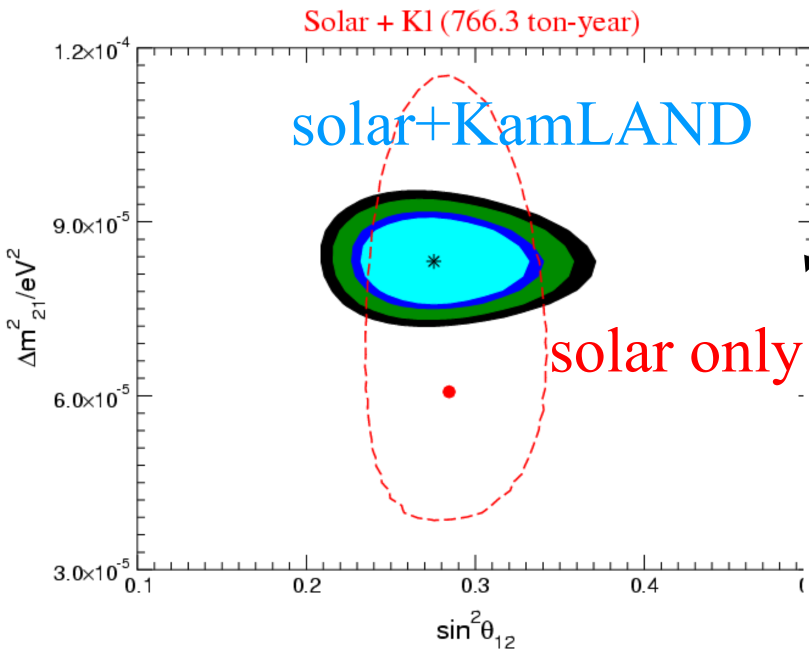
θ_{23} -- Minos will measure d($\sin^2 2\theta_{23}$)~5% (6 years)

T2K will measure d($\sin^2 2\theta_{23}$)~1% (3+5 years)

but you cannot tell if θ_{23}>45° or <45° !!! -- it's degenerate

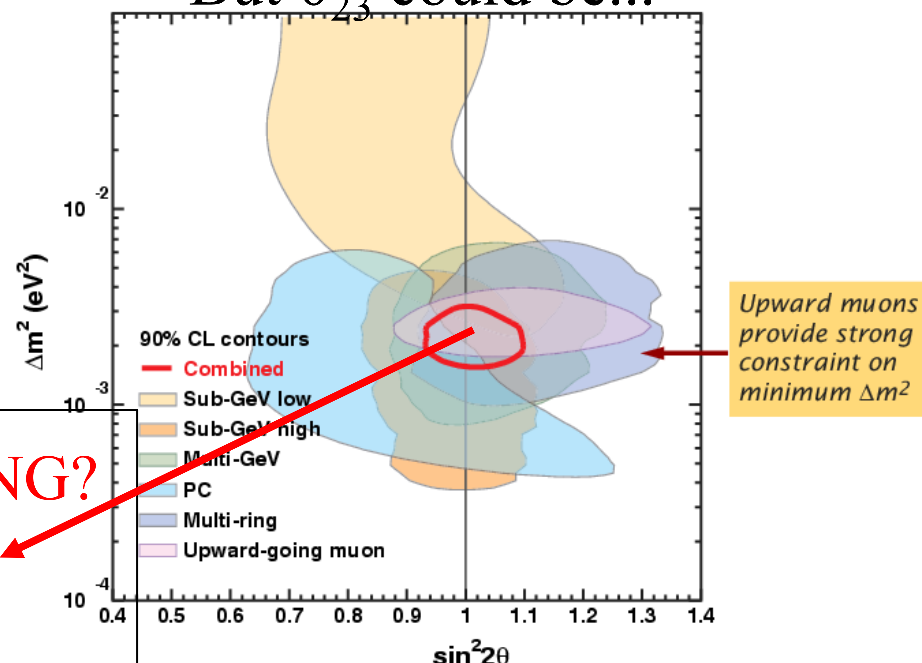
θ_{23} is interesting in and of itself...

<u>None</u> of the "well–measured" angles in the quark sector & the one "well measured angle" in the neutrino sector, <u>are "maximal"</u>



max

But θ_{23} could be...



Implications of MAXIMAL MIXING?

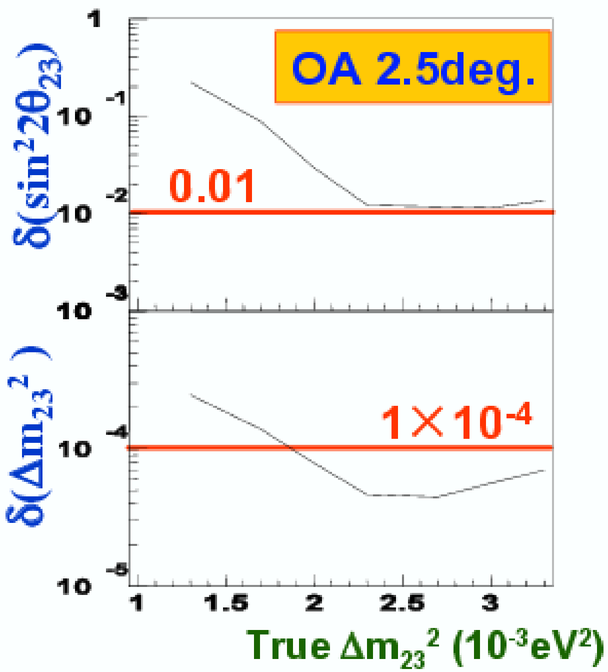
A new symmetry group connecting the μ and τ

max

Problem 3: the precise value of Δm^2_{23}

what can be achieved at T2K (3+5yrs)

ν_μ disappearance

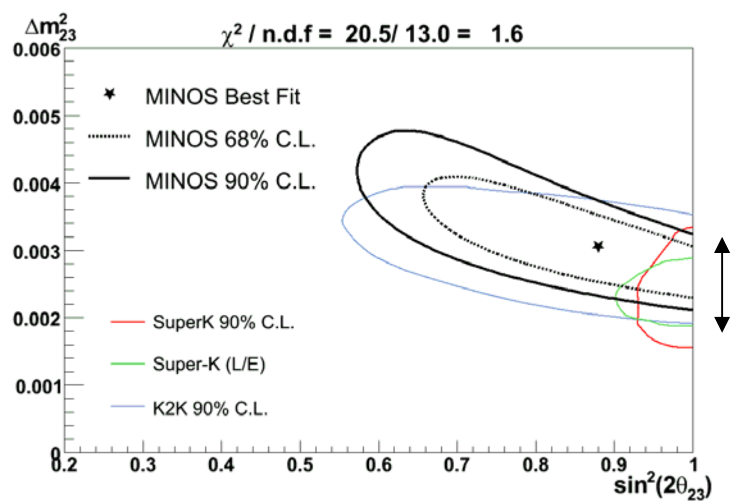


$\delta(\sin^2 2\theta)$ ~0.01

$\delta(\Delta m^2)$ $<1\times10^{-4}(\mathrm{eV}^2)$

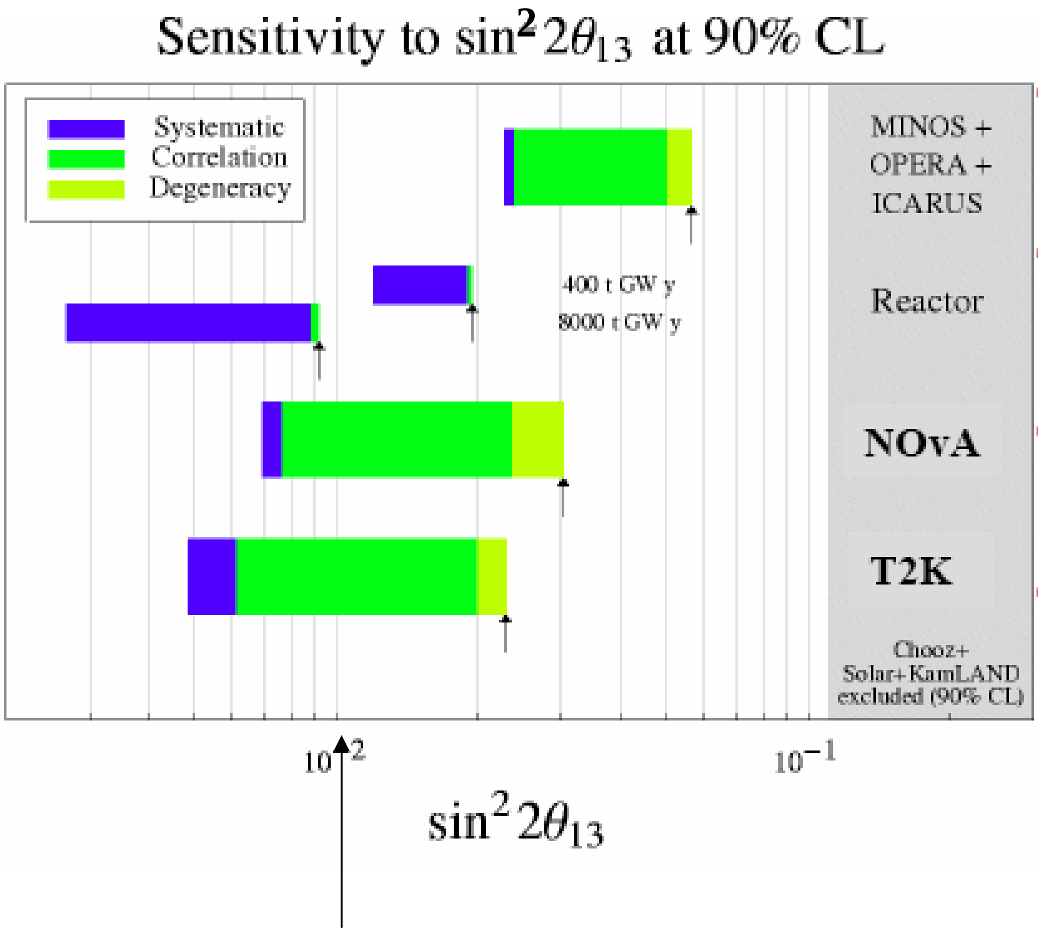
$$P_{long-baseline} \simeq \sin^2 2\theta_{13}\,\sin^2\theta_{23}\sin^2\Delta$$
$$+\ \alpha\ \sin 2\theta_{13}\ \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos\Delta\sin^2\Delta$$
$$+\ \alpha^2\ \cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta$$

$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{23}$$
$$\Delta \equiv \Delta m^2_{31}L/(4E_\nu).$$



shrinks by ×10

Manfred's summary of what you can expect



coming long baseline experiments

1 reactor +2 detectors

next generation long baseline experiments

Compare:

- **5 years each**
- **5% flux uncertainty**

The combination is unlikely to get you 3σ if the right value is here... That's a worry.

Experiments addressing this model:

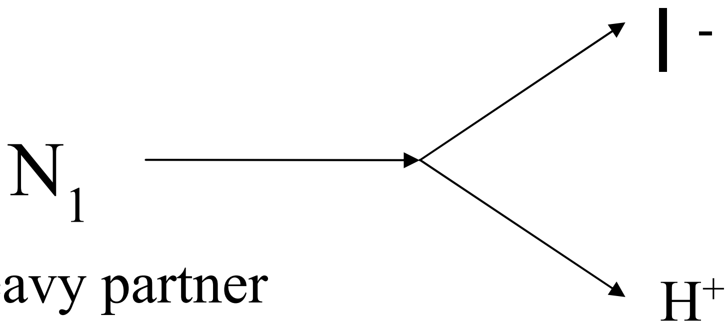
3. Is there CP Violation?

"A smoking gun" for Leptogenesis

The idea:

Before the electroweak phase transition...

These are massless:

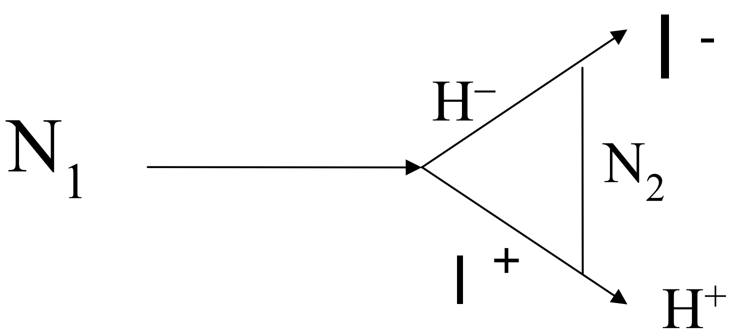


a heavy partner to the ν (getting mass from the Majorana term)

Interference between these two types of diagrams can lead to a different rate of decay to particles than antiparticles

→ **CP Violation**

"Leptogenesis"



Today,
we cannot study the N's
but we can study the ν's...

Putting CP violation into the light neutrino Mixing Matrix:

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

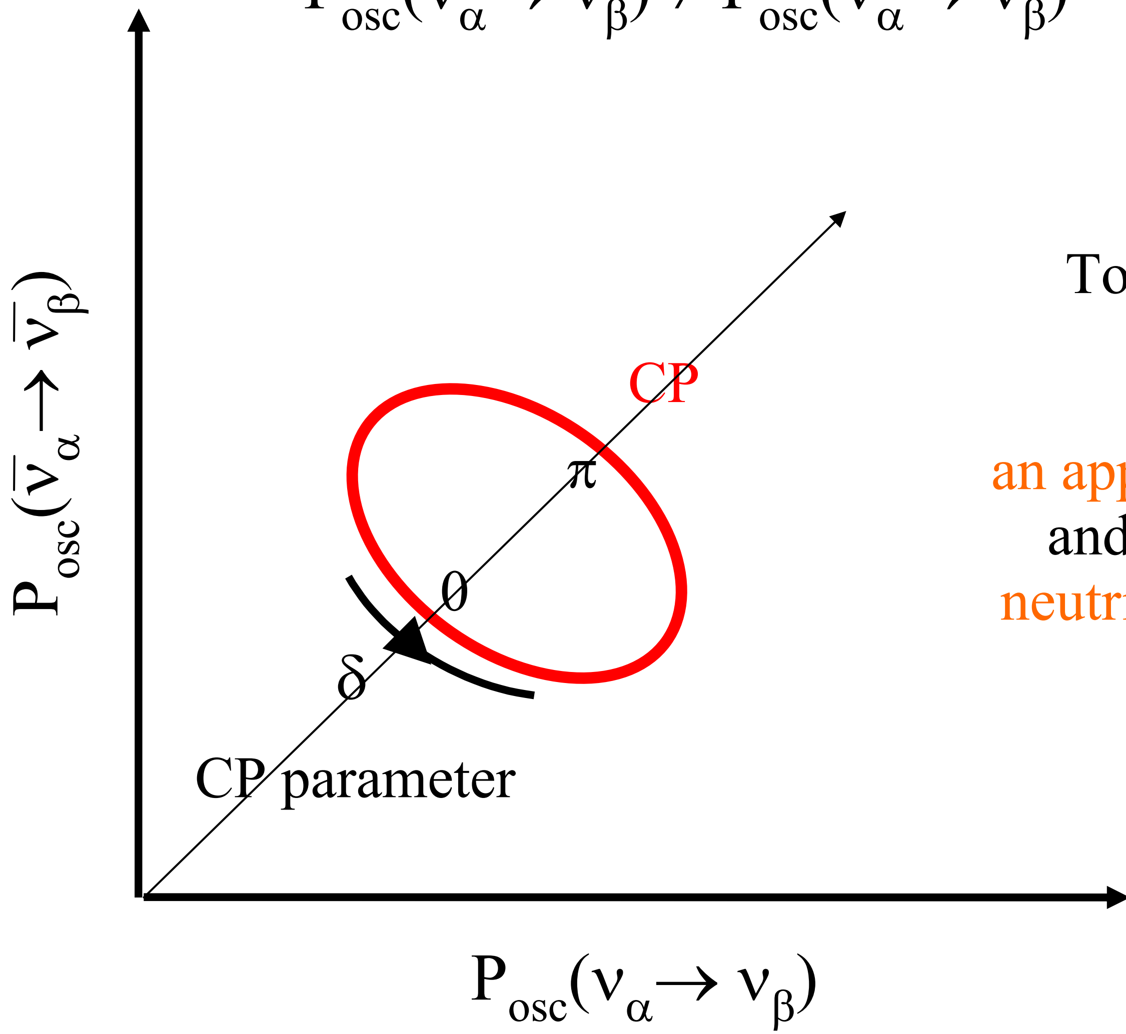
From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

CP violation
& light neutrinos

$$P_{osc}(\nu_\alpha \to \nu_\beta) \neq P_{osc}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

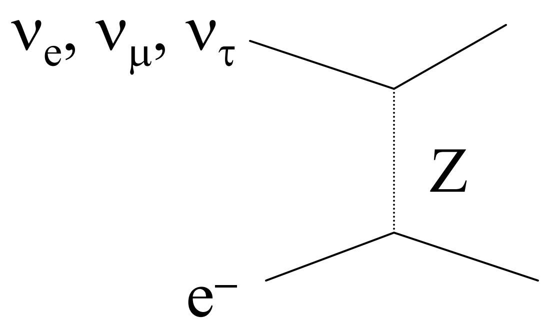


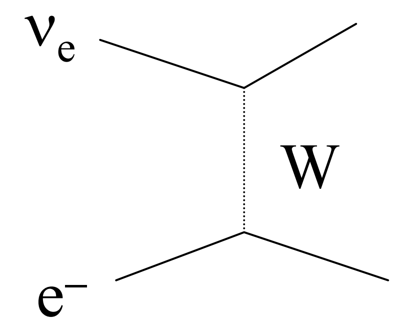
To see CP violation
in oscillations
you need
an appearance experiment
and results from both
neutrino and antineutrino
running

But matter effects also cause $P_{osc}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{osc}(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)$

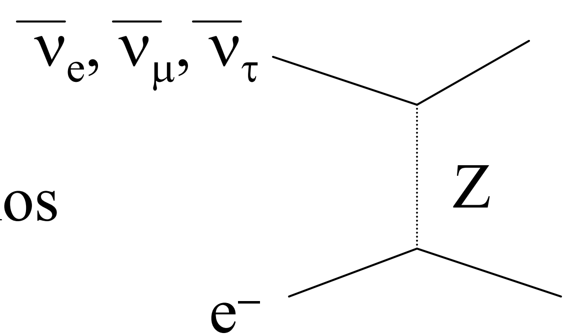
There are two diagrams for the "electron" flavor...

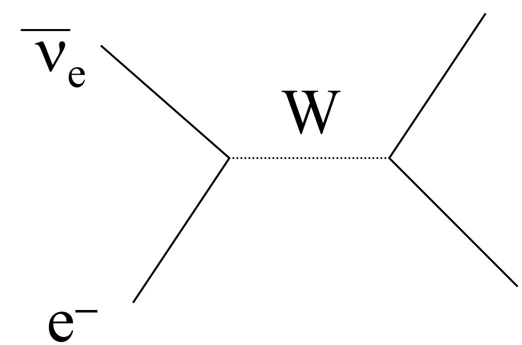
For neutrinos





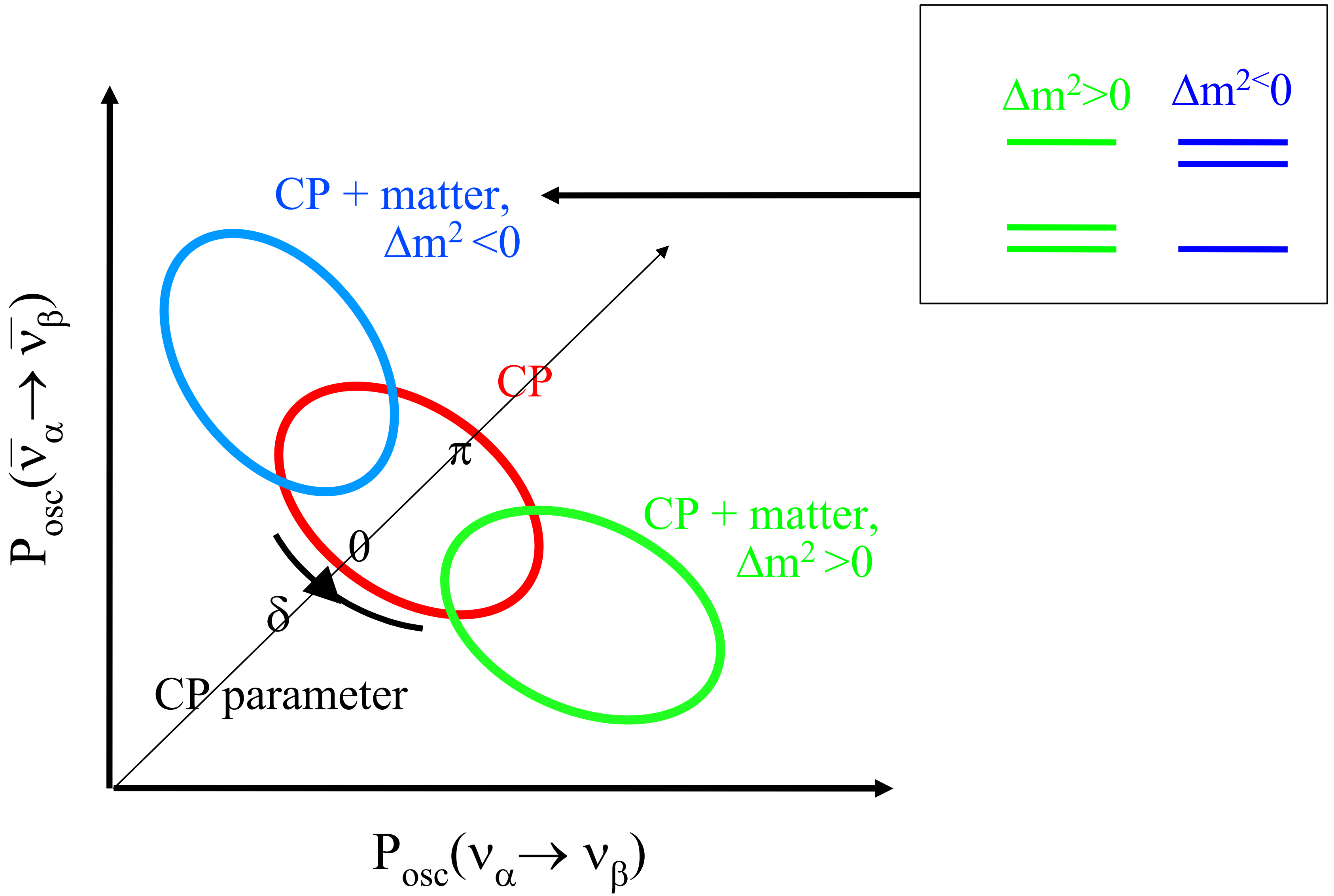
For antineutrinos





But one is t-channel and the other s-channel

And to make matters worse, the sign for each depends on Δm^2!

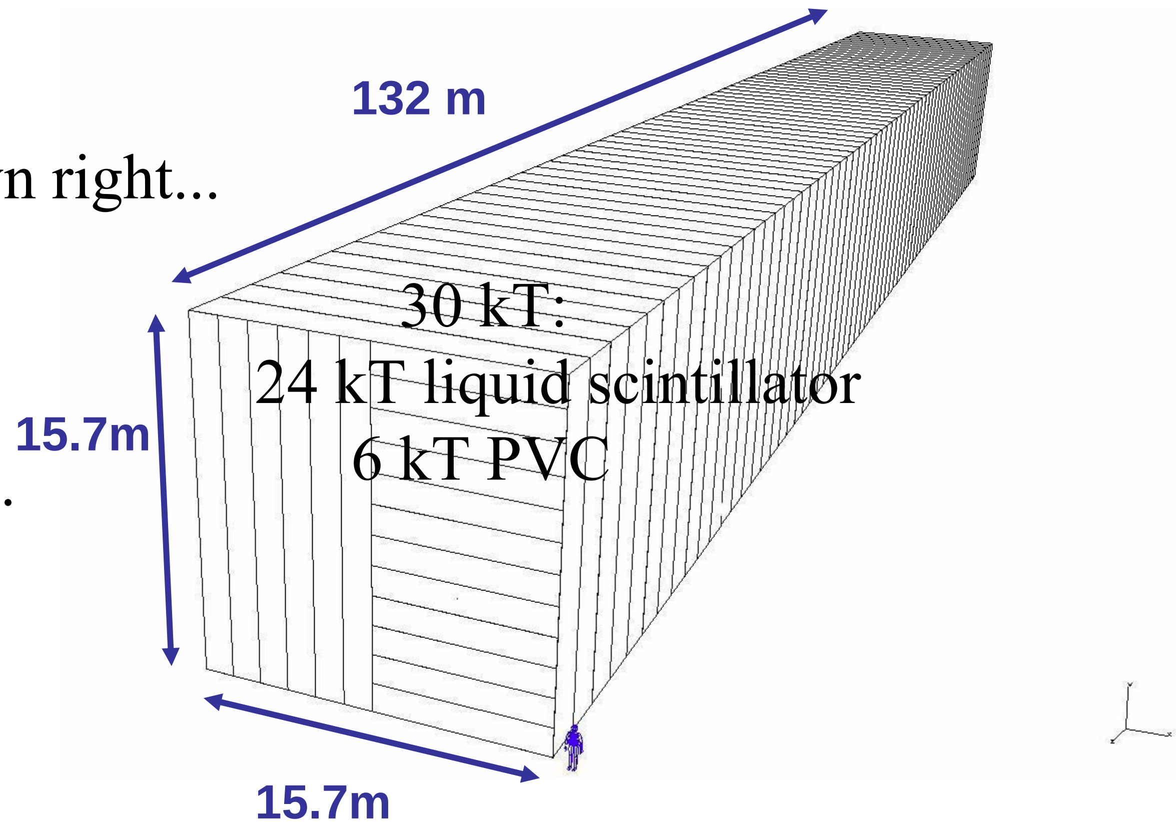


Matter effects are only an important for baselines >500 km

Specifically, the NOνA Experiment: $\langle E_\nu \rangle = 2.3$ GeV, L = 810 km

Arguably,
the mass hierarchy
is interesting in its own right...

It may help
discriminate
between GUT models.



Janet's opinion:

CP violation is going to be hard to measure, and so it is best to do this in an experiment without matter effects...

With CP violation

$$\begin{aligned} P_{long-baseline} &\simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\ &\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\ &+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin^2 \Delta \\ &+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta \end{aligned}$$

... another good reason to know θ_{13} well!

(note: if it is small, you don't see CP)

$$
\begin{aligned}
P_{long-baseline} \simeq\ & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta \\
& \mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta \\
& + \alpha \sin 2\theta_{13} \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \sin^2 \Delta \\
& + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta
\end{aligned}
$$

1 equation and a whole lot of unknowns.

Pick 2 unknowns to plot against one another:

CP δ vs $\sin^2 2\theta_{13}$

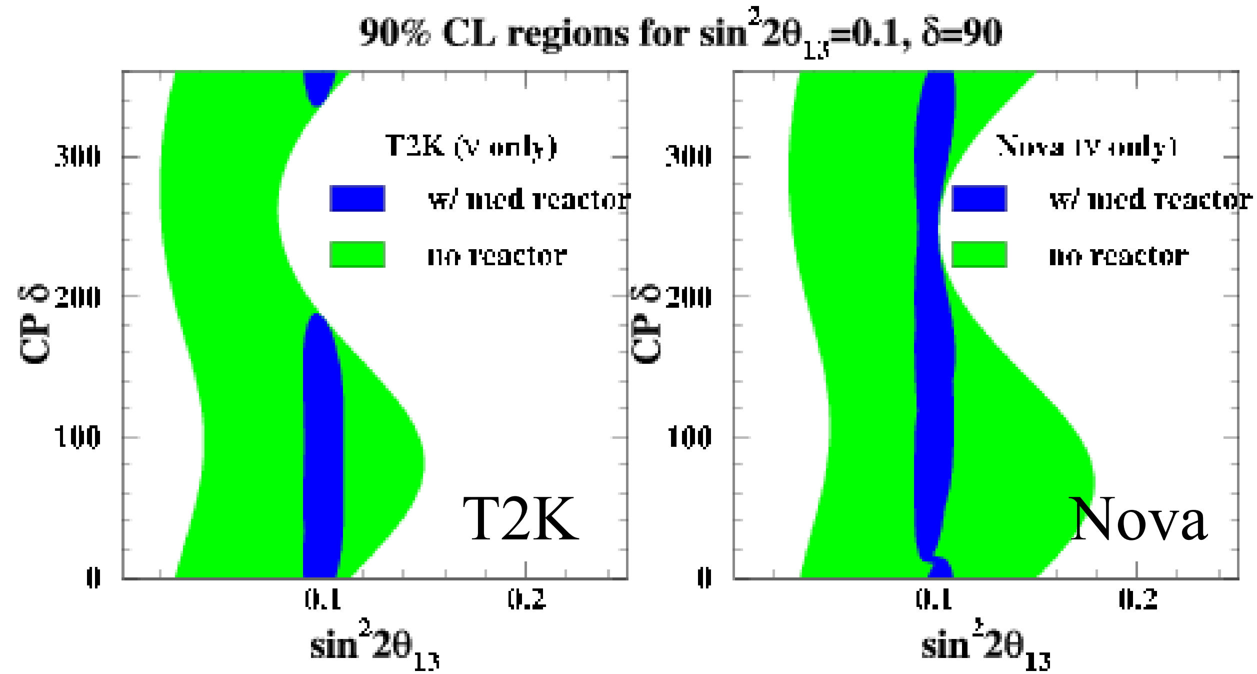
Assume T2K measures $d(\sin^2 2\theta_{23})\sim 1\%$ (3+5 years)

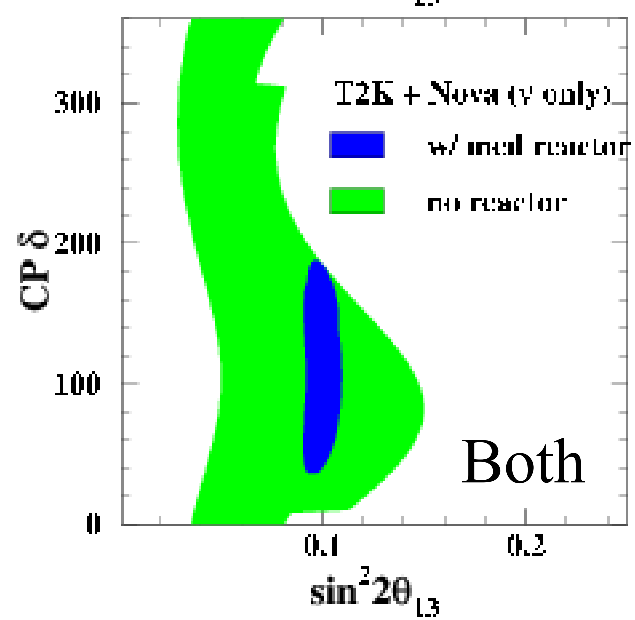
Look at various scenarios...

- without a mid-scale reactor
- with a mid-scale reactor

If the
real value
is 90°

This is what
experiments
extract...

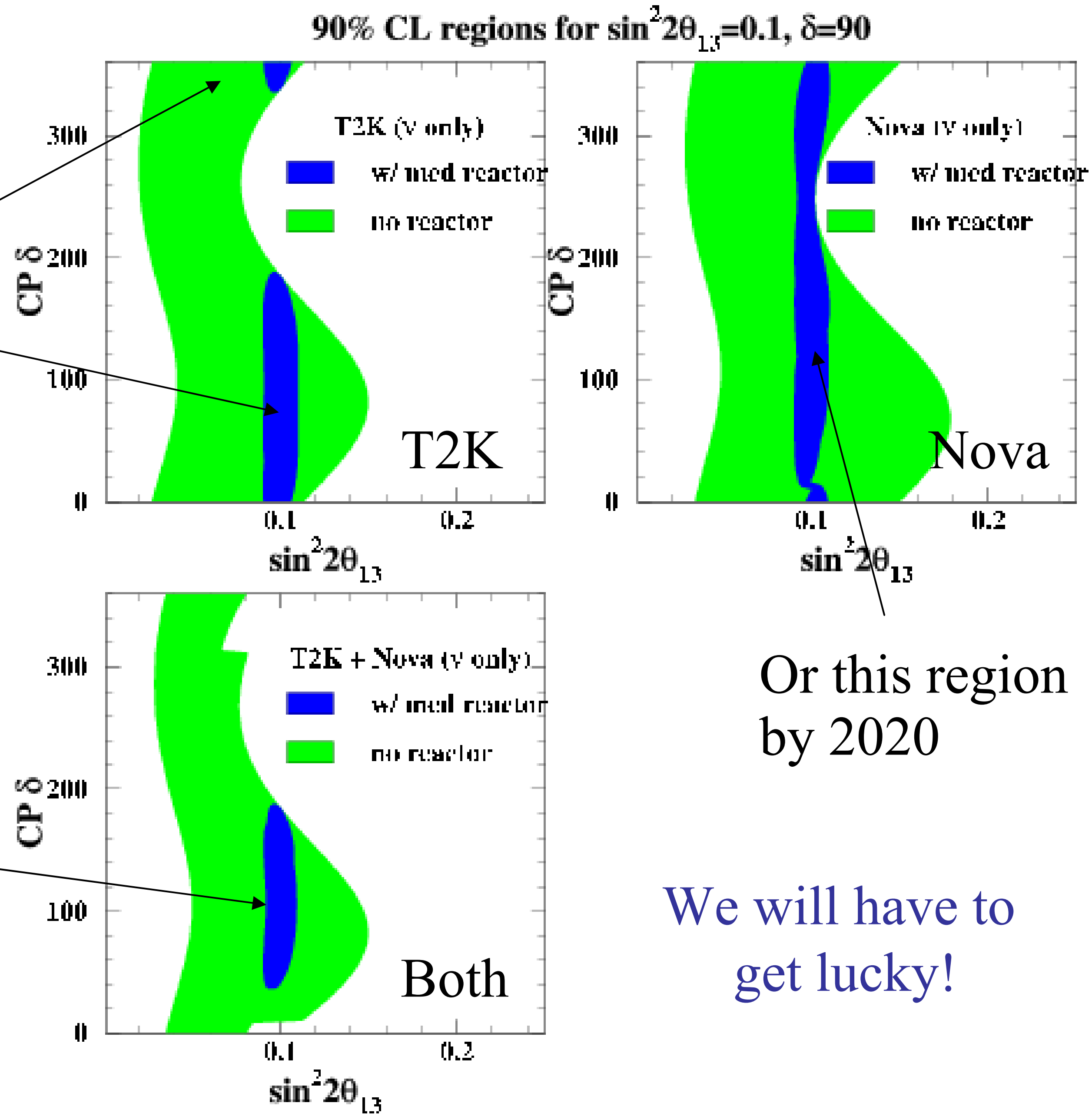




If θ_{13} is too small, the long-baseline experiments have no sensitivity

If θ_{13} is large enough, the reactor slice allows non-zero CP to be distinguished.

You could have just these regions by 2015



Or this region by 2020

Or this by 2020 with both experiments....

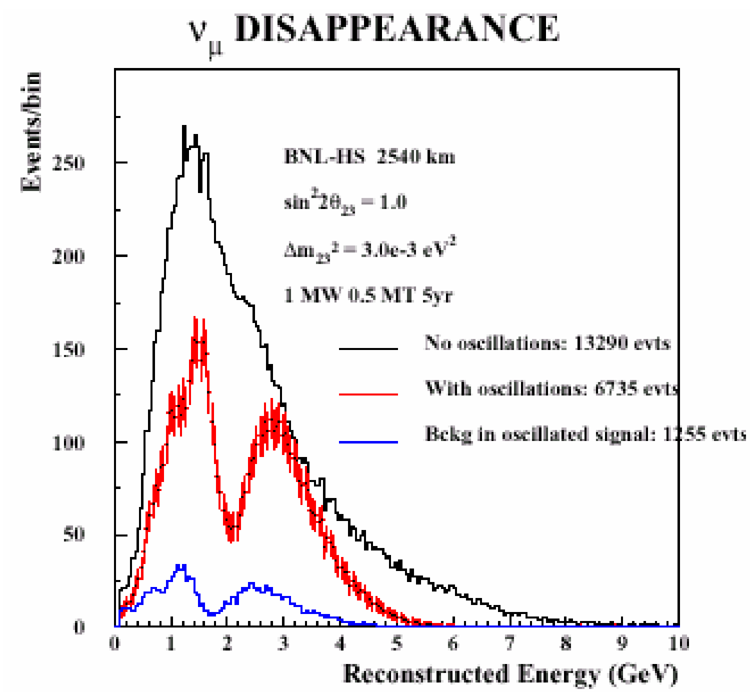
We will have to get lucky!

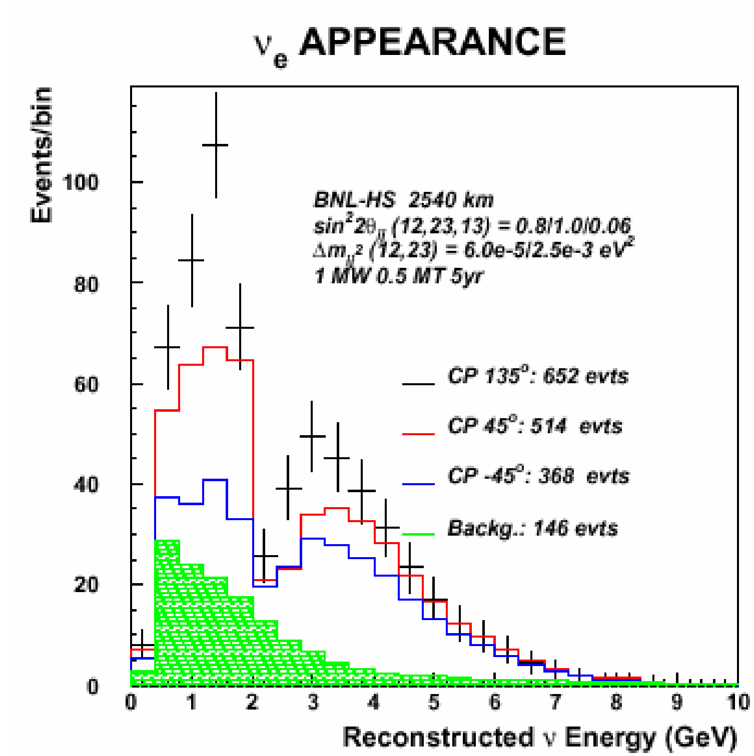
If the CP Violation signal is not 90 or 270 degrees, How can we see it?

2450km baseline
1MW source
MT detector
5×10^7s exposure

VLBνO

A beam from BNL or Fermilab to Homestake or Henderson





A word of caution:

The CP violation accessible in the oscillation matrix,
is not the same as the CP-violation in the Majorana sector
that produced leptogenesis.

But existence of CP-violation in the the oscillation matrix
would make leptogenesis very plausible.

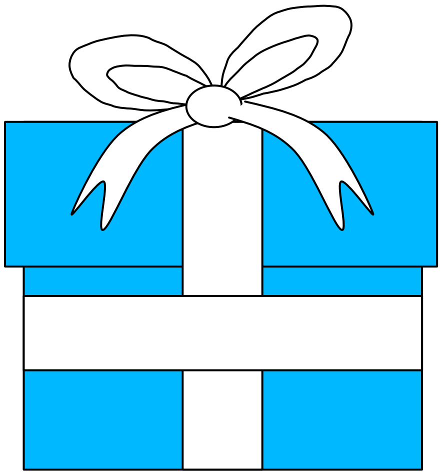
Conclusions for Today

Neutrino mass and mixing must be due to some higher scale physics.

A "natural" candidate is Majorana-neutrino inspired, and makes definite predictions:

1) Neutrinoless double beta decay should be observed.
2) θ_{13} should be relatively large
3) CP violation in oscillations may be observable

Which leads to a very pretty package of experiments....



The Plan for the Future:

Neutrinoless Double Beta Decay:
GERDA/Majorana, CUORE, EXO and others

Reactor (θ_{13}):
Double Chooz, Daya Bay

Long Baseline:
Minos, T2K, Nova, VLBνO