Neutrino Experiments:
ν Questions for a New Decade…

Janet Conrad, SLAC Summer Institute, 2011

My theme:

If I were a graduating student or recent postdoc,
and considering working in neutrino physics,
what would I consider working on?

if you are an experimentalist … what experiments?
if you are a theorist … what questions?

Part I: Neutrino Basics…

The neutrino we once knew and loved

Neutrino Oscillations

A “nu” Standard Model

Part II: Oscillation experiments: 2011-2020

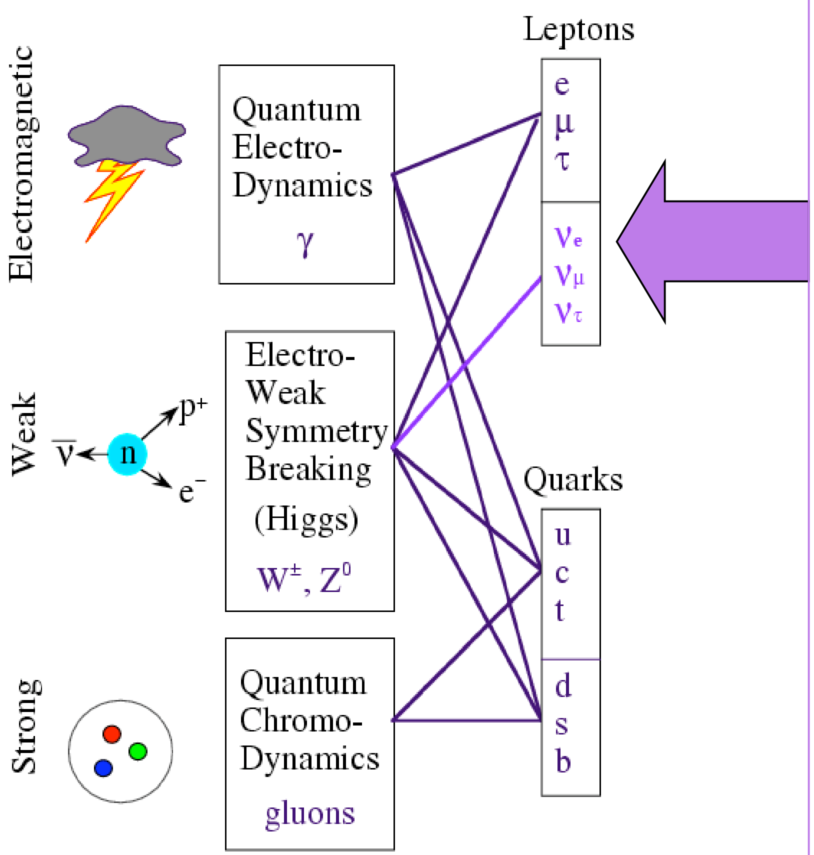
Pursuit of the missing pieces

An unconventional approach: DAEδALUS

Oscillations at short Baseline

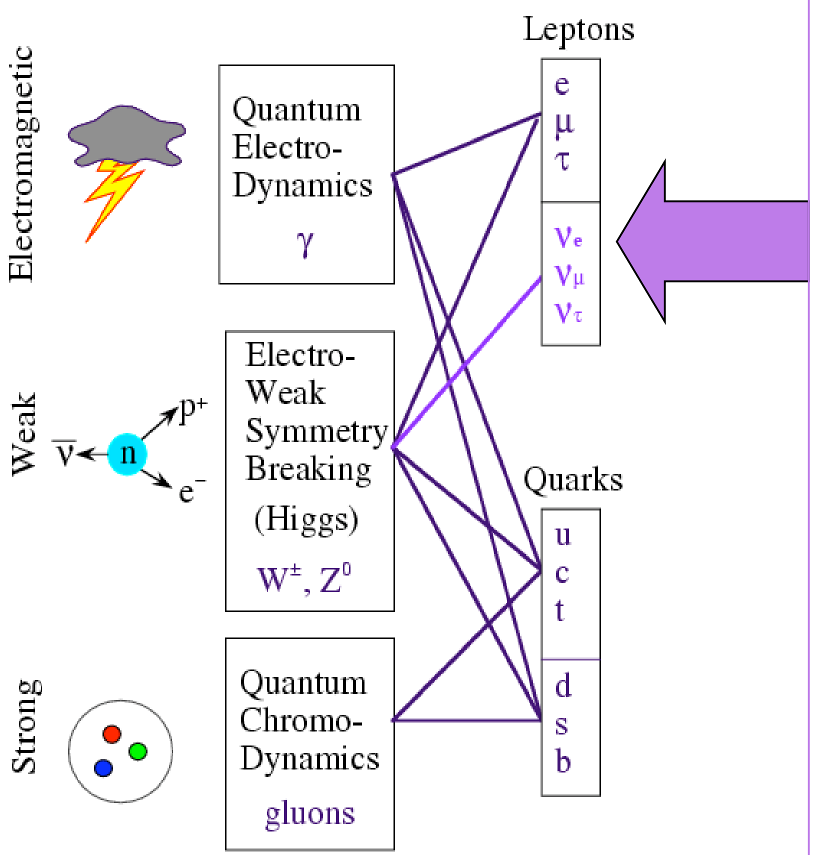
The Neutrino We Used to Know and Love

The Standard Model



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

The Standard Model



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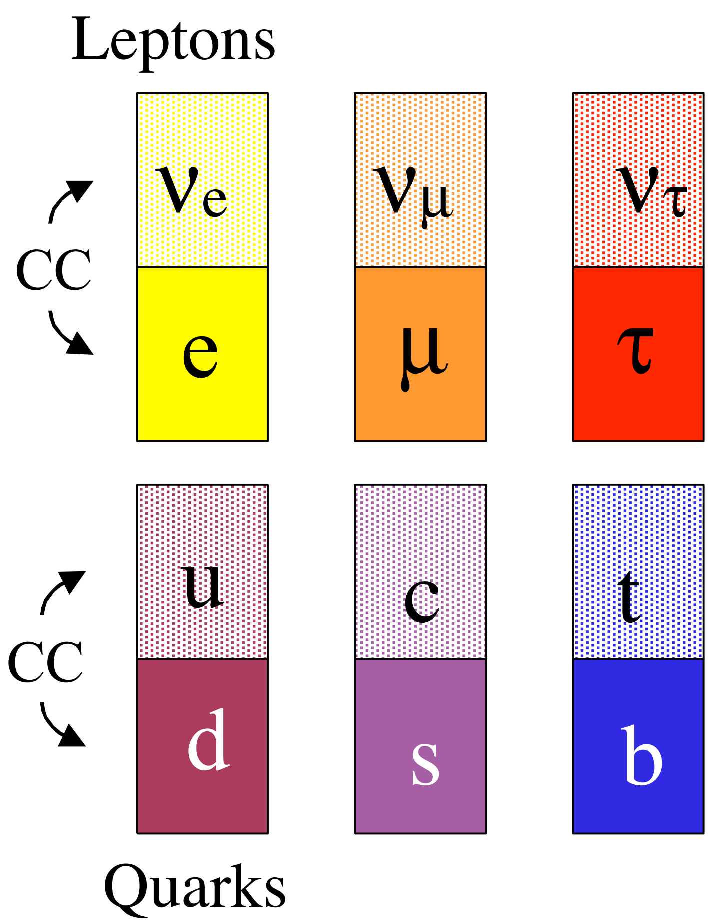
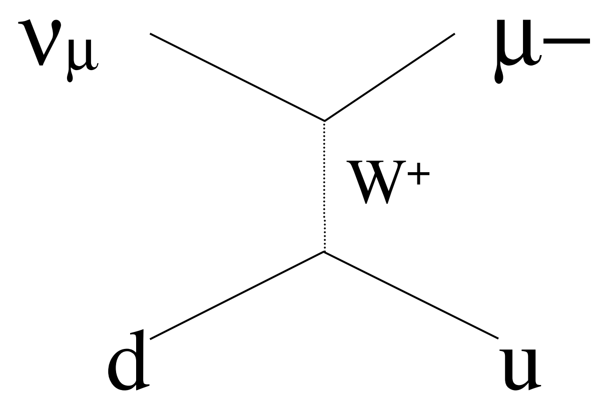
In the Standard Model, Neutrinos are part of the lepton "weak doublets"



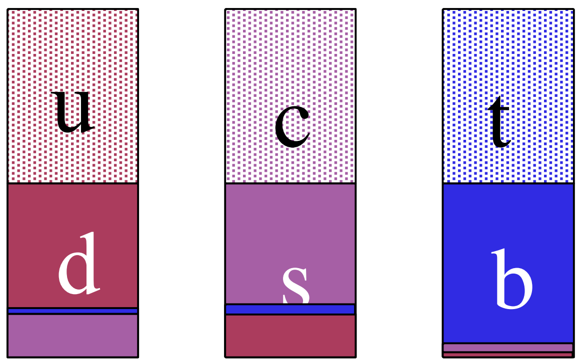


For a CC interaction to occur you need enough energy to produce the massive final state particles

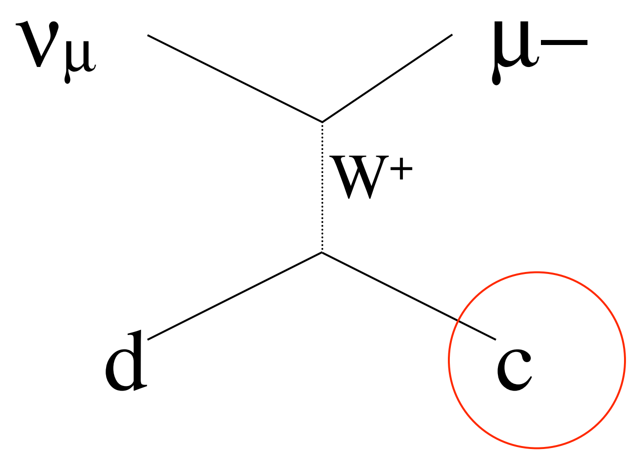
The quarks also form weak doublets…

In the quark sector, we have "mixing"

quark mass eigenstates $\neq$ quark weak eigenstates



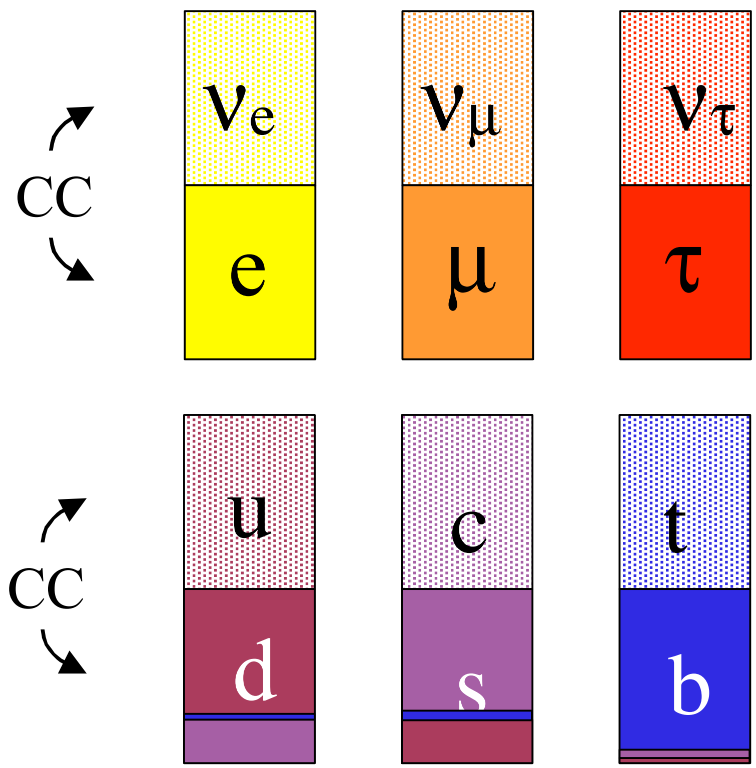
Small effect, but clearly seen in weak interactions...



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

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

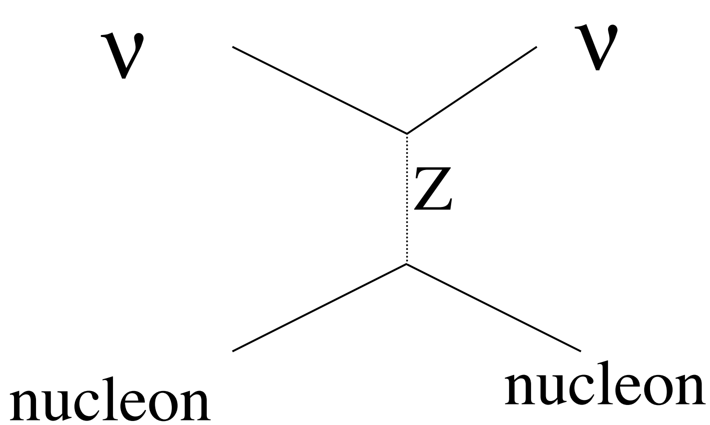
But within the model,
there is no mixing in the lepton sector



Which looks
a little strange,
doesn't it?

Neutrinos can also have Neutral Current (NC) Interactions

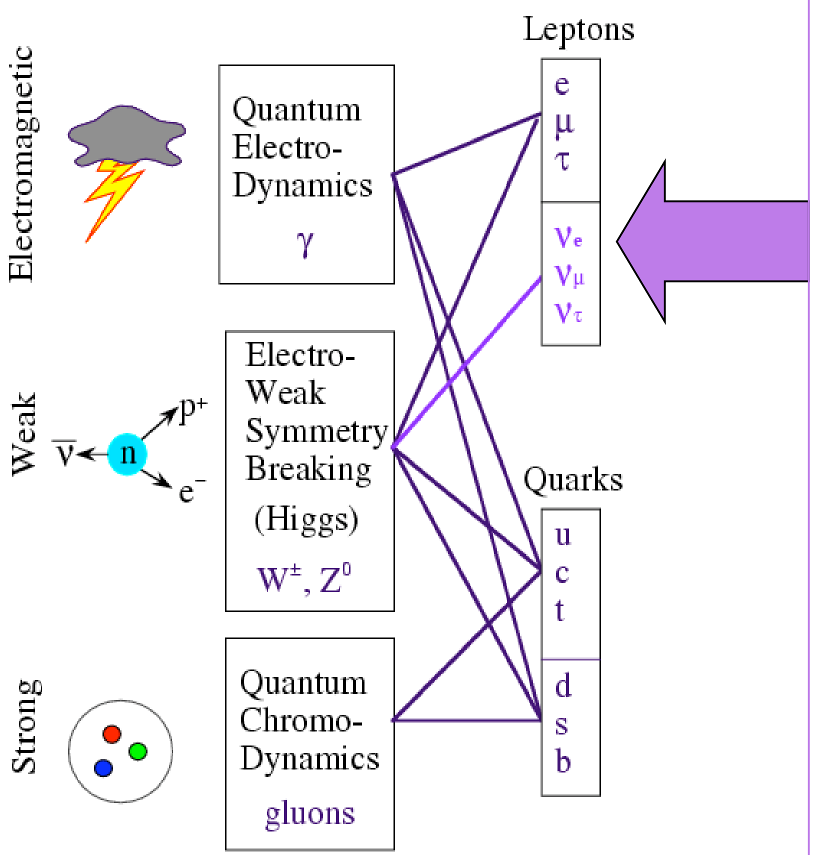
e.g.



I have no way of knowing the flavor in this case!

If I am interested in neutrino flavor,
I have to rely upon the CC interaction!

The Standard Model



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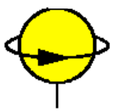
A quick reminder about parity violation...

All spin 1/2 particles have "helicity"

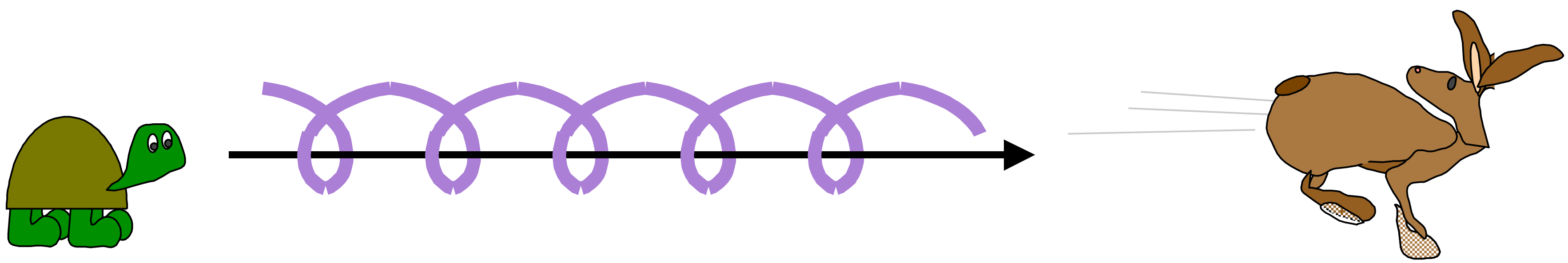
The projection of spin along the particle's direction

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

right-helicity 

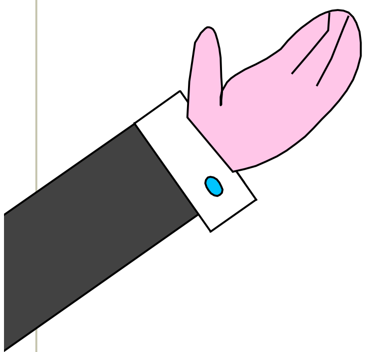
left-helicity 

Frame dependent (if particle is massive)



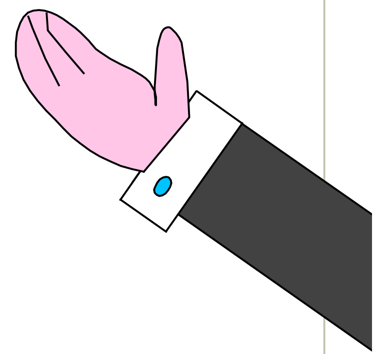
Handedness (or chirality) is the Lorentz-invariant counterpart

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



Hello!

Hello!

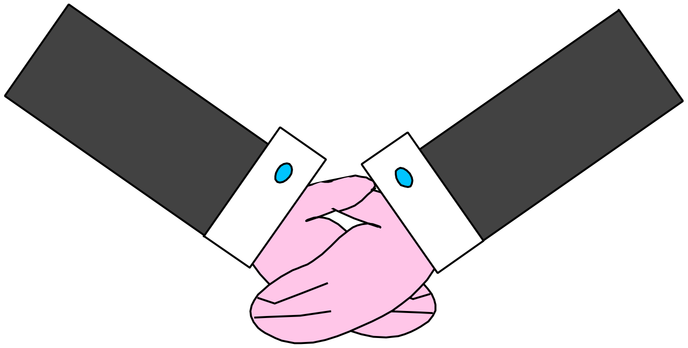


Naively
you would think nature would make
an equal left-handed/right-handed mix.

But NO!
The weak interaction produces
right-handed antiparticles
and left-handed particles

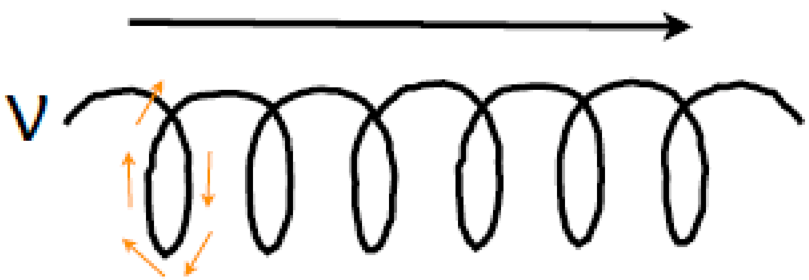
100% of the time!

"The W only shakes
with the left hand"

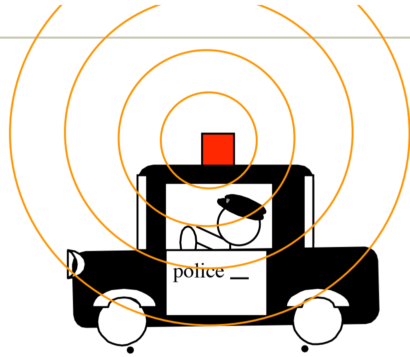


Since neutrinos ONLY interact via the weak interaction

Neutrinos are always left-handed



And antineutrinos are right-handed



How do you enforce the law of left-handedness?

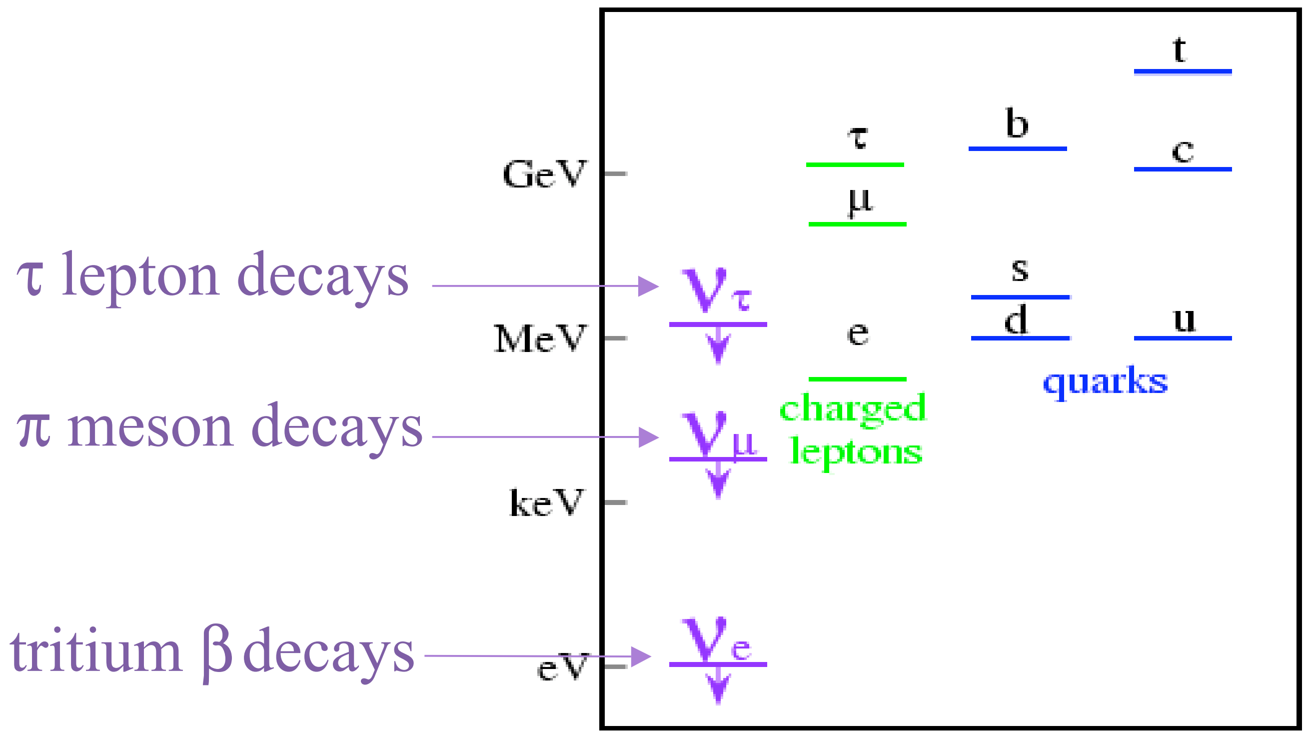
Well... what couples left-handed particles to right?

A Dirac mass term
in the SM Lagrangian:

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

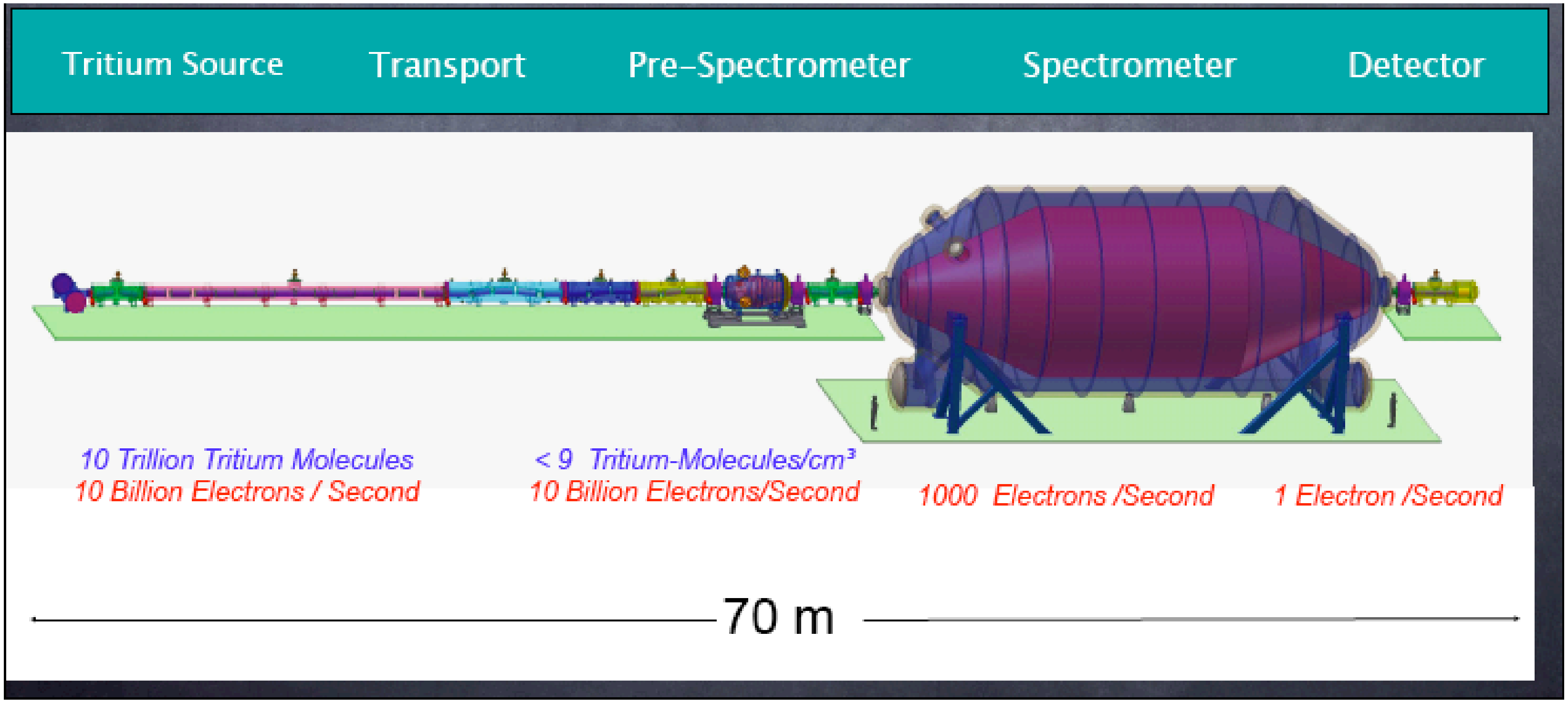
If you want to build parity violation into “the law”
you have to keep this term out of the Lagrangian...
a simple solution is: m=0

Direct (kinematic) searches are consistent with massless ν's:



We only have limits!

The future of direct mass measurement is the KATRIN Experiment:

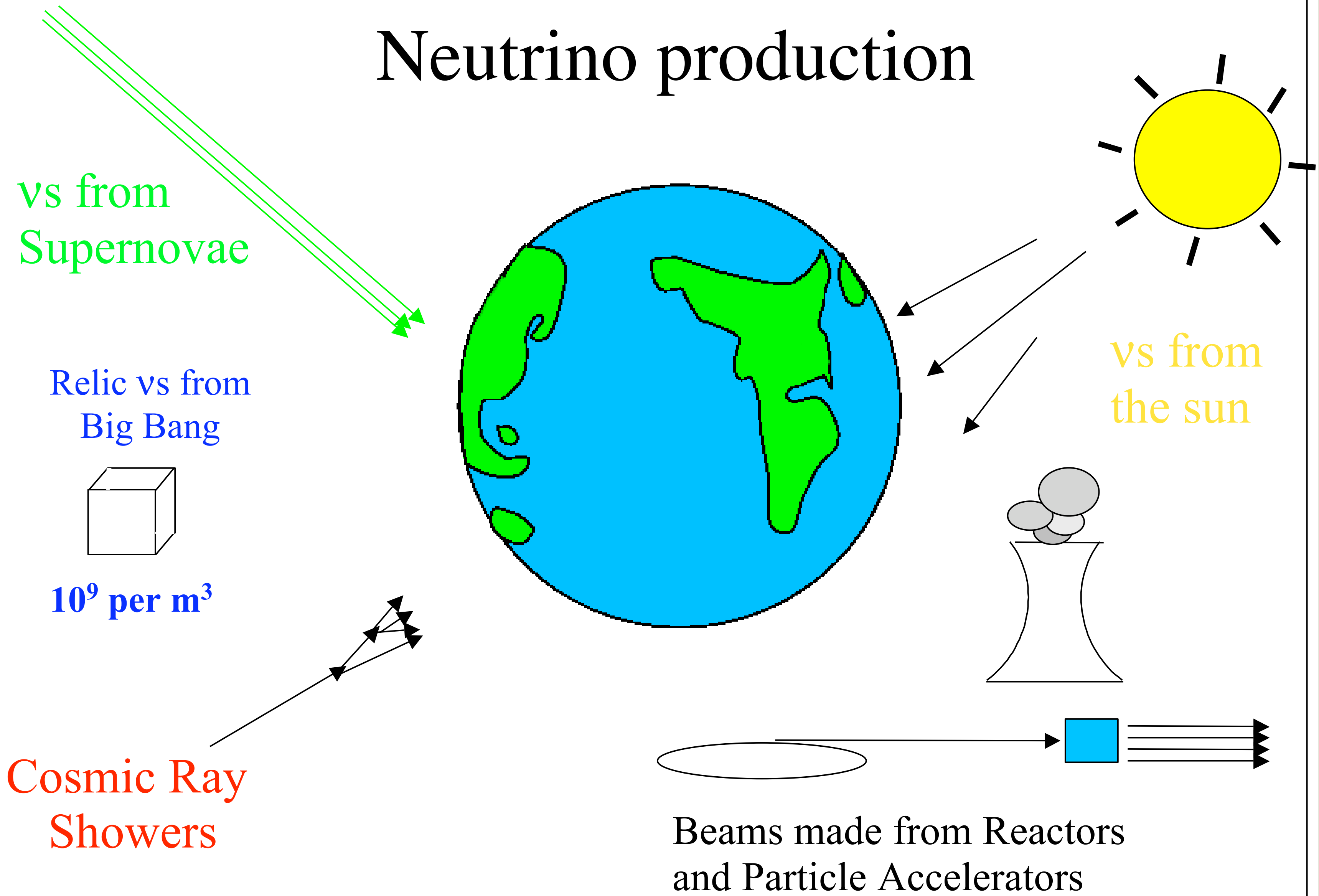


Probes to m_ν<0.2 eV @90% CL

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

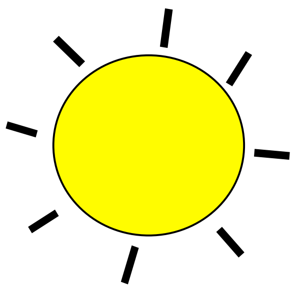
Just to set the scale of the size of KATRIN…

Neutrino production



Low energy sources produce neutrinos via beta decay and electron capture

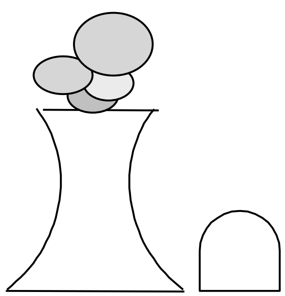
Both involve the electron flavor



electron neutrinos

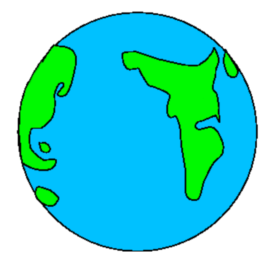
(< 15 MeV)

Production is very flavor pure!



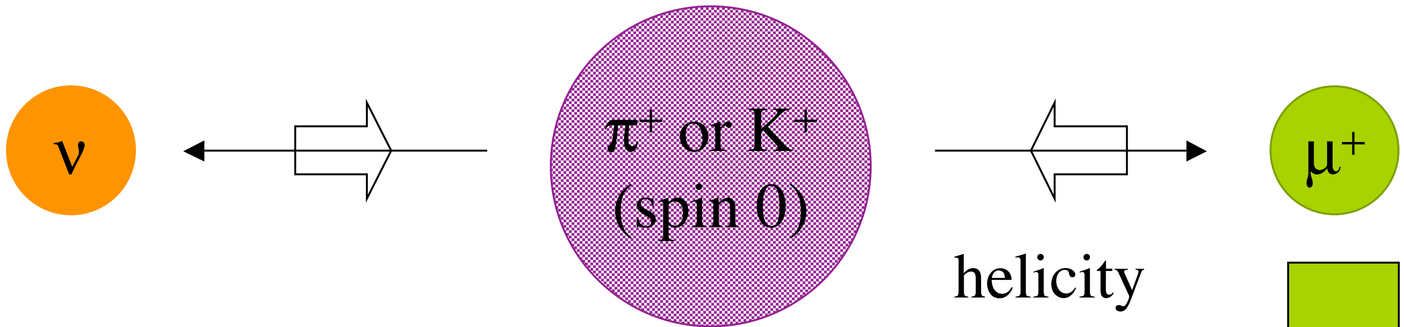
electron antineutrinos

(< 10 MeV)



But observing low energy neutrinos is difficult

Sources with enough energy to produce muons,
will dominantly produce muon flavor neutrinos



~1E-4 electron flavor

helicity supression $\sim(m/E)^2$

But the muon will also decay!
and the Kaon has 3 body decays!
Both produce electron flavor

Conventional high energy sources are mostly muon neutrino, but generally have a few % electron flavor at production

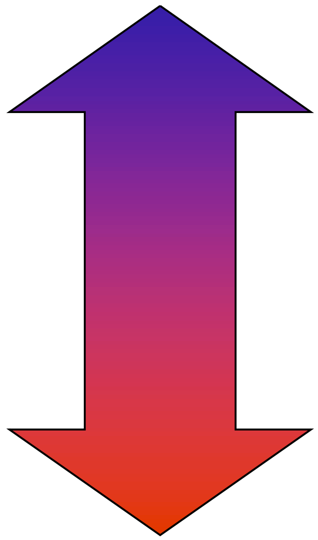
The interaction depends upon the ν energy...

The main sources

Useful interactions

Few MeV

Reactors,
The Sun



Elastic (esp. $\nu e \rightarrow \nu e$)

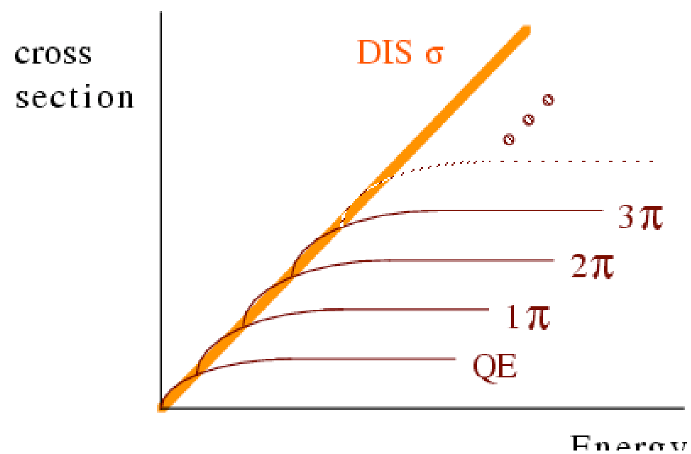
Quasielastic ($\nu N \rightarrow \ell N'$)

Single Pion Production (resonant & coherent)

Deep Inelastic Scattering

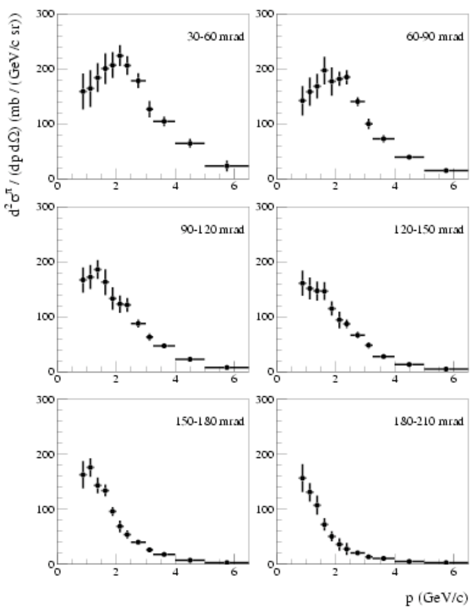
Cosmic rays,
accelerators

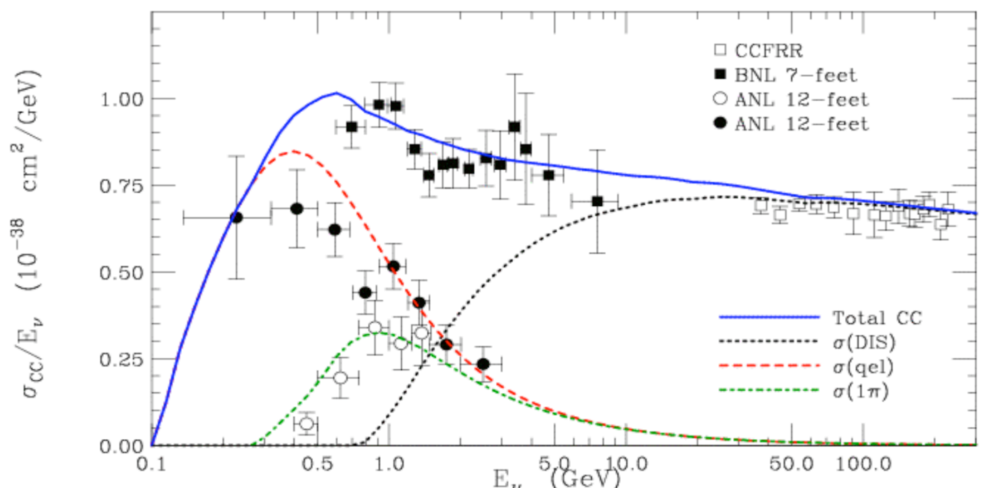
Multi-GeV+



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

In neutrino physics, these are experiments like:





HARP
MIPP
SHINE

These are crucial experiments

SciBooNE
Argoneut
Minerva
MicroBooNE

So lets review…

We have a Standard Model Neutrino

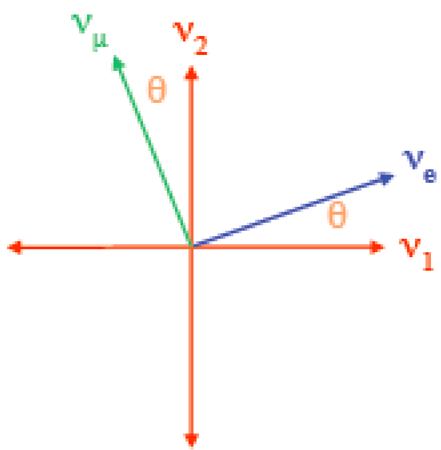
But it isn't very standard

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

The Neutrinos We Know Today…

Lets say that neutrinos can mix, like the quarks…

And lets say that neutrinos do have mass states, like the quarks…



For Two Neutrinos....

flavor mass

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

The mixing of the states is expressed by a rotation matrix.

The neutrino flavor states in bra-ket notation.

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

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

So starting with the mixing matrix.

$$|\nu_\mu(0)\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

The state at time t=0.

$$|\nu_\mu(t)\rangle = -\sin\theta e^{-iE_1 t}\,|\nu_1\rangle + \cos\theta e^{-iE_2 t}\,|\nu_2\rangle$$

The state's evolution in time.

Then the probability is given by the amplitude squared.

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

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

$$E_i = \sqrt{p^2 - m_i^2} \approx p + m_i^2/2p$$

$$t/p = L/E$$

We know the mass is small so we can use a Taylor expansion and then change some units.

$$P_{osc} = \frac{1}{2} \sin^2 2\theta \left(1 - \cos\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)\right)$$

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

Look! It depends on mass differences, so if neutrinos oscillate they must have mass!

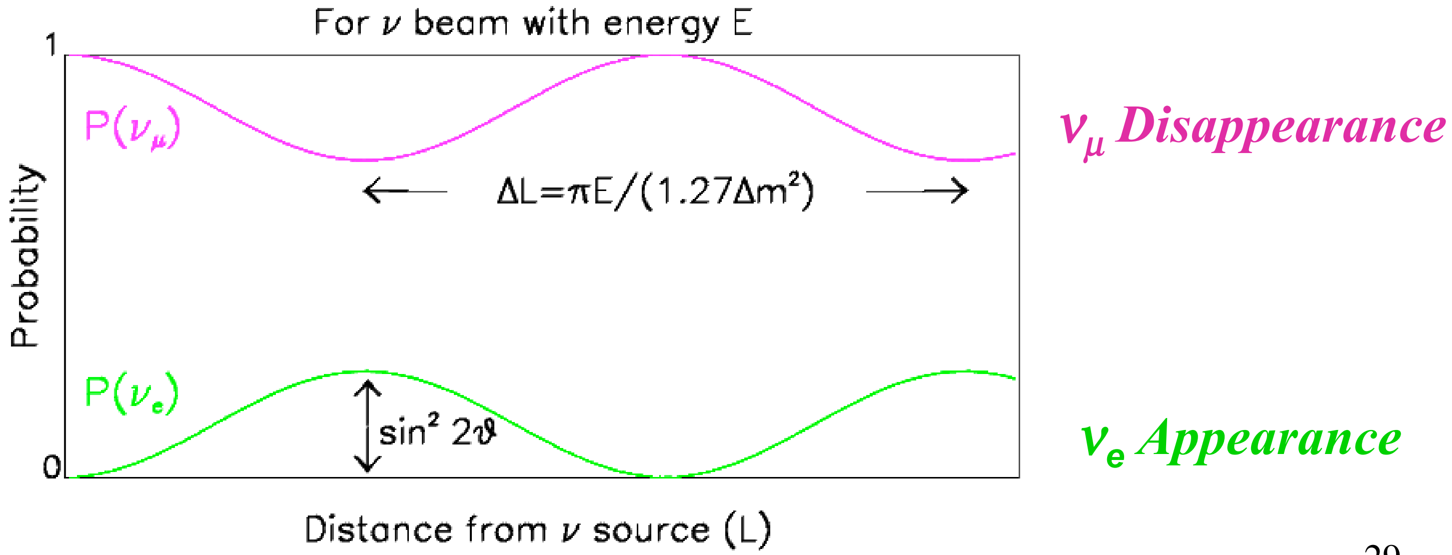
$$P_{Osc} = \sin^2 2\theta \, \sin^2\left(1.27\Delta m^2 L / E\right)$$

...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:

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

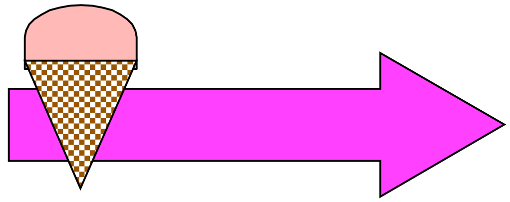


Disappearance experiments

source

detector

start with a certain flavor

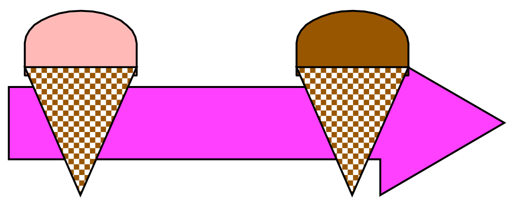


Do you see the same flavor?

New flavor components may be too massive to produce in a CC interaction

Appearance experiments

start with a certain flavor



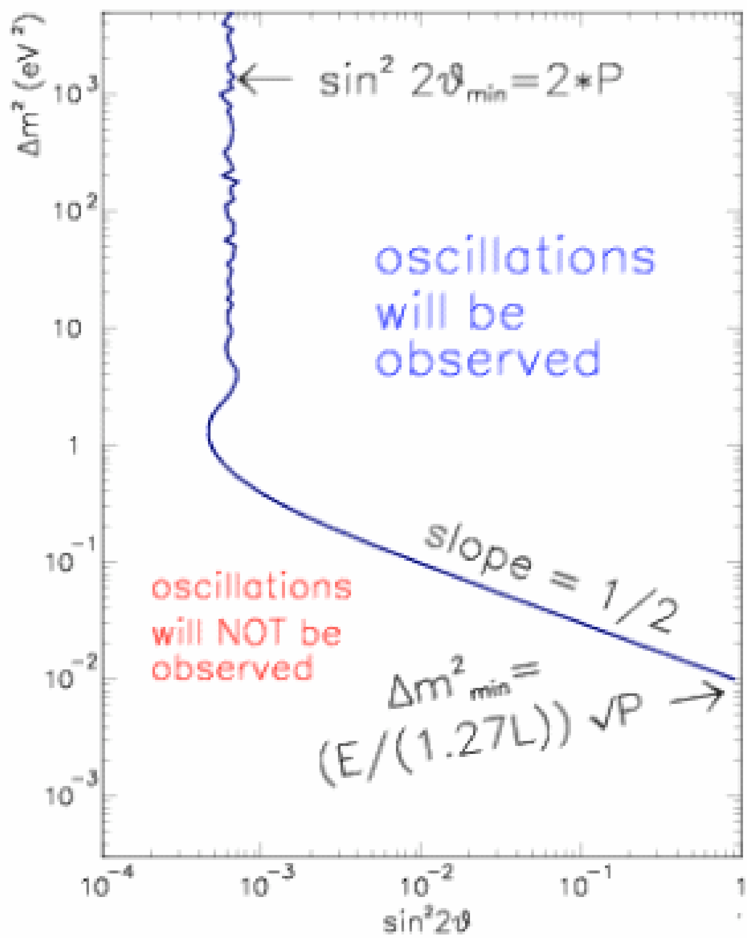
Do you see a new flavor?

New flavor components may “ stick out” clearly in the event sample

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

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

1 measurement
and
2 parameters...



At low Δm^2
use the
small angle
approx.

Allowed regions will look like "blobs"

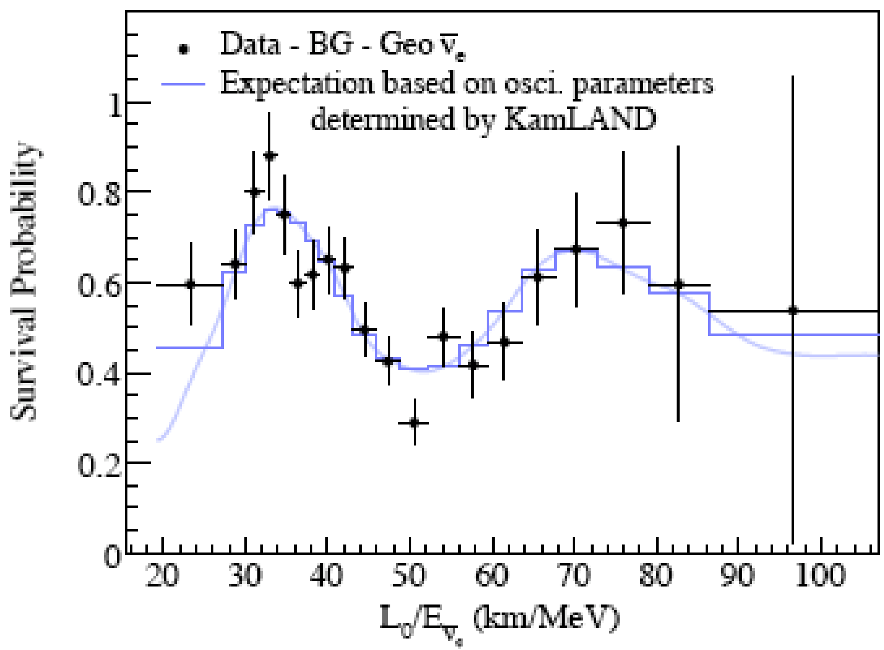
Exclusions by experiments with no signal are indicated by lines...

The Probability for Oscillations...

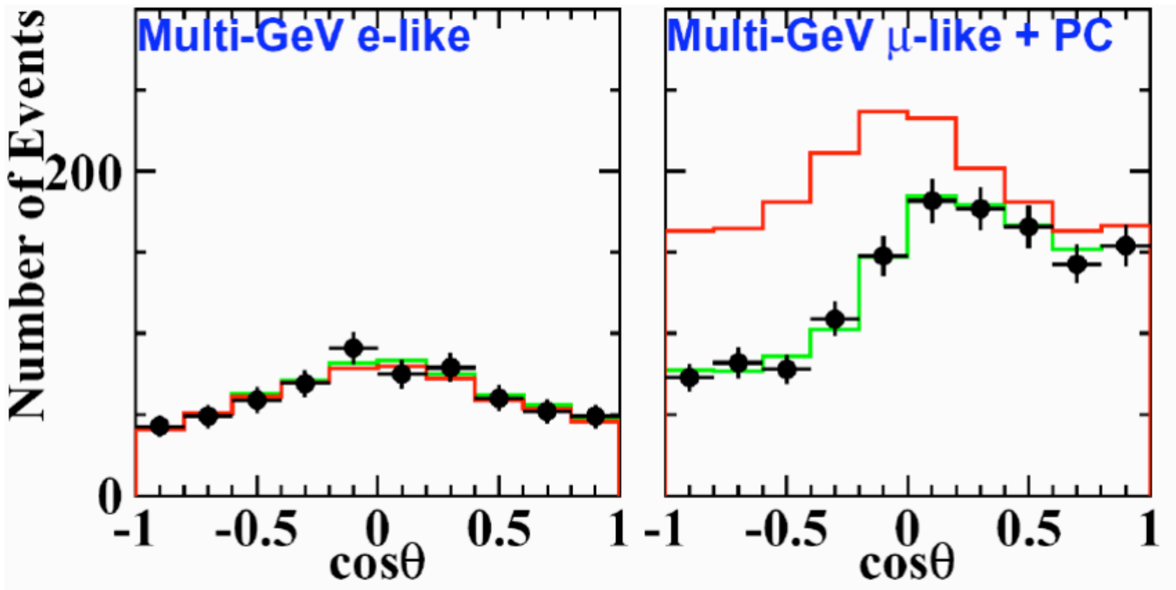
$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

For example, in Kamland!

anti-electron neutrinos from a reactor disappear with a wavelength consistent with ➡ $\Delta m^2 \sim 5E\text{-}5 \ eV^2$



The Super-K experiment showed that atmospheric muon neutrino disappearance fits an oscillation hypothesis



with $\Delta m^2 \sim 3E\text{-}3\ eV^2$

Confirmed by K2K and MINOS accelerator beam expts

Right now, we have no clear evidence for appearance

in any oscillation experiment

But we do have evidence for both disappearance and appearance
in another effect that requires
both mixing and mass differences

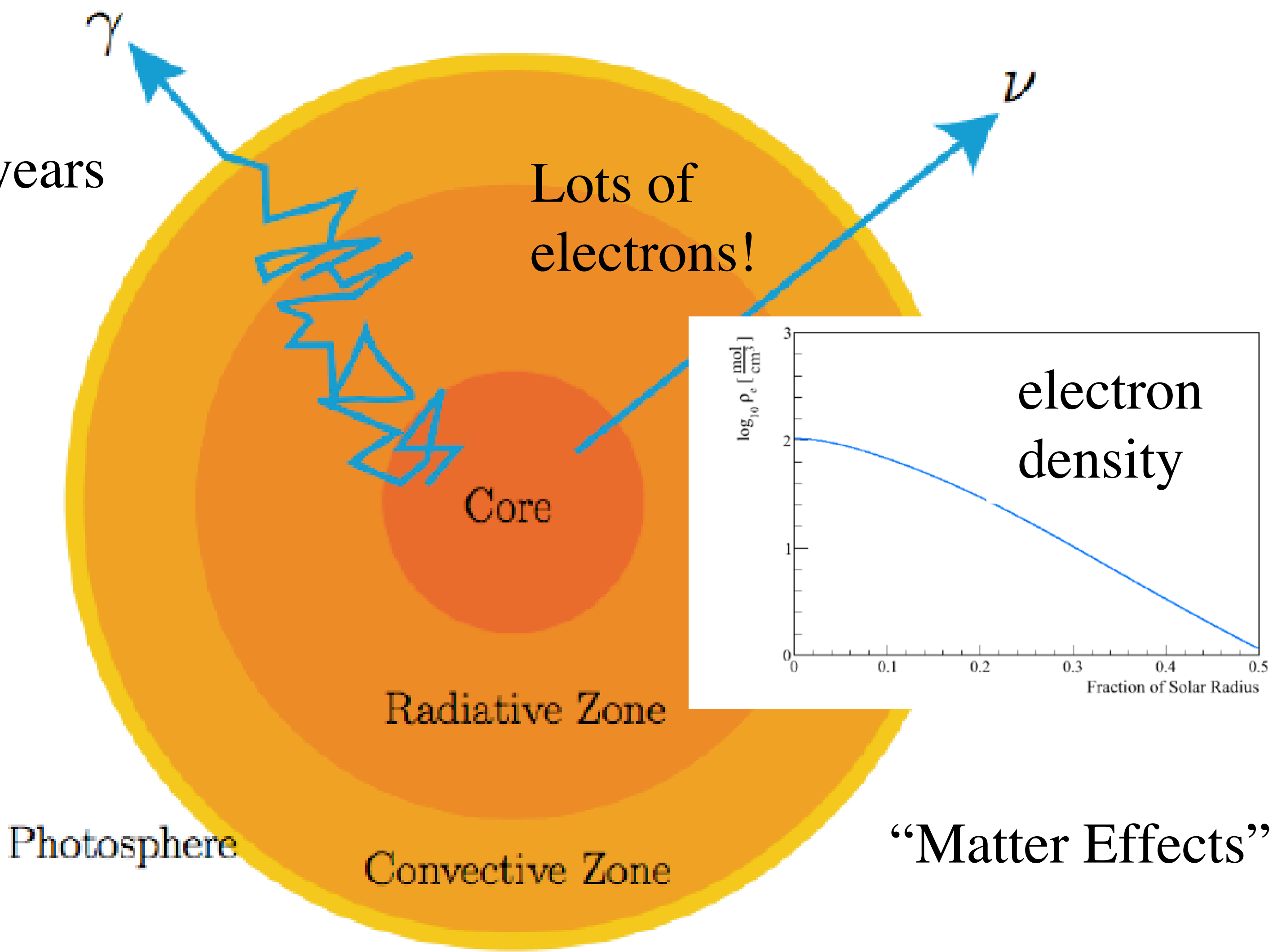
Solar Neutrino ~~Oscillations~~

Morphing

The Sun

10,000 years

immediate

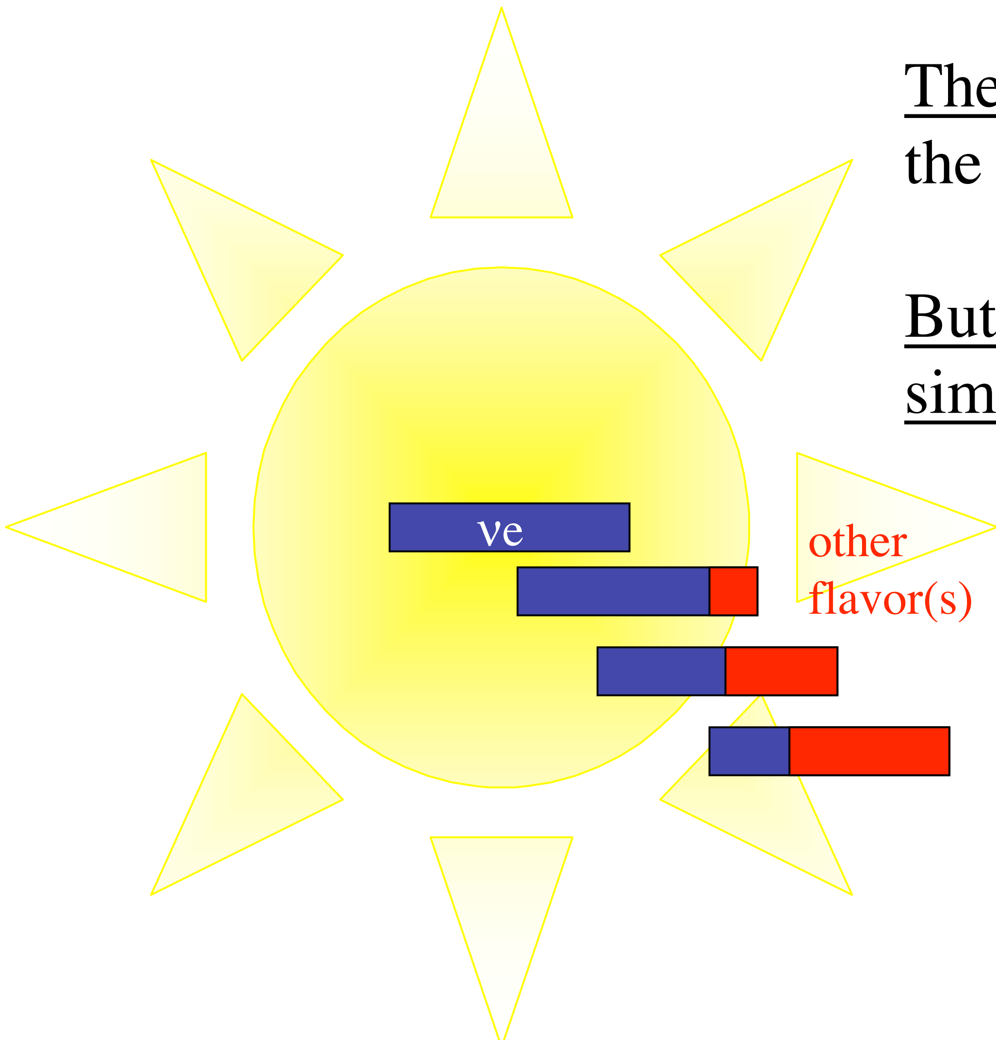


"Matter Effects"

In the electron "soup"

The ν_e sees a CC and NC potential

The ν_μ and ν_τ see only the NC potential

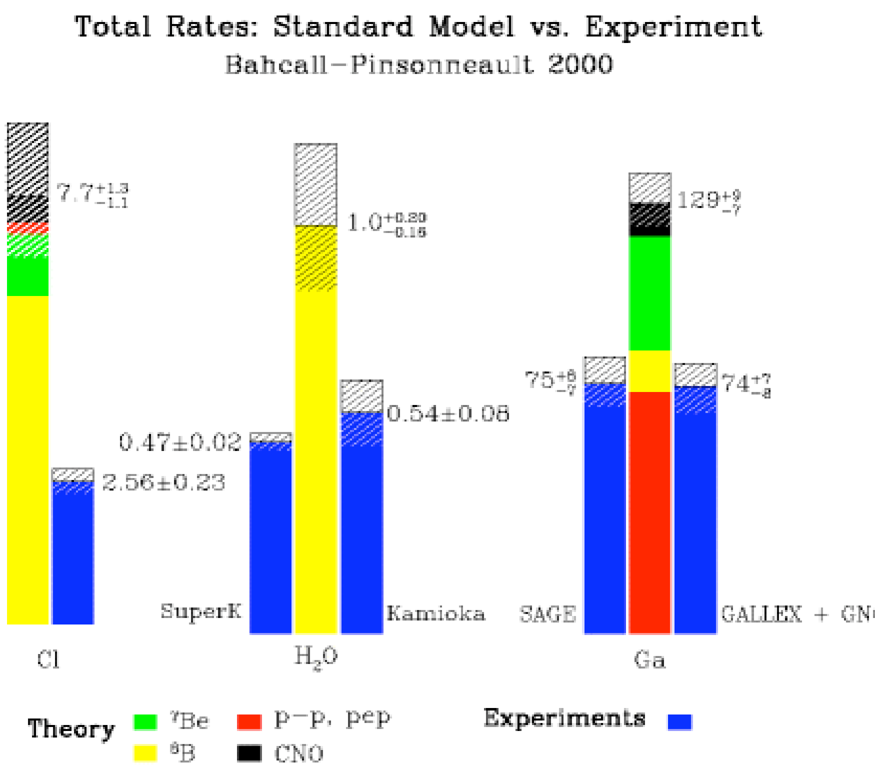


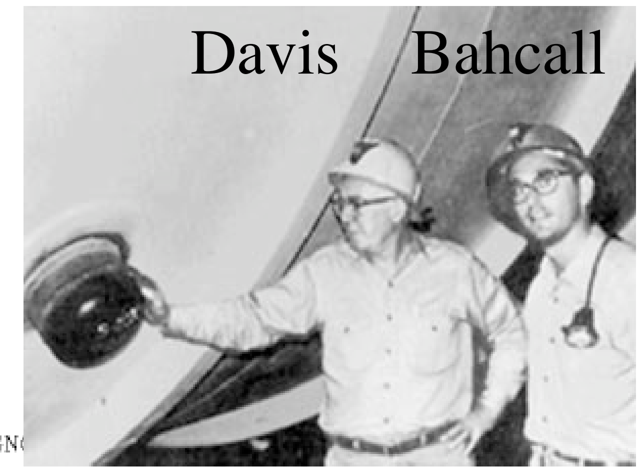
There is flavor evolution as the neutrinos traverse the sun.

But the equations do not simplify to oscillations

The result looks like disappearance in detectors sensitive to only ν_e flavors...

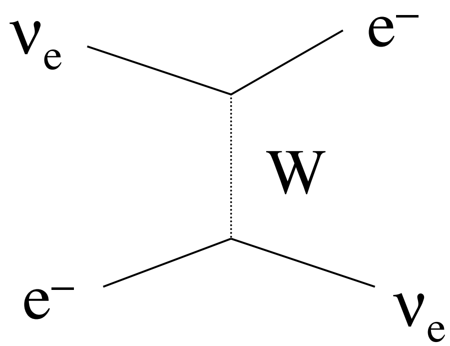
The famous "Solar Neutrino Deficit"



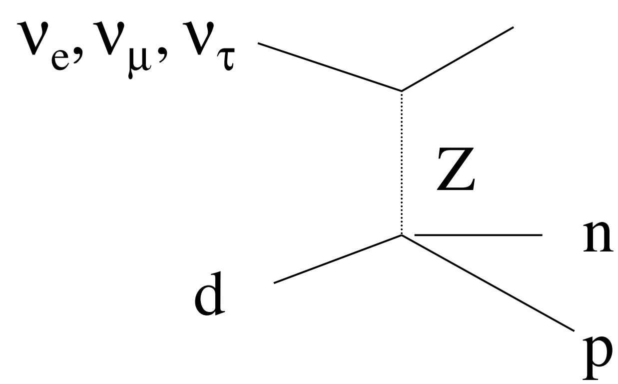


The rate of morphing with energy depends on Δm^2 and the mixing angle

Of course it is only a deficit if you can only see ν_e CC scatters!



most solar experiments



SNO

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

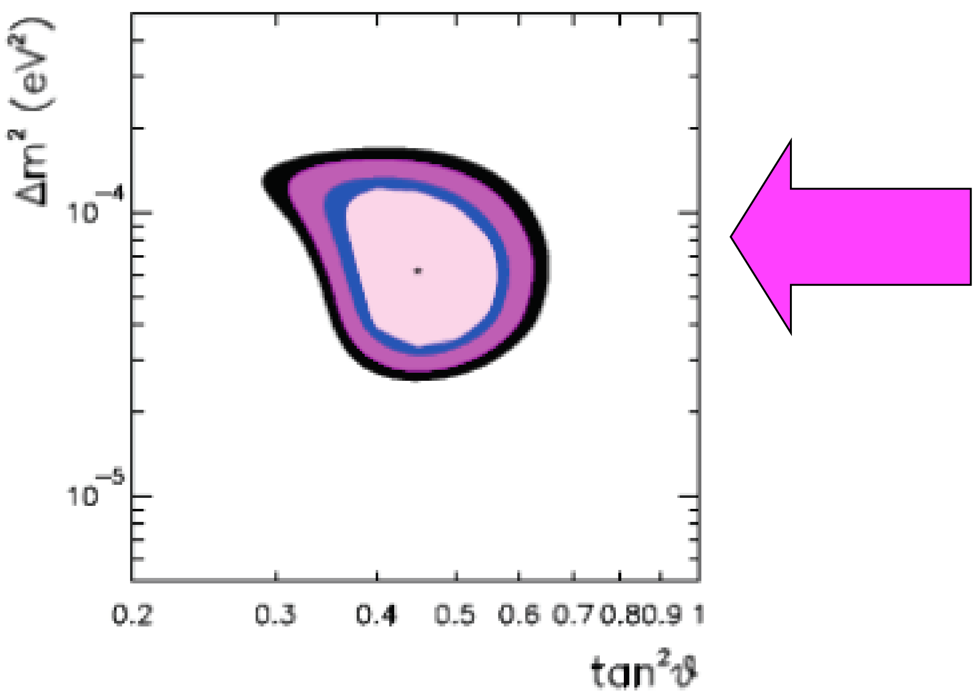
Theory: $\phi_{total} = (5.69 \pm 0.91) \times 10^6/\text{cm}^2\text{sec}$

Bahcall, Basu, Serenelli

The NC interaction shows the neutrinos are still there!

Using the energy dependence of solar morphing…

You can extract an allowed region in the oscillation parameter space from solar neutrinos alone



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

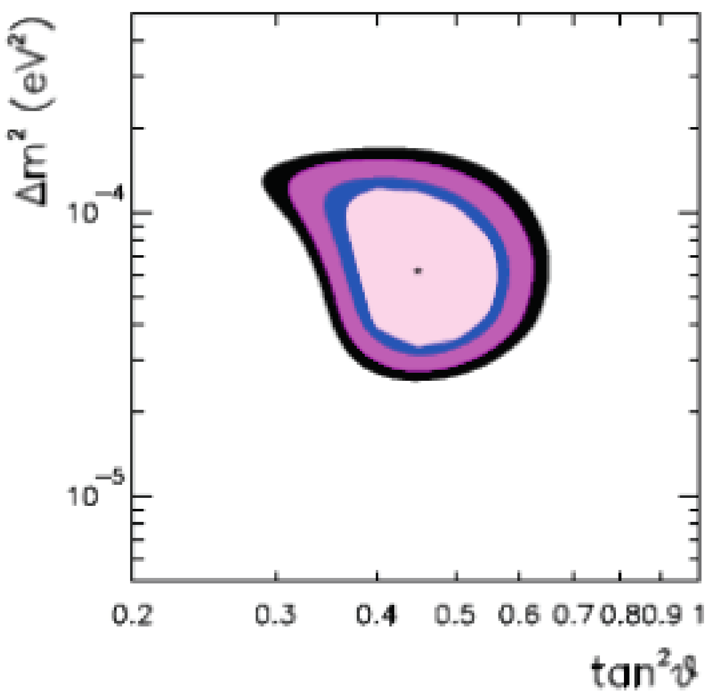
then $\overline{\nu}_e \rightarrow \overline{\nu}_{other}$ should be observable here too!

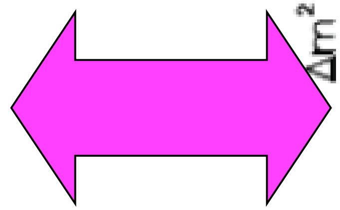
fit by Gonzalez-Garcia

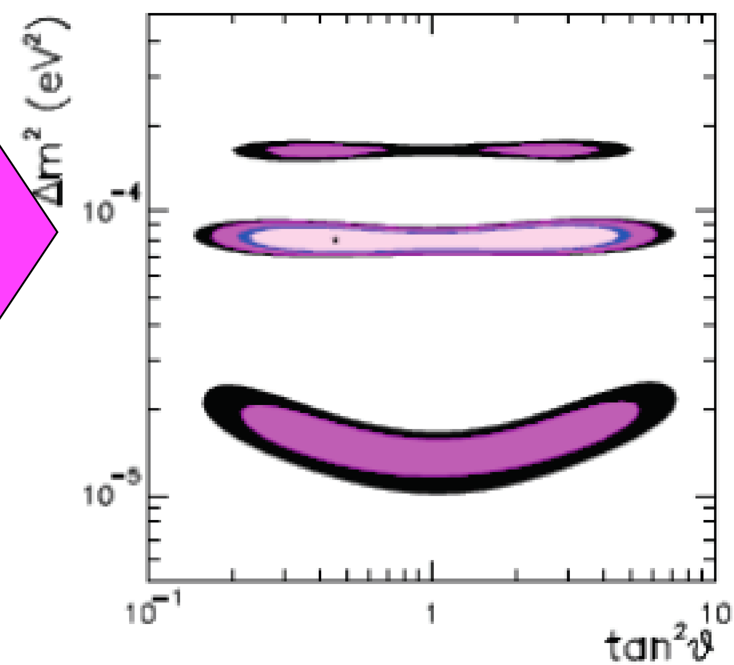
It all fits together

Allowed region for solar neutrino oscillation measurements,

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







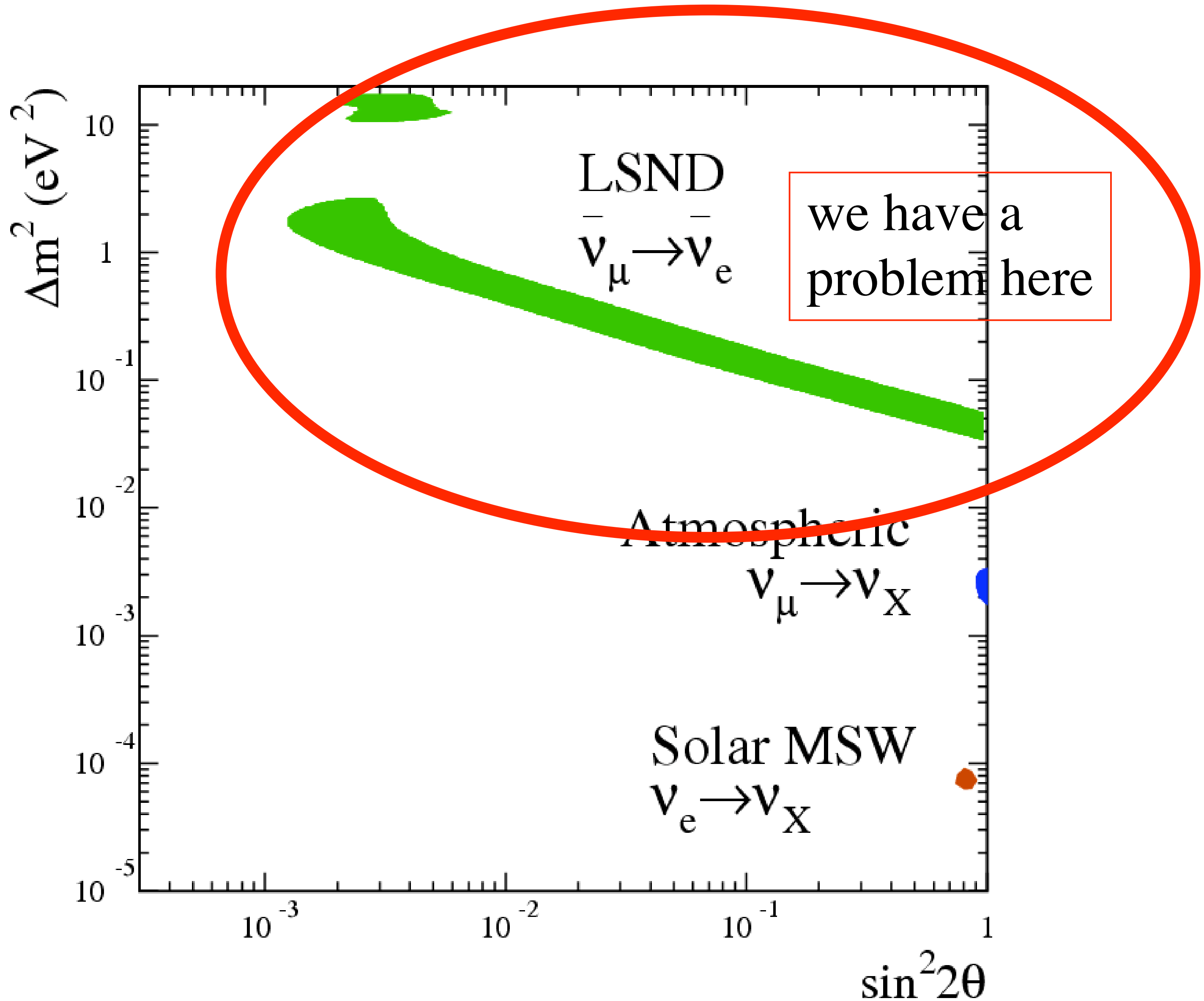
fits by Gonzalez-Garcia

So… where are we?

Our world view has changed because we see…

Oscillations at Δm^2 at ~ 10^{-3} and 10^{-5} eV^2
We see solar neutrino "morphing" that fits in.

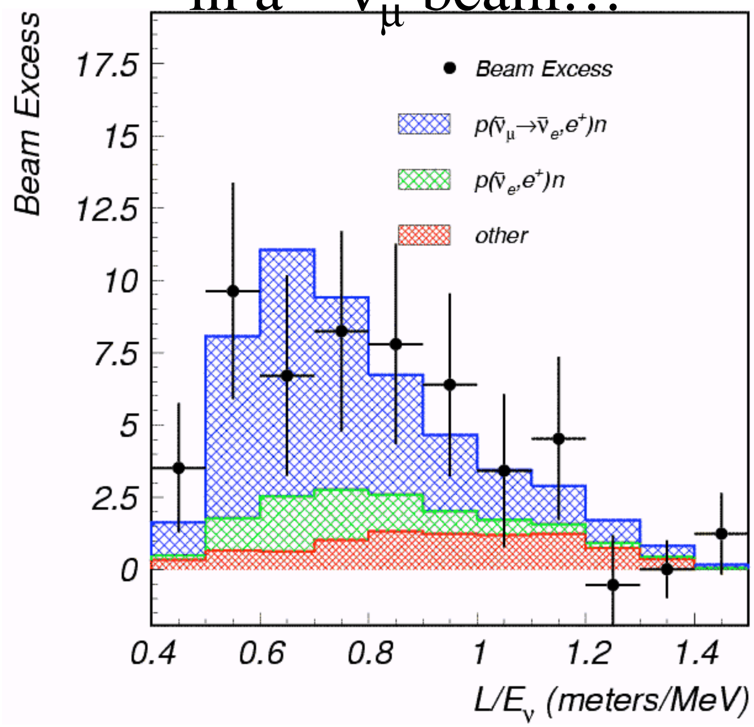
But there is other data out there,
and it's a problem…



LSND
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
we have a problem here
Atmospheric
$\nu_\mu \rightarrow \nu_X$
Solar MSW
$\nu_e \rightarrow \nu_X$
Δm^2 (eV^2)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$

LSND ran in the 1990's

An excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam…

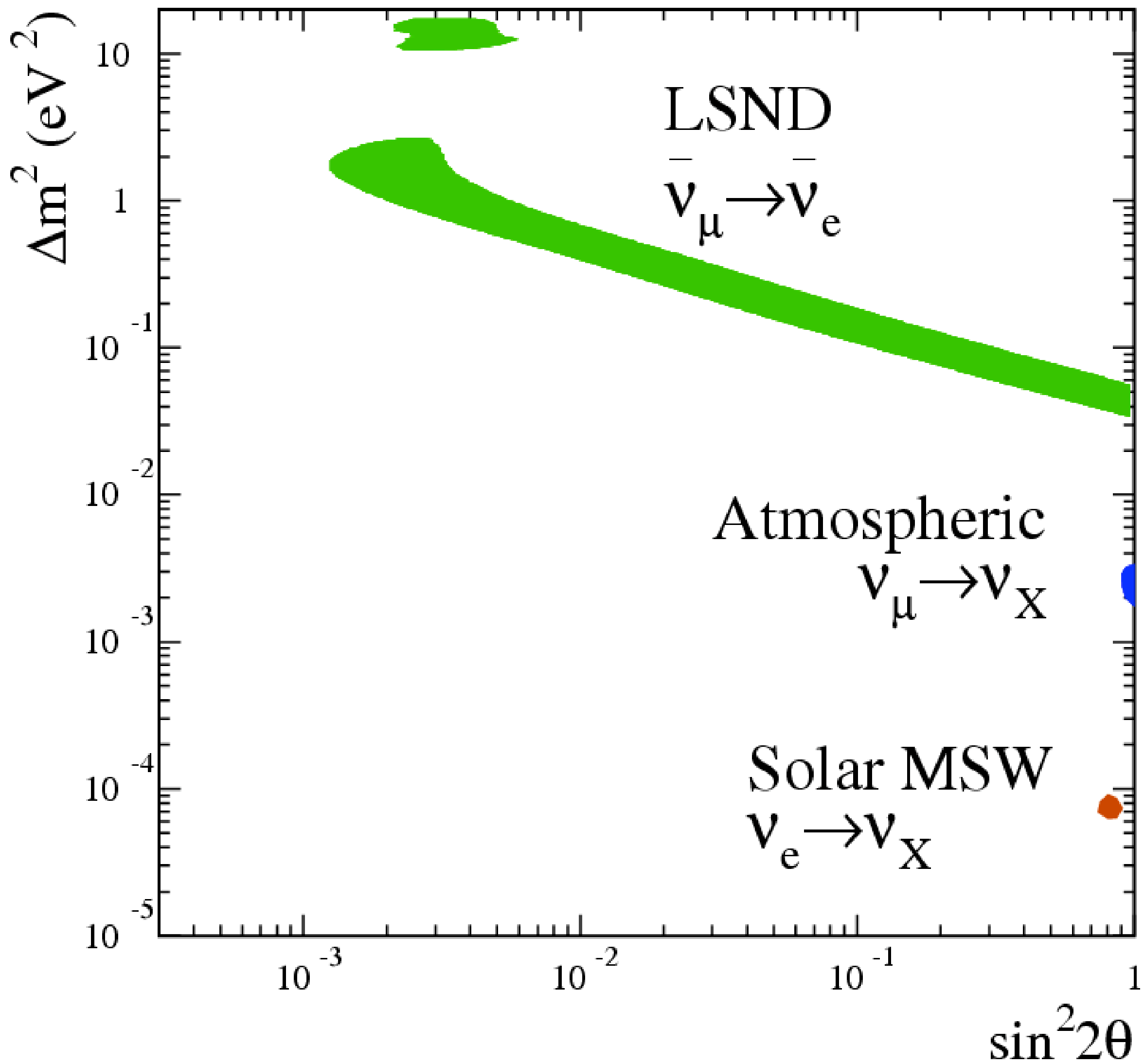


Consistent with high Δm^2
2 neutrino oscillations

This signal was a big surprise!
Best solution was very different from other signals!

- high Δm^2
- small mixing

Why is this a problem?



Three neutrino mass states yield only 2 independent mass differences

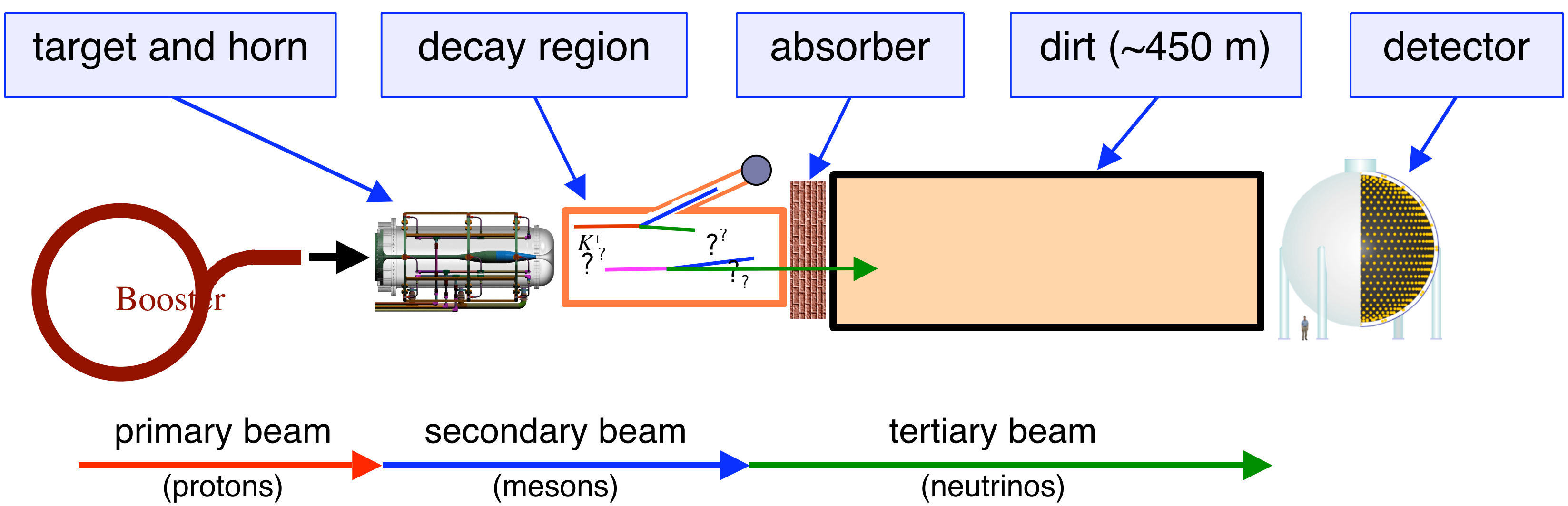
And

1E-5 + 1E-3 ≠ 1

There have now been follow-up experiments, looking for the same appearance signal and also looking for disappearance at high Δm^2

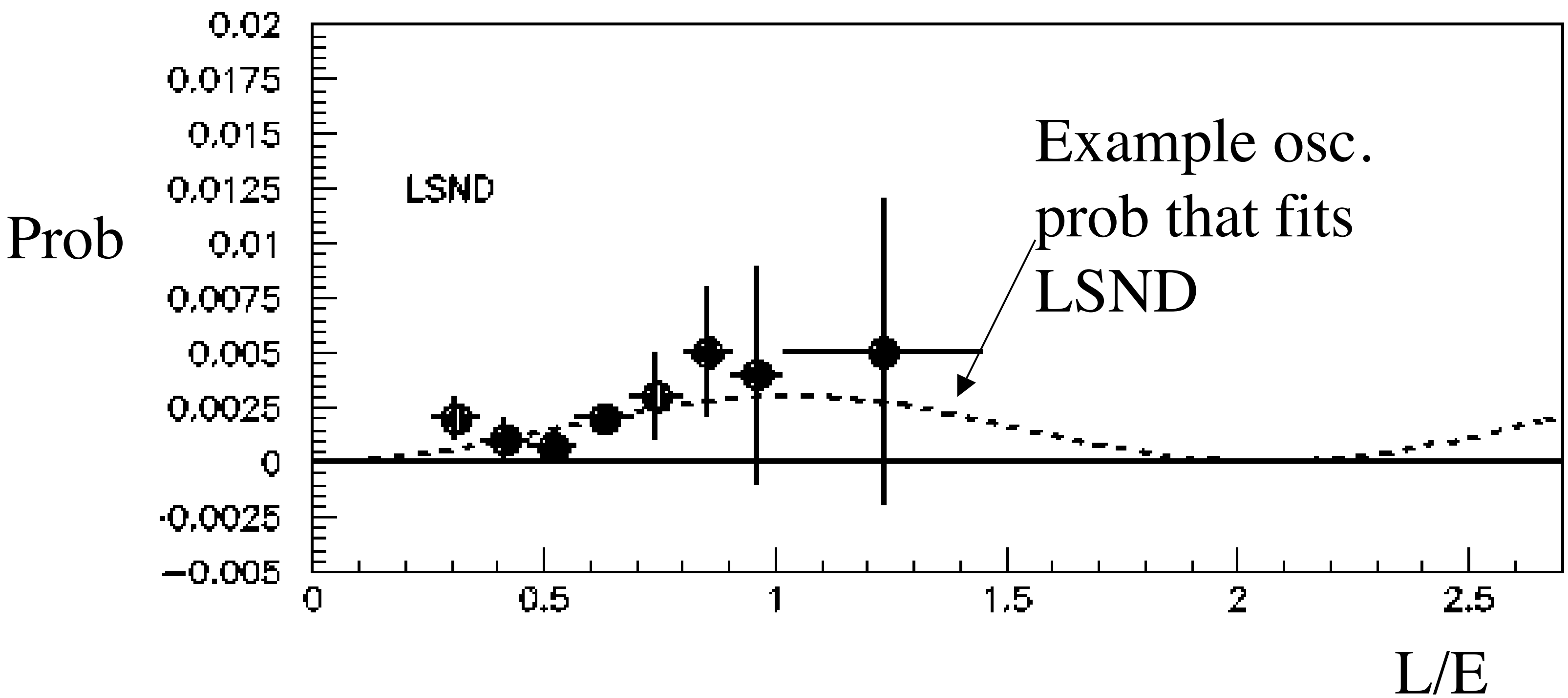
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$$

Keep L/E same while changing systematics



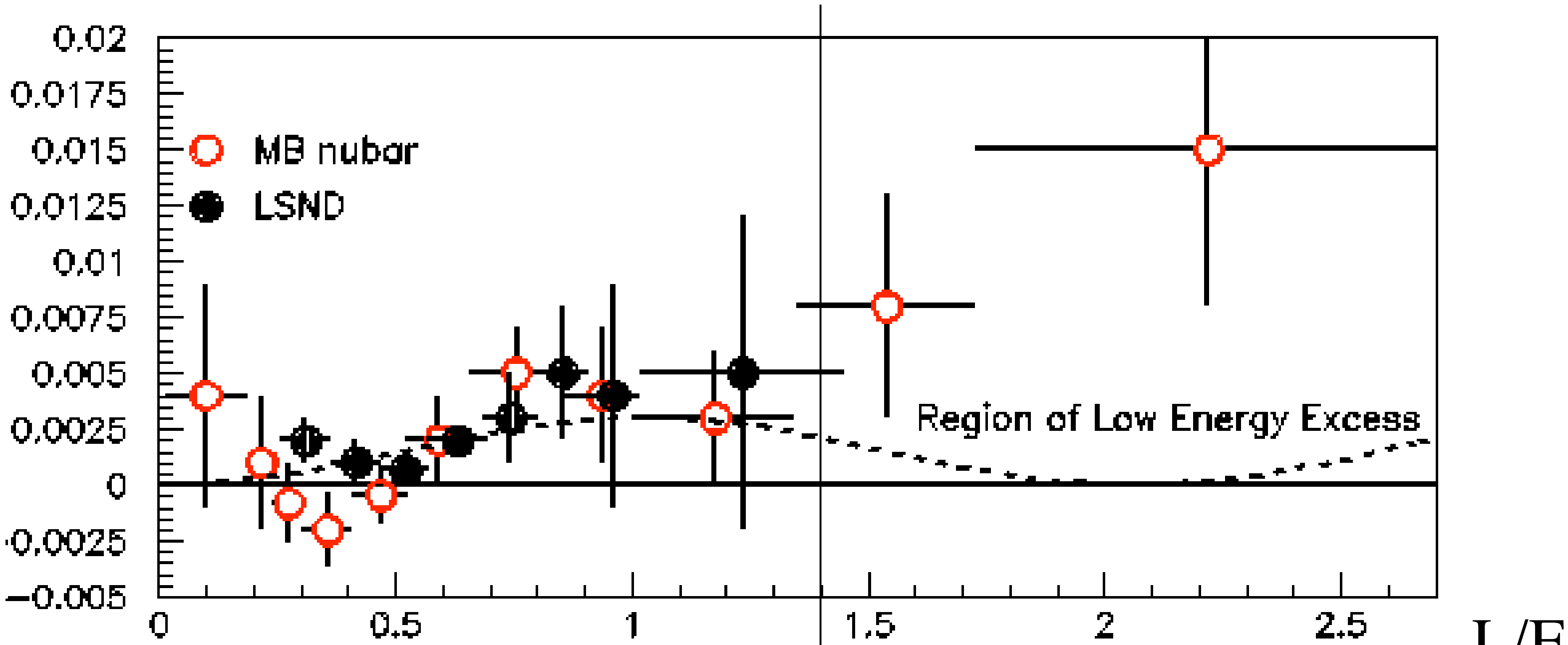
MiniBooNE

To compare LSND to other experiments,
that will have different beam energies and distances,
convert the excess into an oscillation probability
bin-by-bin…



Now lets add results from MiniBooNE, with different L and E but same L/E ratio…

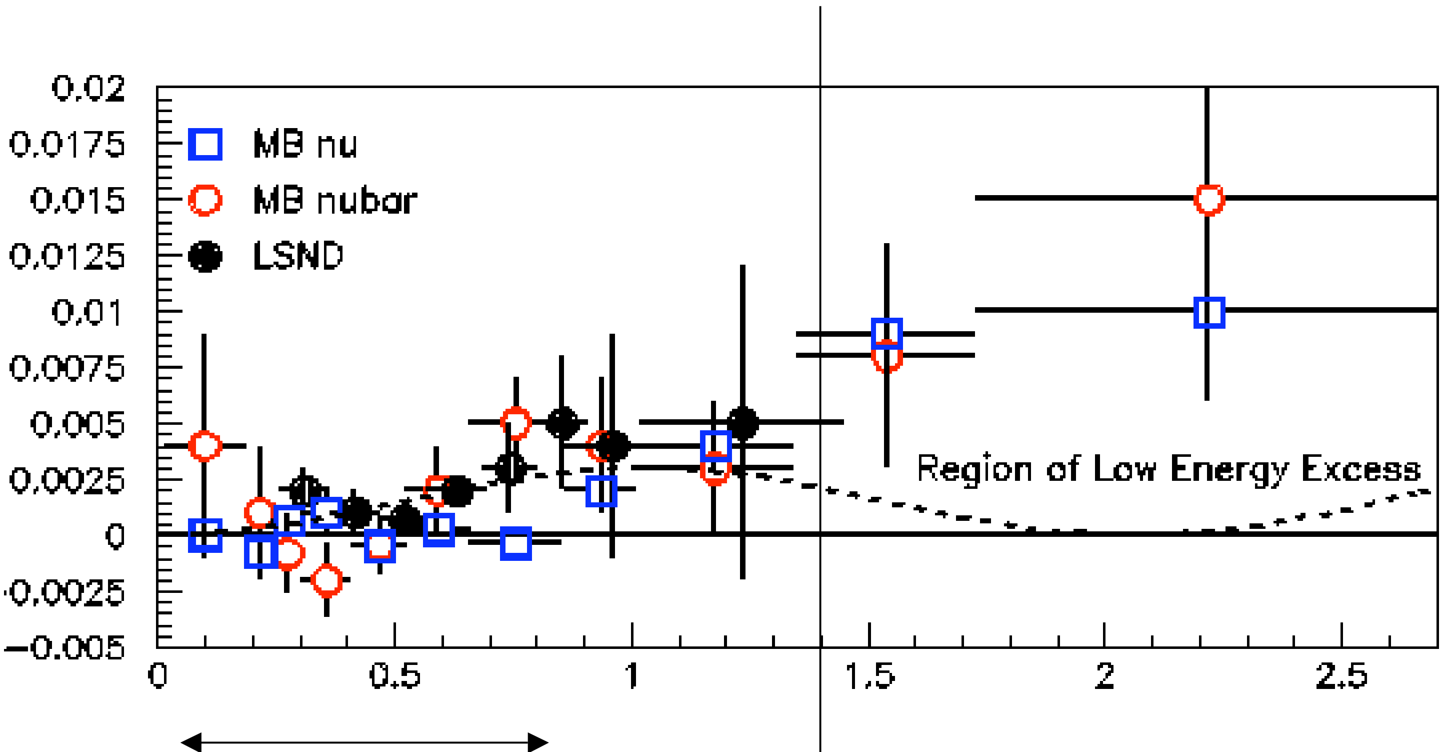
Antineutrino data first



Hmmm…
similar in this range.

What's going on here where LSND had no data?

But the neutrino data shows no oscillation in the LSND-region!



Flat and consistent with zero

But shows the same strange rise…

The issue is murky…

LSND (antinu) is the only >3σ signal

MiniBooNE has an ~2s signal in antinu mode
and no signal in neutrino mode.

Hot off the press: The reactor data (antinu) seems to be
indicating disappearance
in an overlapping Δm^2 range,
at 2.7σ

Putting these together with all other results
(nu and antinu), it is very hard to fit in models!

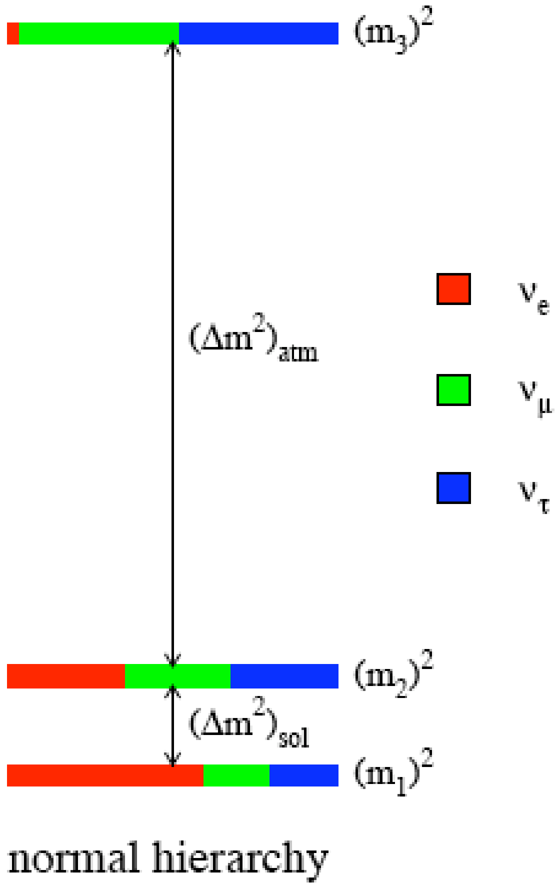
We just had a terrific workshop,
that reviewed all of these results and opportunities…

Short Baseline Neutrino Workshop -- SBNW11

https://indico.fnal.gov/conferenceDisplay.py?confId=4157

There are interesting opportunities here!

But for our discussion,
lets leave this and go back to
the atmospheric and solar oscillations.
Let’s try to make a model…

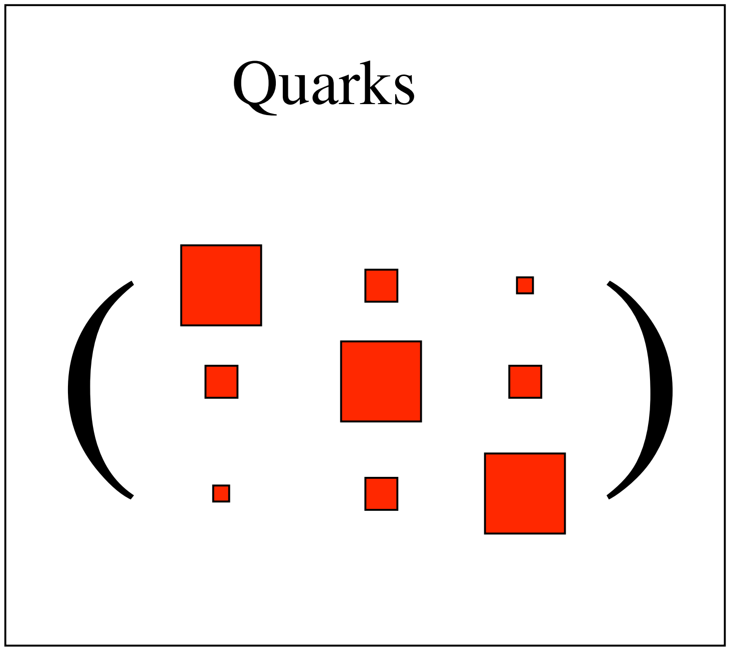


Our Model

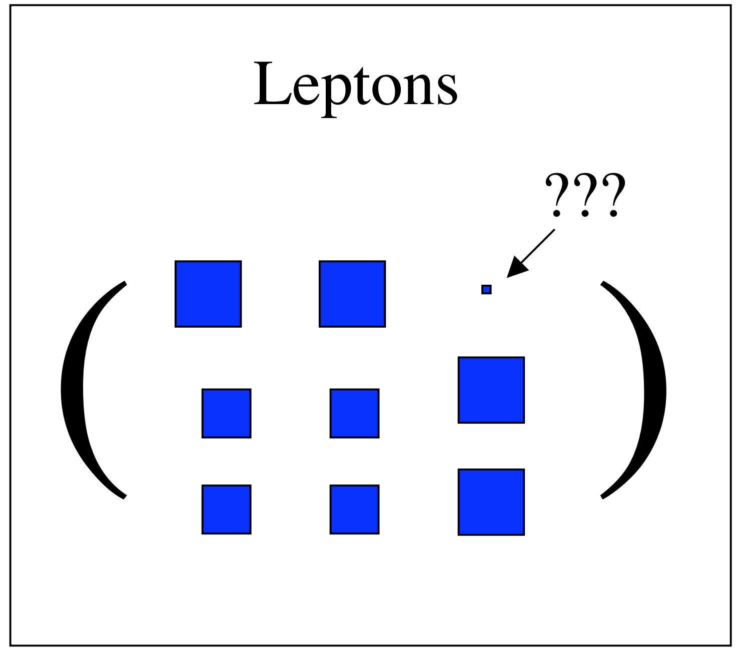
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

What we know about mixing



vs.



Large entries on diagonal
small off diagonal

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

From last week's SSI lecture

The CP Violation Parameter

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

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

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

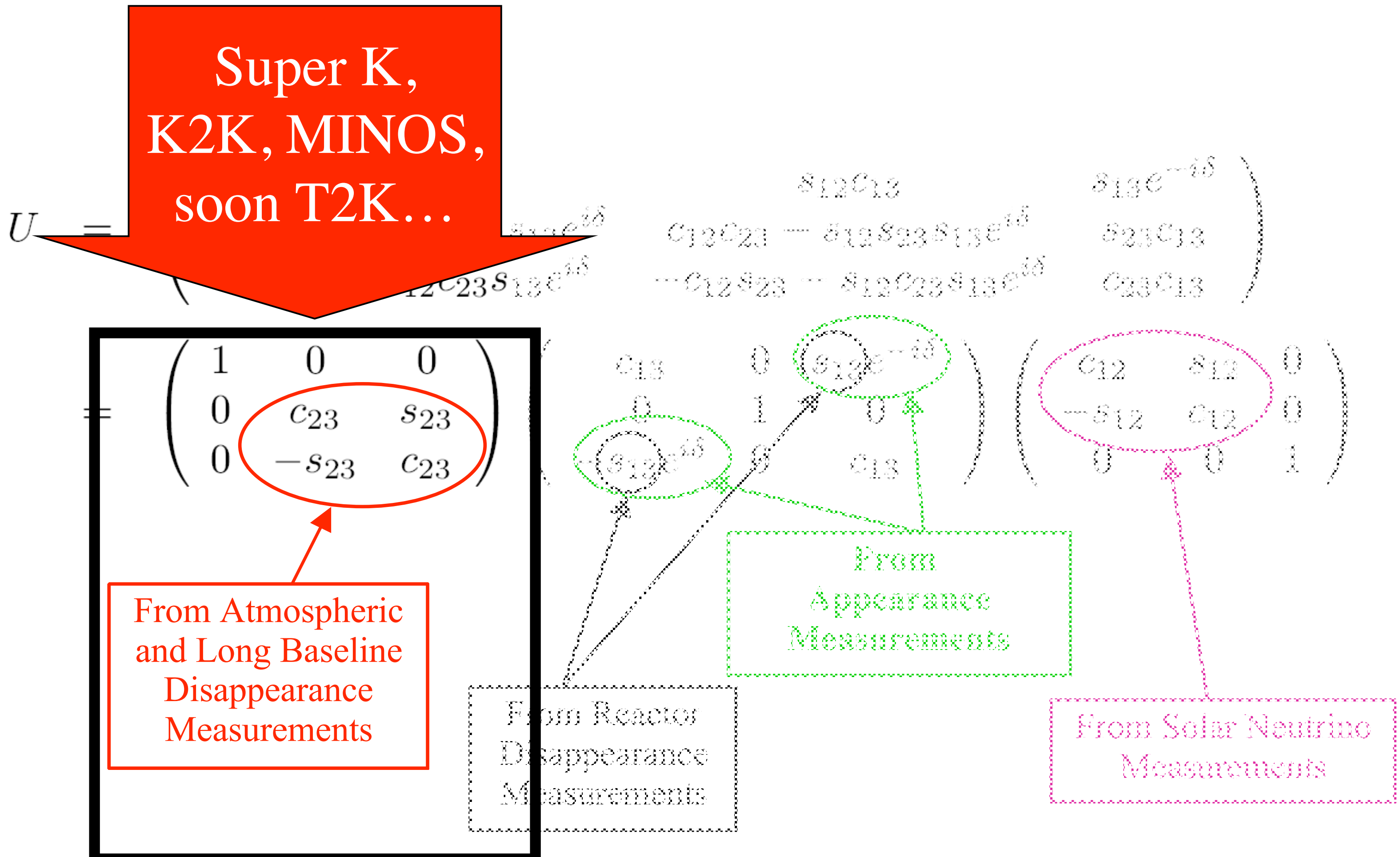
From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

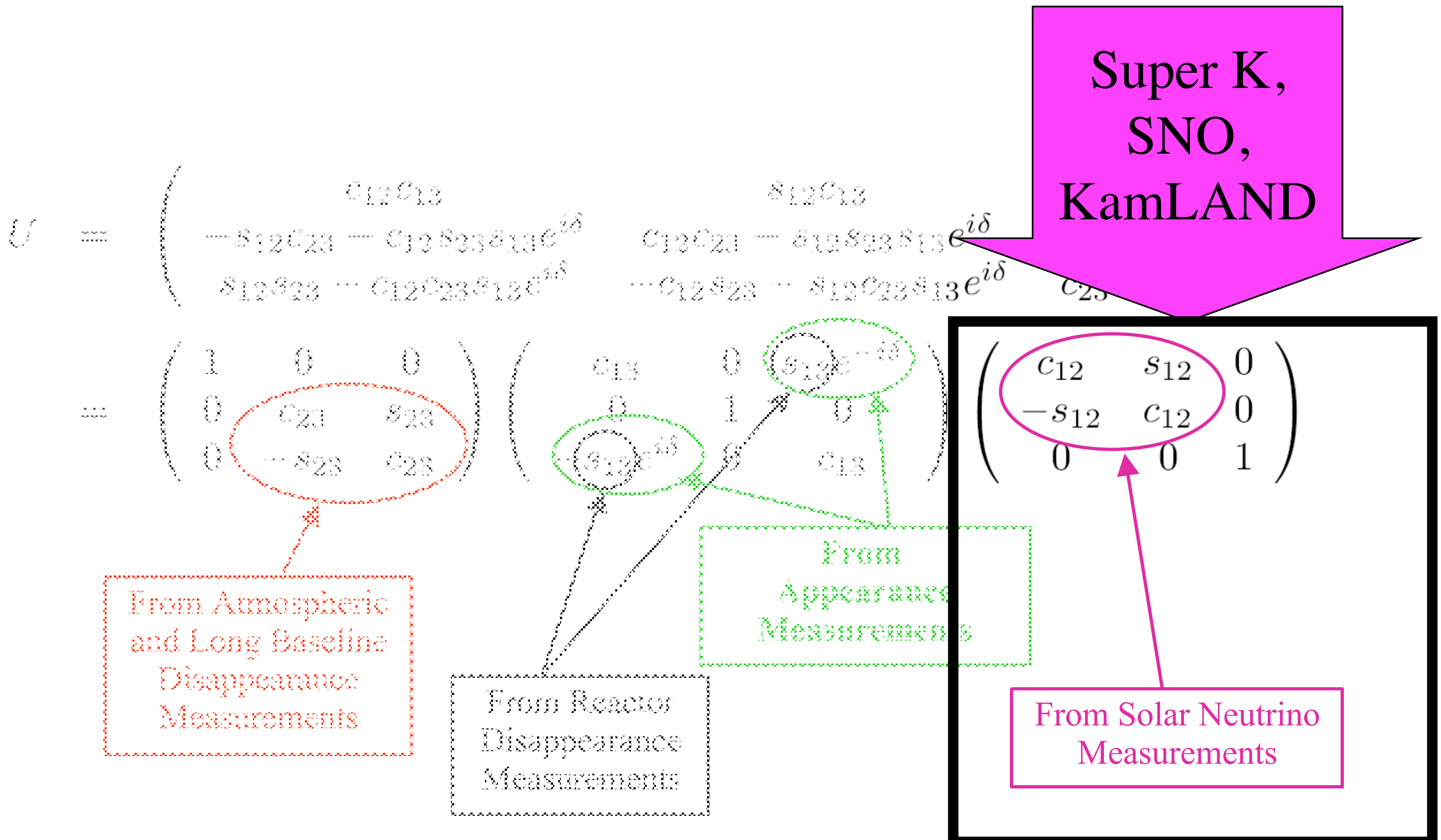
From Appearance Measurements

From Solar Neutrino Measurements

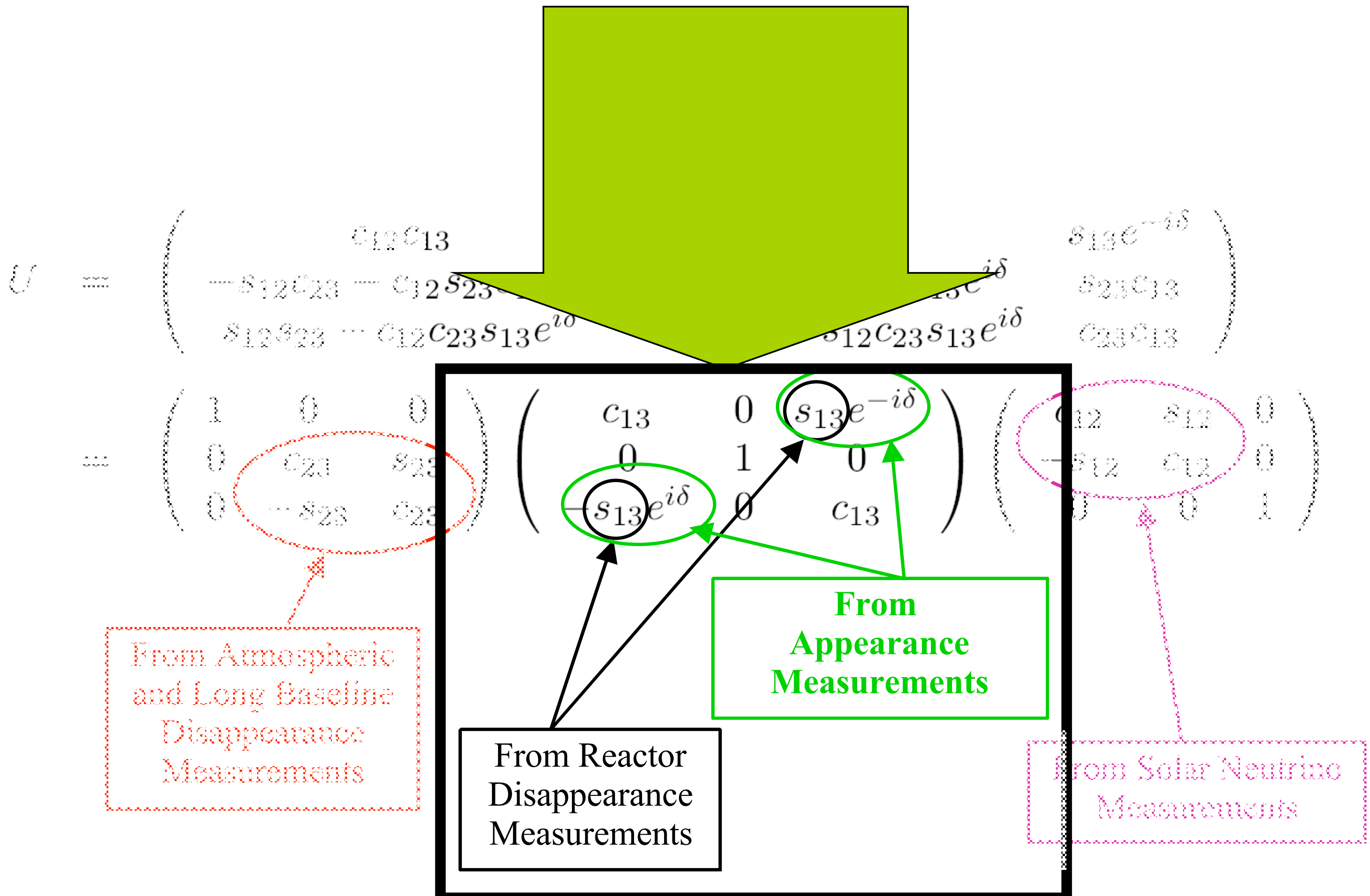
This matrix is well-known



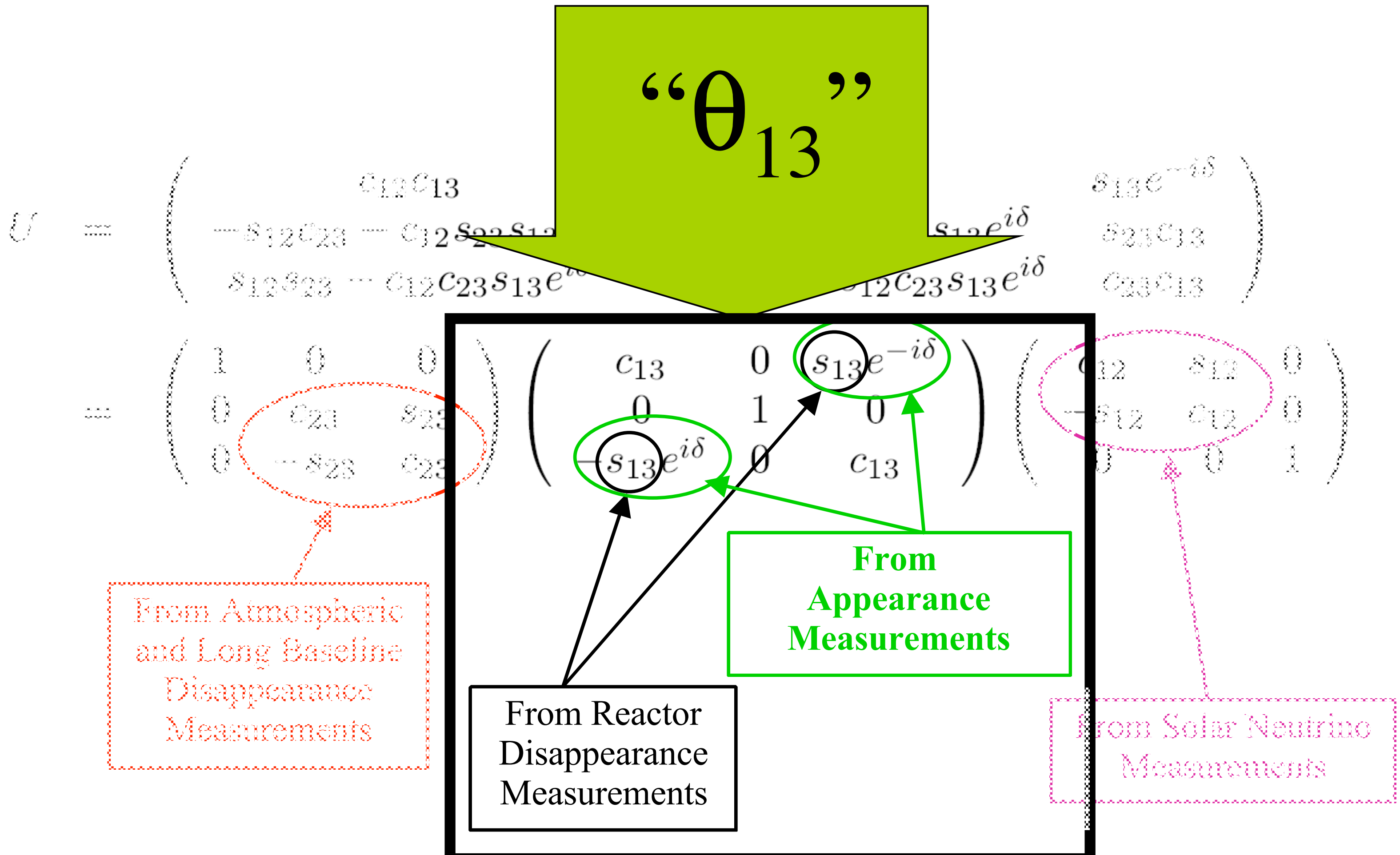
& this matrix is well-known



But this one is not known at all!

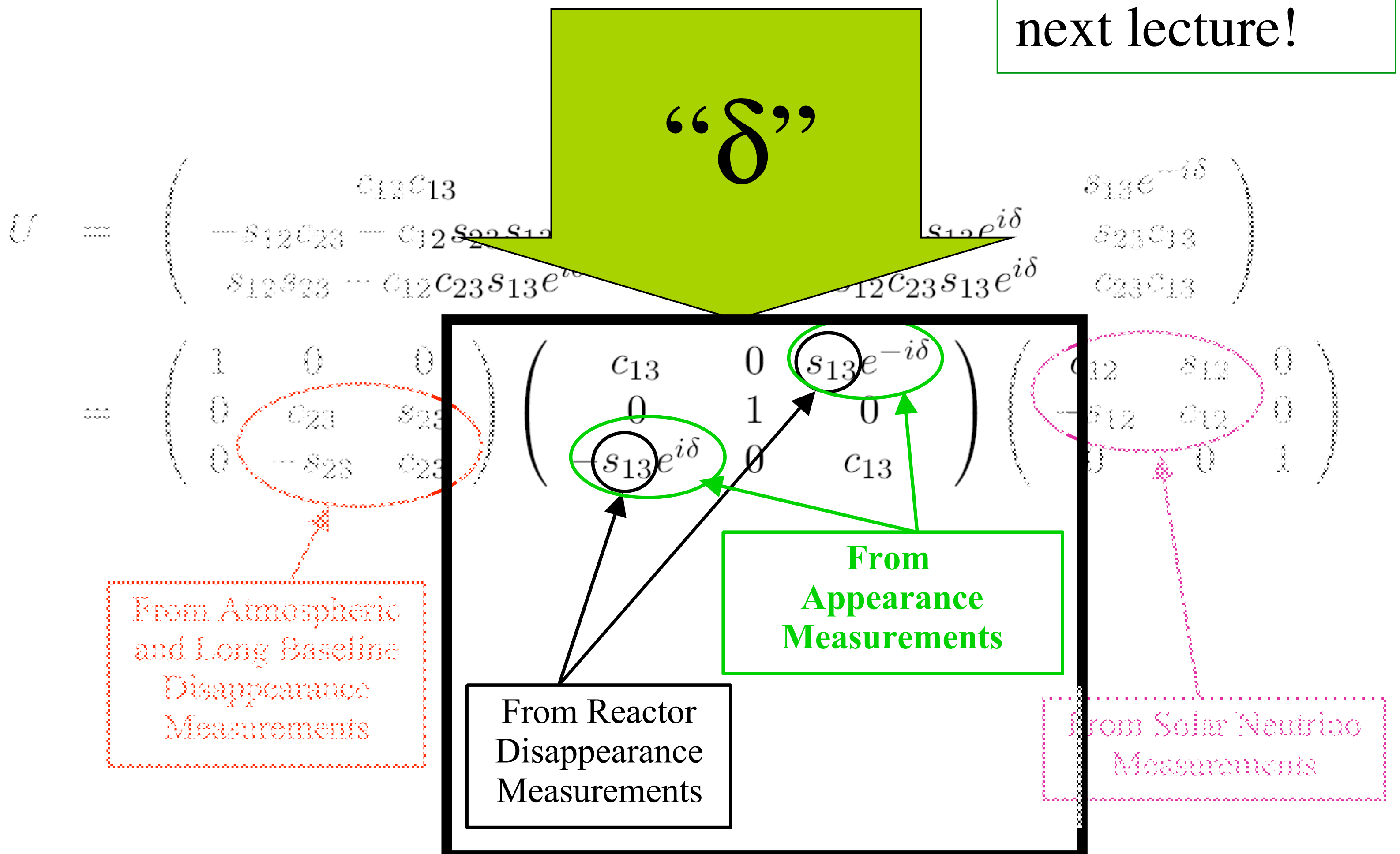


Many experiments are searching for the last mixing angle



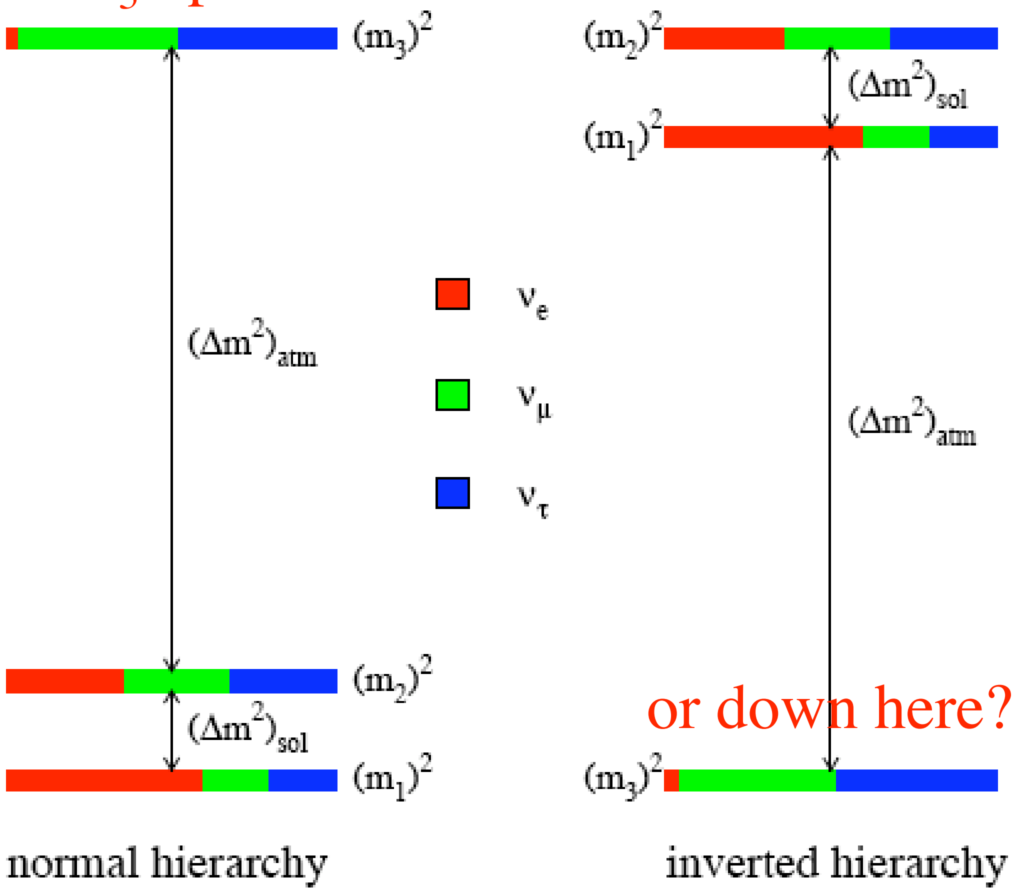
We'll discuss both parameters more in the next lecture!

As well as …

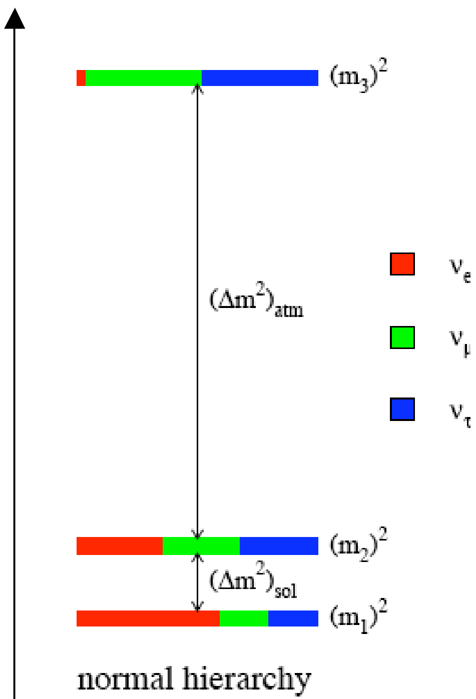


What do we not know about the masses?
The hierarchy:

Is ν_3 up here?



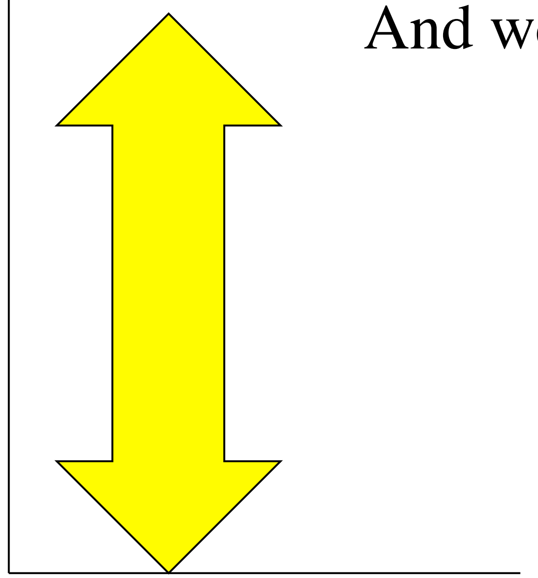
} we know the order of these two from the solar neutrino morphing model



And now in our model,
the mass an experiment like KATRIN measures
is much more complicated

$$\langle m_\beta \rangle^2 = \sum_j m_j^2 |U_{ej}|^2 = m_1^2 |U_{e1}|^2 + m_2^2 |U_{e2}|^2 + m_3^2 |U_{e3}|^2$$

And we do not know the offset!



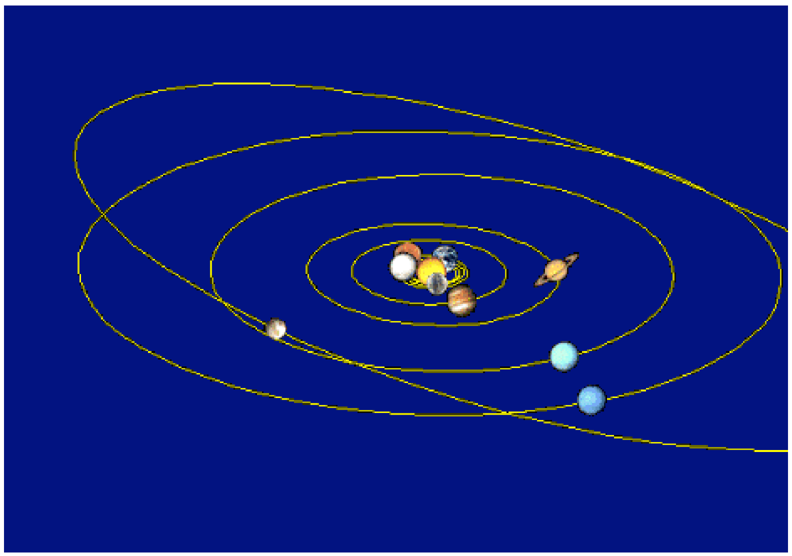
The smallest that the neutrino masses can possibly be, is the case where the lowest state is exactly zero (which would be weird)

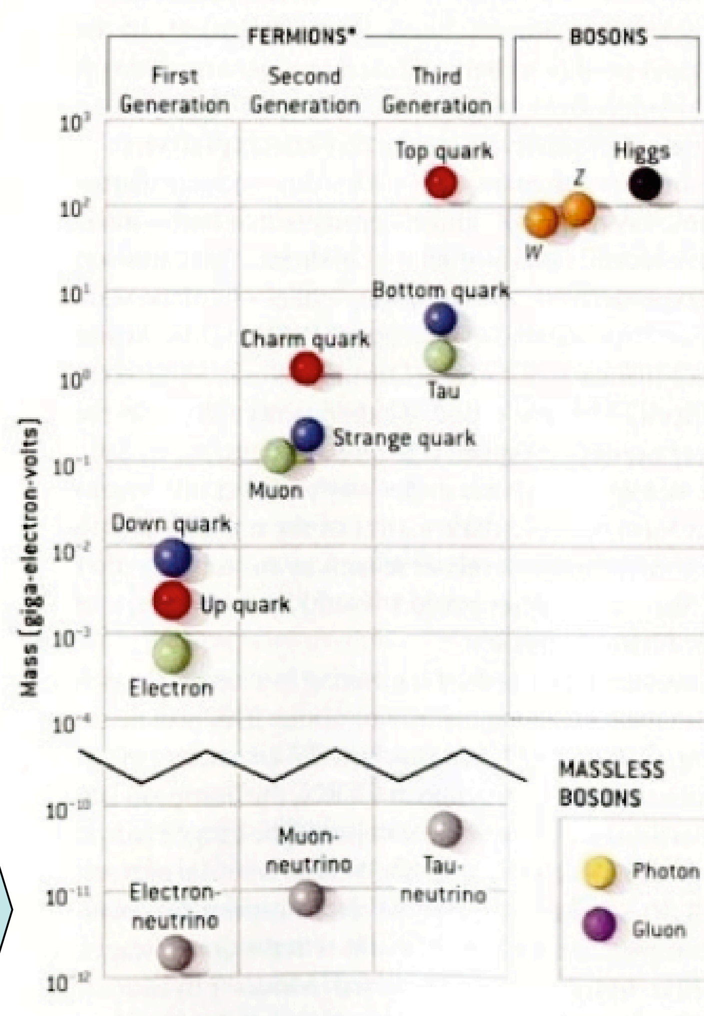
Just to be provocative….

Does the smallness of the mass *really* mean anything?

Or is the smallness an accident of a huge range of choices?

Like the orbits of planets?



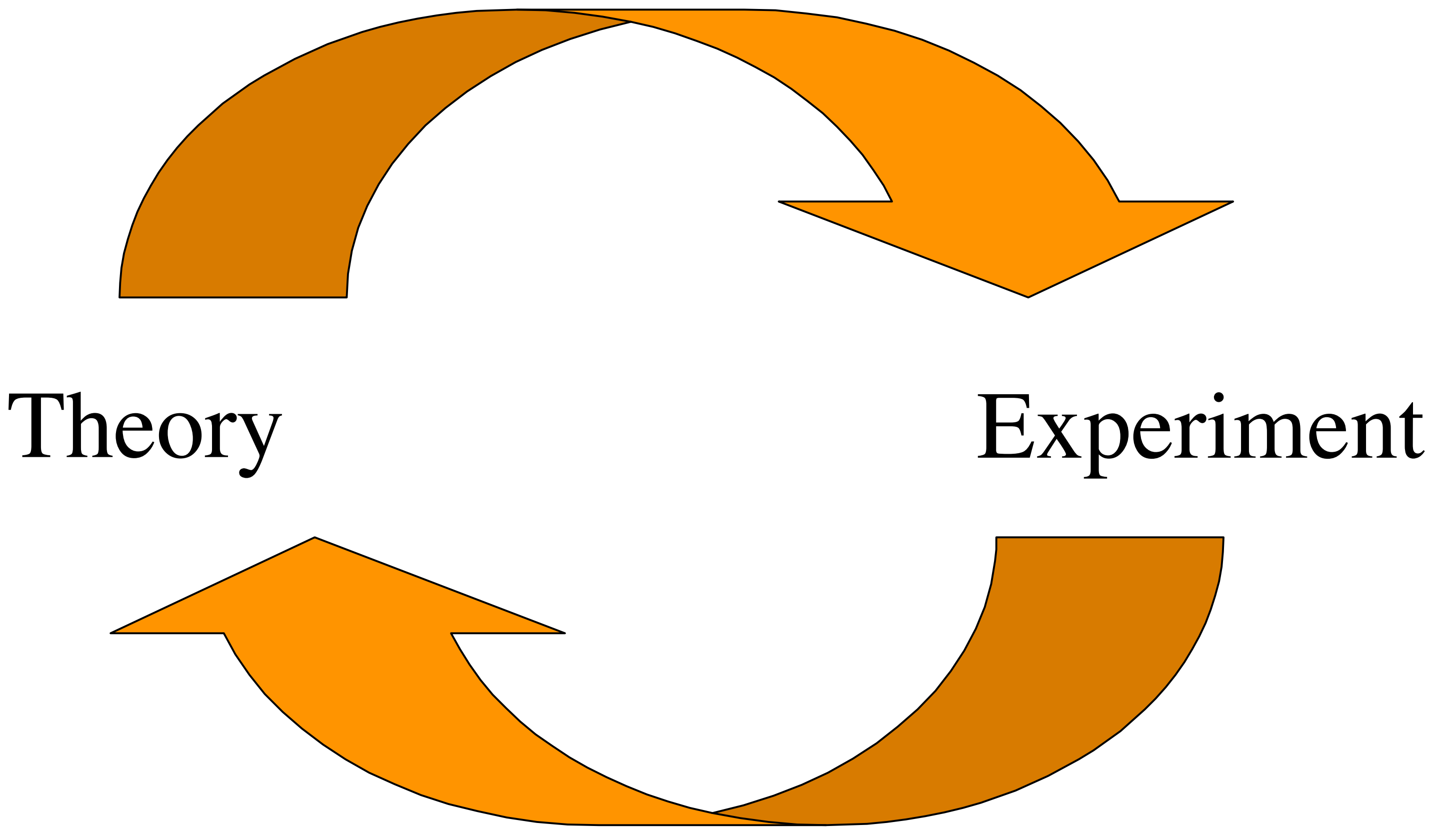


mass if you just take

$\sqrt{\Delta m^2}$ as the mass

ν ν ν

Can we make a “nu” Standard Model?


Theory
Experiment

1. Neutrinos are Majorana
2. And have CP violation
3. and GUT scale partners

Three happy theoretical consequences:

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

1. Neutrinos are Majorana
2. And have CP violation
3. and GUT scale partners

Three happy theoretical consequences:

1) You get a neutrino which is very light
2) You get a natural connection to GUT models
3) There is a mechanism for leptogenesis

What’s a Majorana neutrino?

The spin defines particle vs. antiparticle

This is the antiparticle

and this is the particle

… but it is all the same “thing”

A simple solution to the handedness problem in the theory!

This is only possible if there is no charge that distinguishes a particle vs antiparticle

Clearly not true in EM!

Also not true for the strong force.

But possibly true of the weak force!

Our Model:

1. Neutrinos are Majorana
2. And have CP violation
3. and GUT scale partners

Recall from the lecture on CP-violation

Any 3×3 unitary matrix has

3 associated free parameters (Euler angles)

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

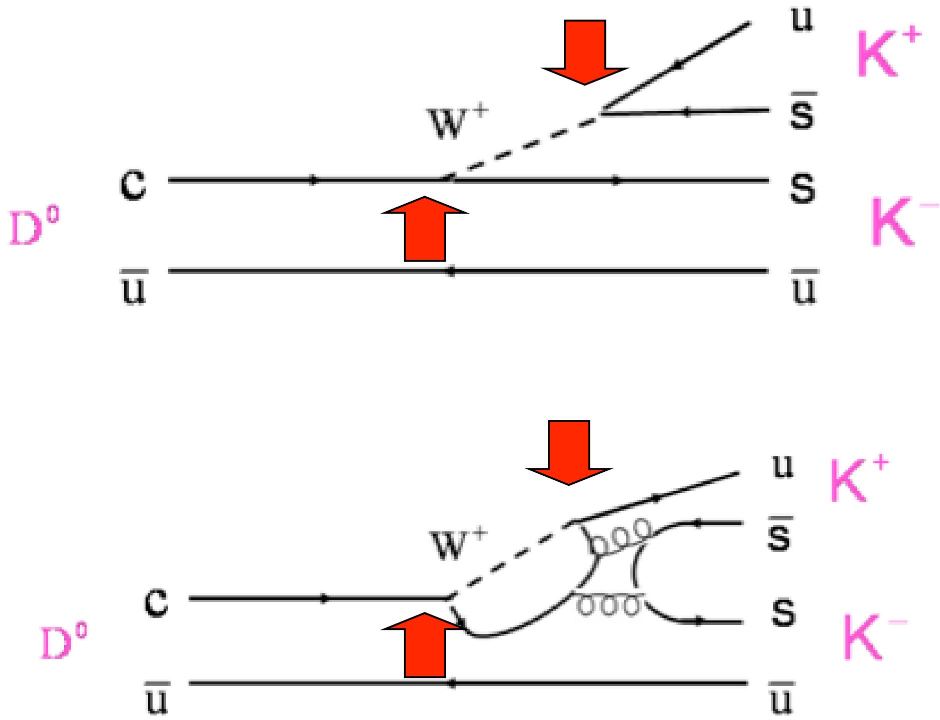
& can have a complex phase hidden in it!

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

This “CP violating phase” can lead to a different decay rate for matter vs. antimatter

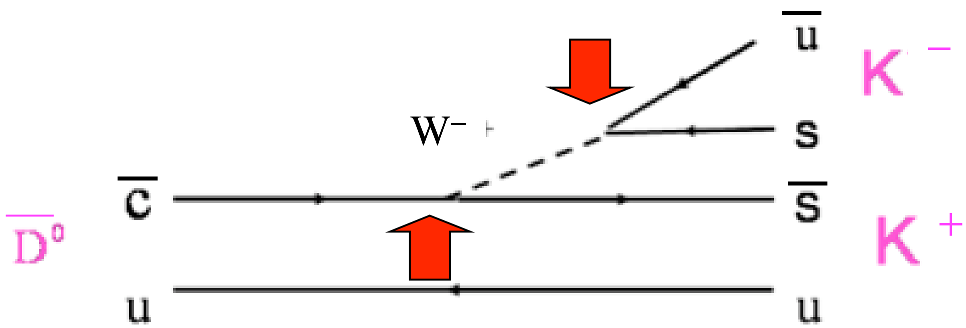
The effect shows up in weak decays

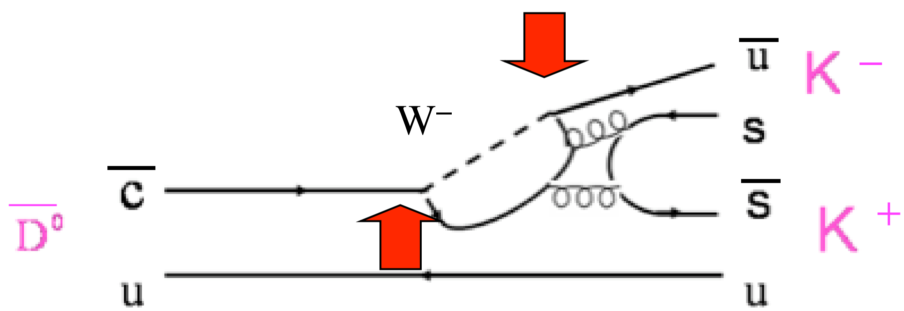
when you have 2 paths to the same outcome…



You will get an
<u>interference term</u>
in the decay probability…

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





There are still 2 paths to the outcome.

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

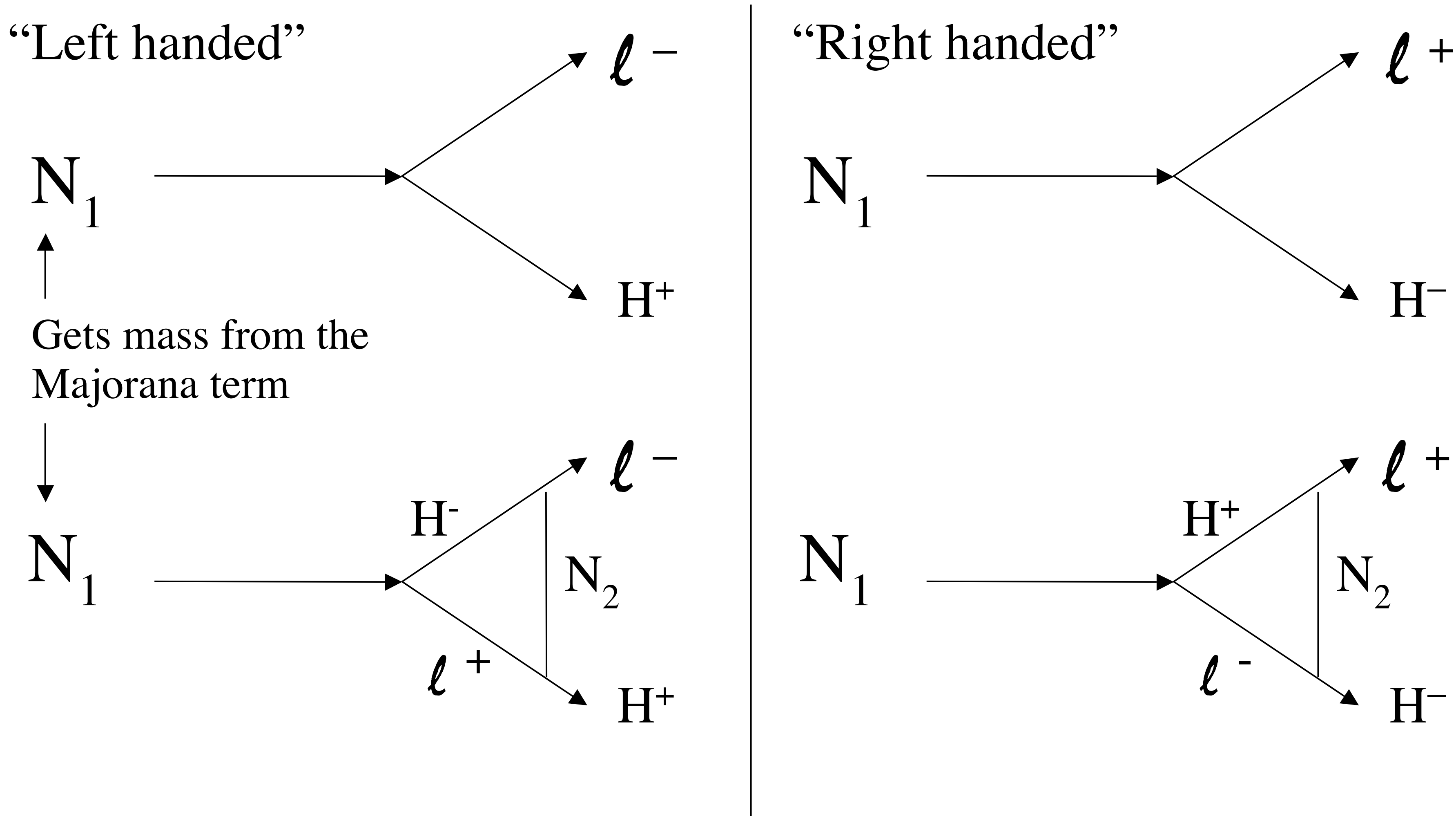
e.g. D^0 and $\overline{D^0}$ decays can have different decay rates
if δ is nonzero!

Our Model:

1. Neutrinos are Majorana
2. And have CP violation
3. and GUT scale partners

Lets say neutrinos have VERY heavy partners,
and those partners can decay,
and that a phase appears in the loops associated
with the decay…

Before the electroweak phase transition…



The interference terms will have opposite sign!

(This should tie back to your SSI lectures on Leptogenesis)

This phase is a “Majorana Phase”

A similar Majorana phase would appear in U
if the light neutrinos are Majorana

$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\theta_{23} & s\theta_{23} \\ 0 & -s\theta_{23} & c\theta_{23} \end{pmatrix} \begin{pmatrix} c\theta_{13} & 0 & s\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s\theta_{13}e^{i\delta} & 0 & c\theta_{13} \end{pmatrix} \begin{pmatrix} c\theta_{12} & s\theta_{12} & 0 \\ -s\theta_{12} & c\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

And in most theories, if the α’s are nonzero
then δ is nonzero…

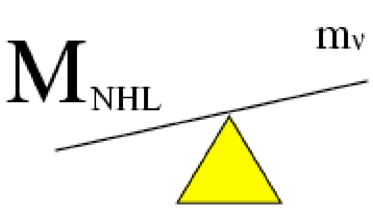
A great topic for young theorists:
understanding the connections better, making them predictive

Connecting the circle back to light neutrino mass….

If the neutrino is Majorana, then
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:
  $(M_L/2)(\bar{\psi}^c{}_L \psi_L) + (M_R/2)(\bar{\psi}^c{}_R \psi_R) + \ldots$
  "Majorana mass terms"

This provides a natural explanation for tiny neutrino masses, through mixing with the heavy partner
(The same heavy partner responsible for leptogenesis)



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

Proof of this "New Paradigm" will be circumstantial for a while…

It will be a long, long time,
before experiments are sensitive to GUT scale particles.

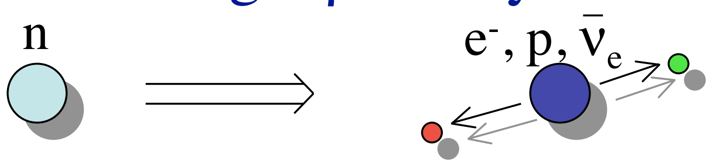
But…

You can have modified seesaw models that invoke
particles at LHC scales!

You can look for CP violation in the light neutrinos (δ)
because this is expected to be connected to the α's

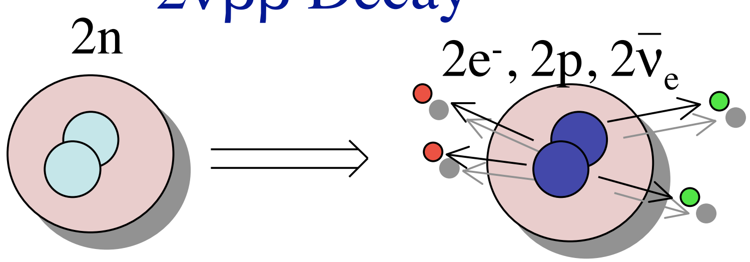
You can test if neutrinos are Majorana…

Single β Decay

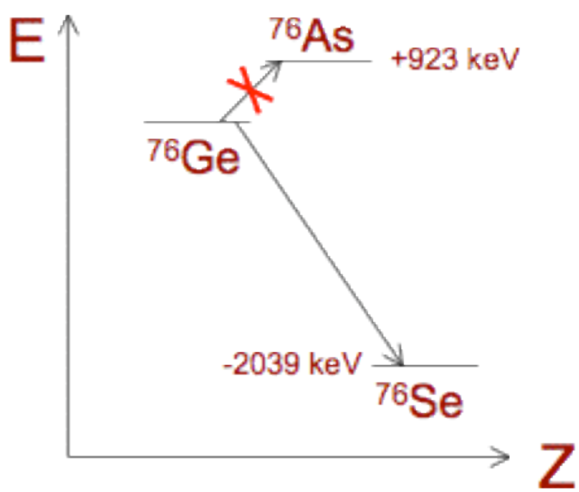


Half-life: About 10 minutes

2νββ Decay



Can occur if single β decay is energetically forbidden



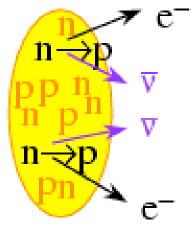
Half-life: $10^{18\text{-}24}$ years

^{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

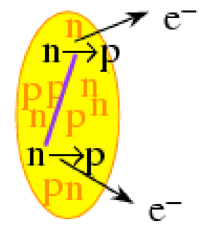
$$(Z,A) \rightarrow (Z+2,A) + (e\text{-}\ e\text{-}\ \cancel{\bar{\nu}_e\ \bar{\nu}_e})$$

Nuclei that do this…



2νββ

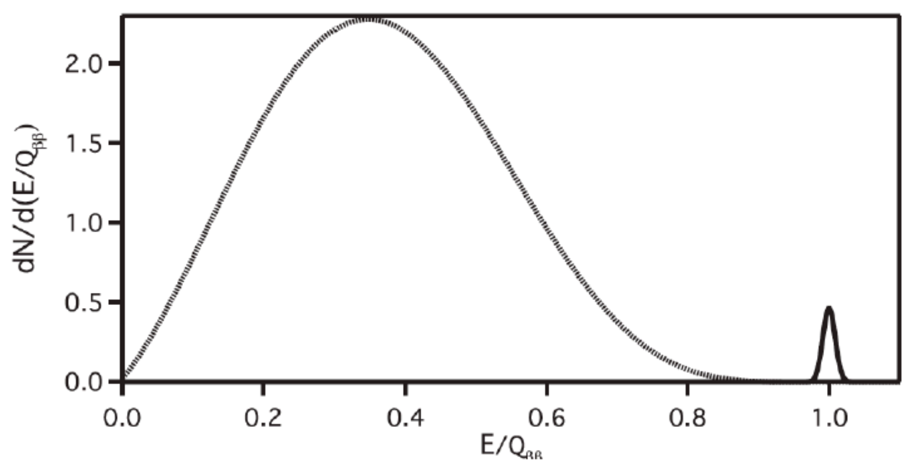
Can sometimes also do this



0νββ

IF neutrinos are their own antiparticles

The tell-tale signature is in the electron energy spectrum:



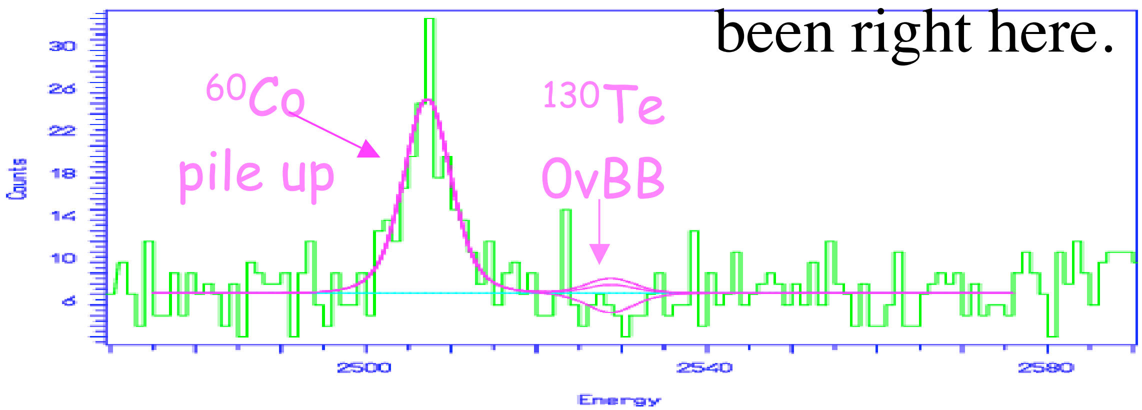
The Q-value of the decay tells you exactly where to look

Knowing where to look is crucial to rejecting backgrounds!

e.g. results from Cuoricino

This peak is a background

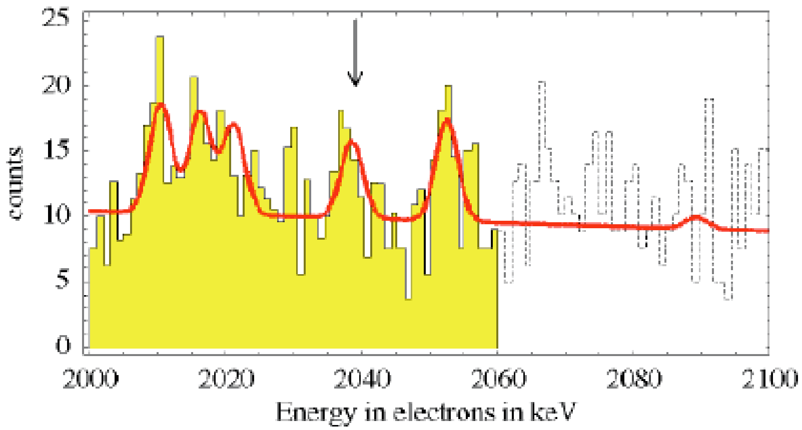
If a signal had been seen it would have been right here.



From this, Cuoricino sets a limit on this process

A controversial result! The Heidelberg-Moscow Signal

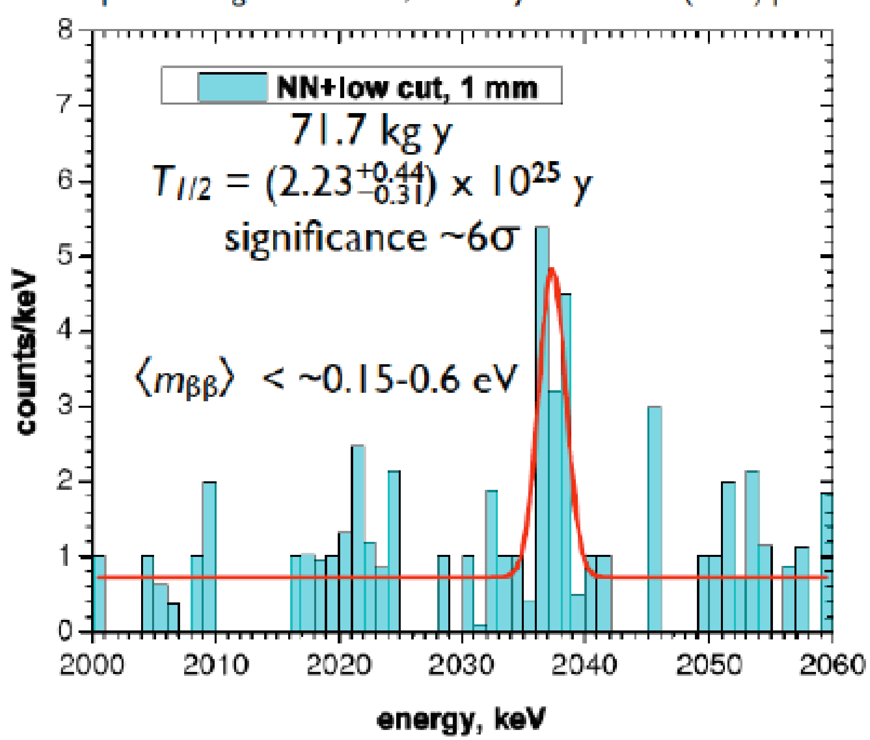
The first result:



This is where $0\nu\beta\beta$ says there should be a peak…

The final analysis had cuts to eliminate backgrounds:

Klapdor Kleingrothaus *et al.*, Mod. Phys. Lett. A **21** (2006) p 1547.



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?)

From this you can see why measuring the Majorana CP violation phases (ϕ_1,ϕ_2) is very difficult…

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

You need to compare the measured lifetime to the predicted lifetime,

Where this term is predicted from the light neutrino mixing matrix…

The problem is here!
This has theoretical errors ~ ×2 !!!

Allowing for CP Violation…

$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\theta_{23} & s\theta_{23} \\ 0 & -s\theta_{23} & c\theta_{23} \end{pmatrix} \begin{pmatrix} c\theta_{13} & 0 & s\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s\theta_{13}e^{i\delta} & 0 & c\theta_{13} \end{pmatrix} \begin{pmatrix} c\theta_{12} & s\theta_{12} & 0 \\ -s\theta_{12} & c\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

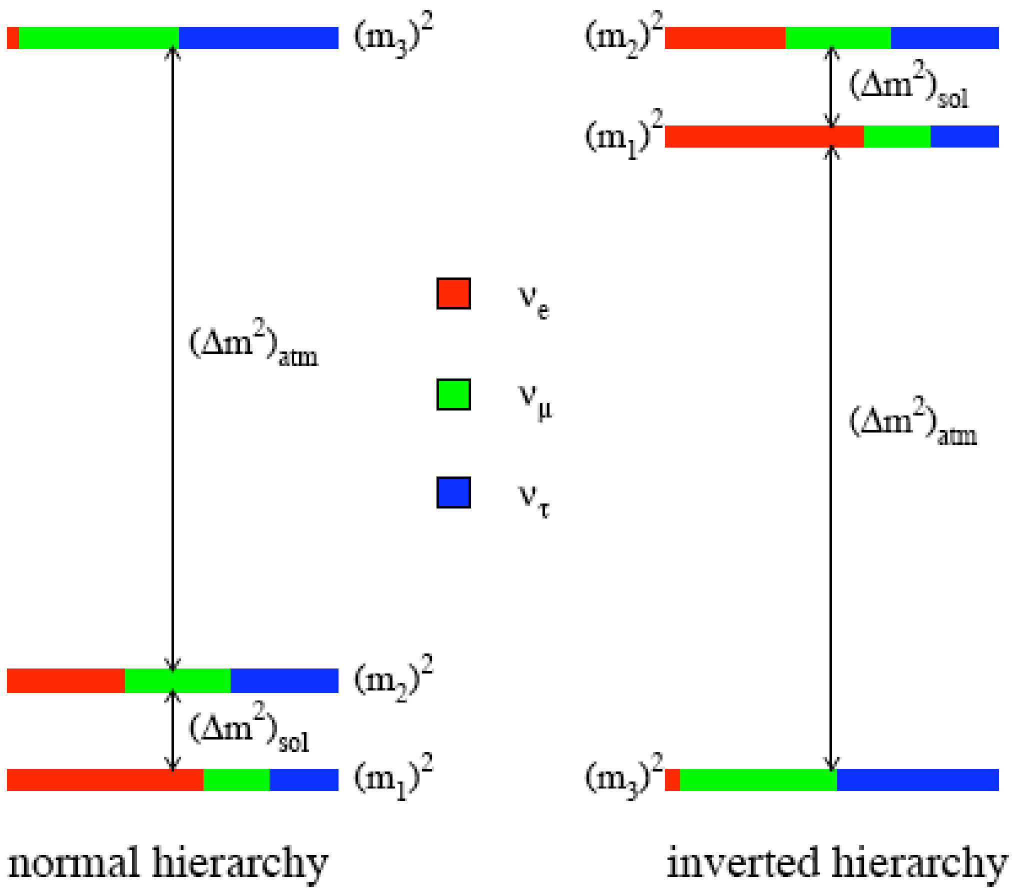
$$\langle m_{\beta\beta} \rangle \equiv \left| \sum_k m_k U_{ek}^2 \right| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i(\alpha_2 - \alpha_1)} \right.$$

$$\left. + m_3 |U_{e3}|^2 e^{i(-\alpha_1 - 2\delta)} \right|$$

Complementary to what you measure in direct searches, like Katrin (or infer from cosmology)…

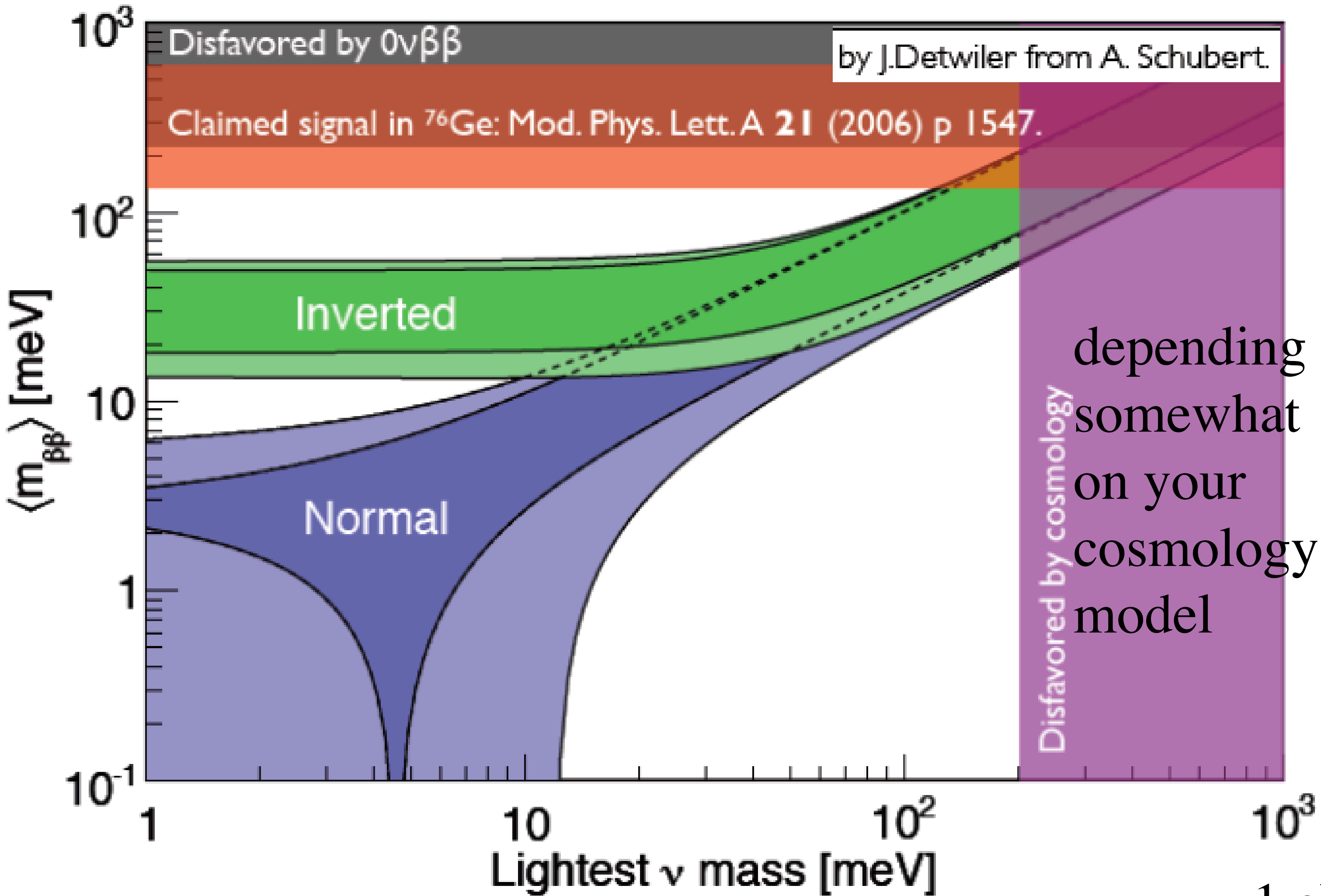
$$\langle m_\beta \rangle^2 = \sum_j m_j^2 |U_{ej}|^2 = m_1^2 |U_{e1}|^2 + m_2^2 |U_{e2}|^2 + m_3^2 |U_{e3}|^2$$

In 0νββ, having the inverted hierarchy really helps the search!



It means a lot of electron flavor in the <u>highest</u> mass state!

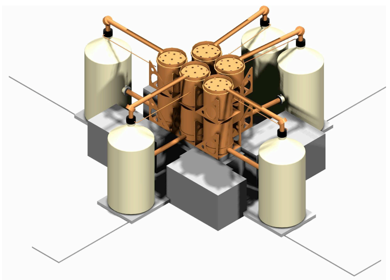
Where we are at right now…

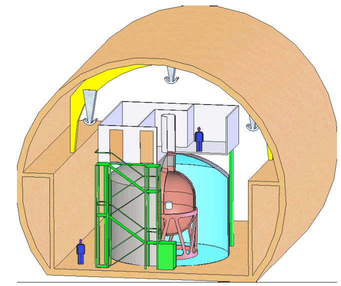


depending somewhat on your cosmology model

1 eV

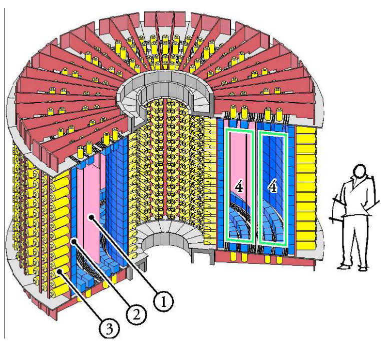
$0\nu\beta\beta$ is a big industry for the future!

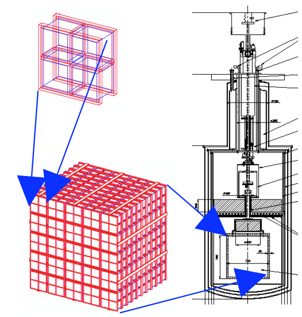




GERDA: Bare Ge crystals in LN

CUORE: TeO_2 crystal bolometer

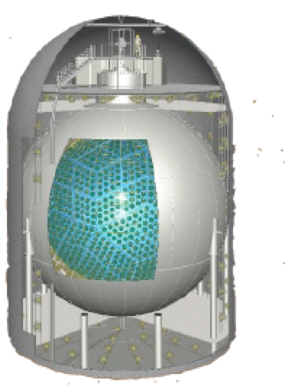


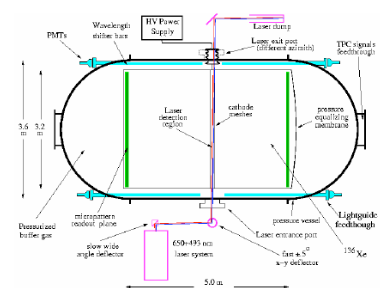


EXO: Liquid Xenon with Ba tagging

XEN: KamLAND w/ Xe gas

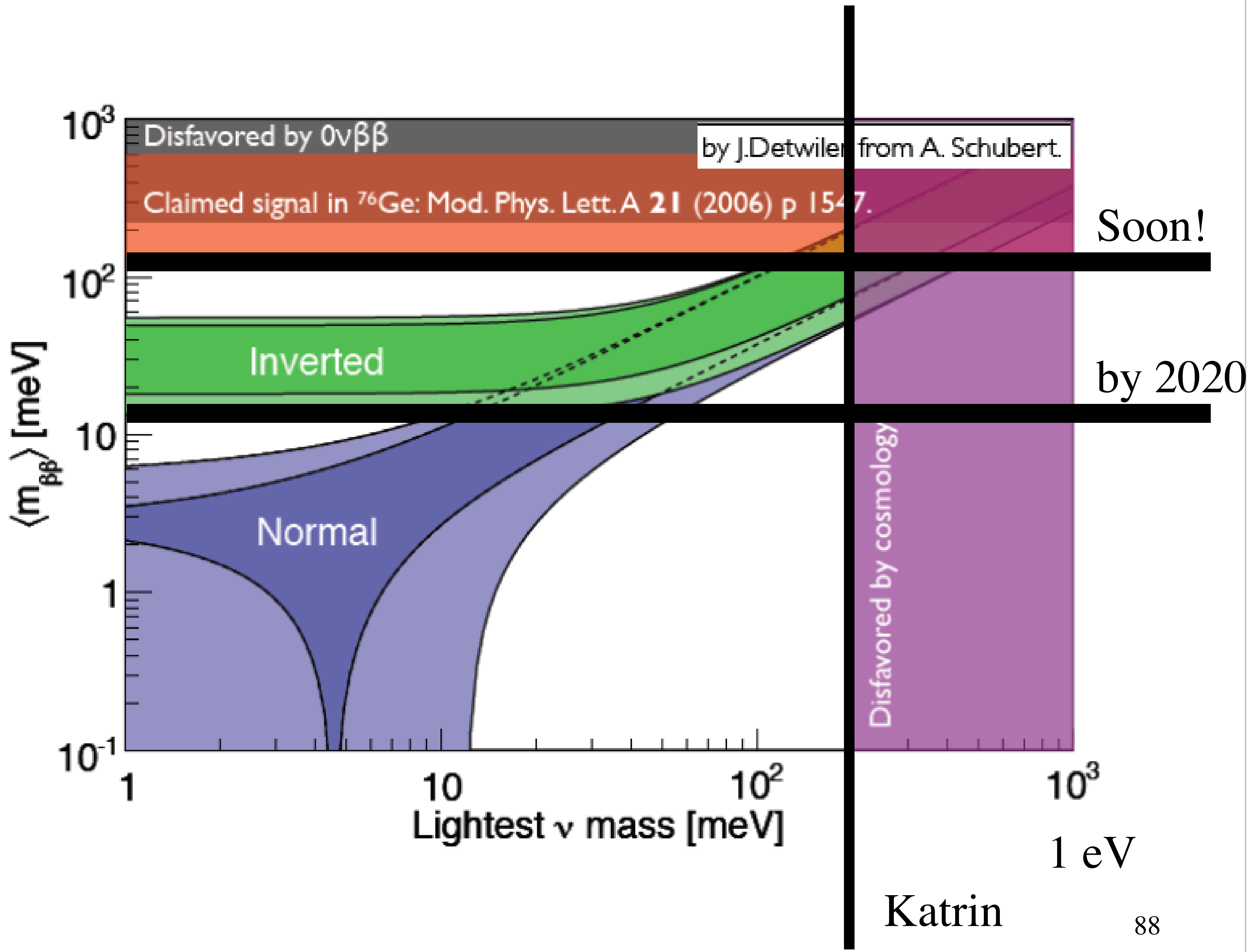
SuperNemo: Many types of foils,
with tracking and scintillator



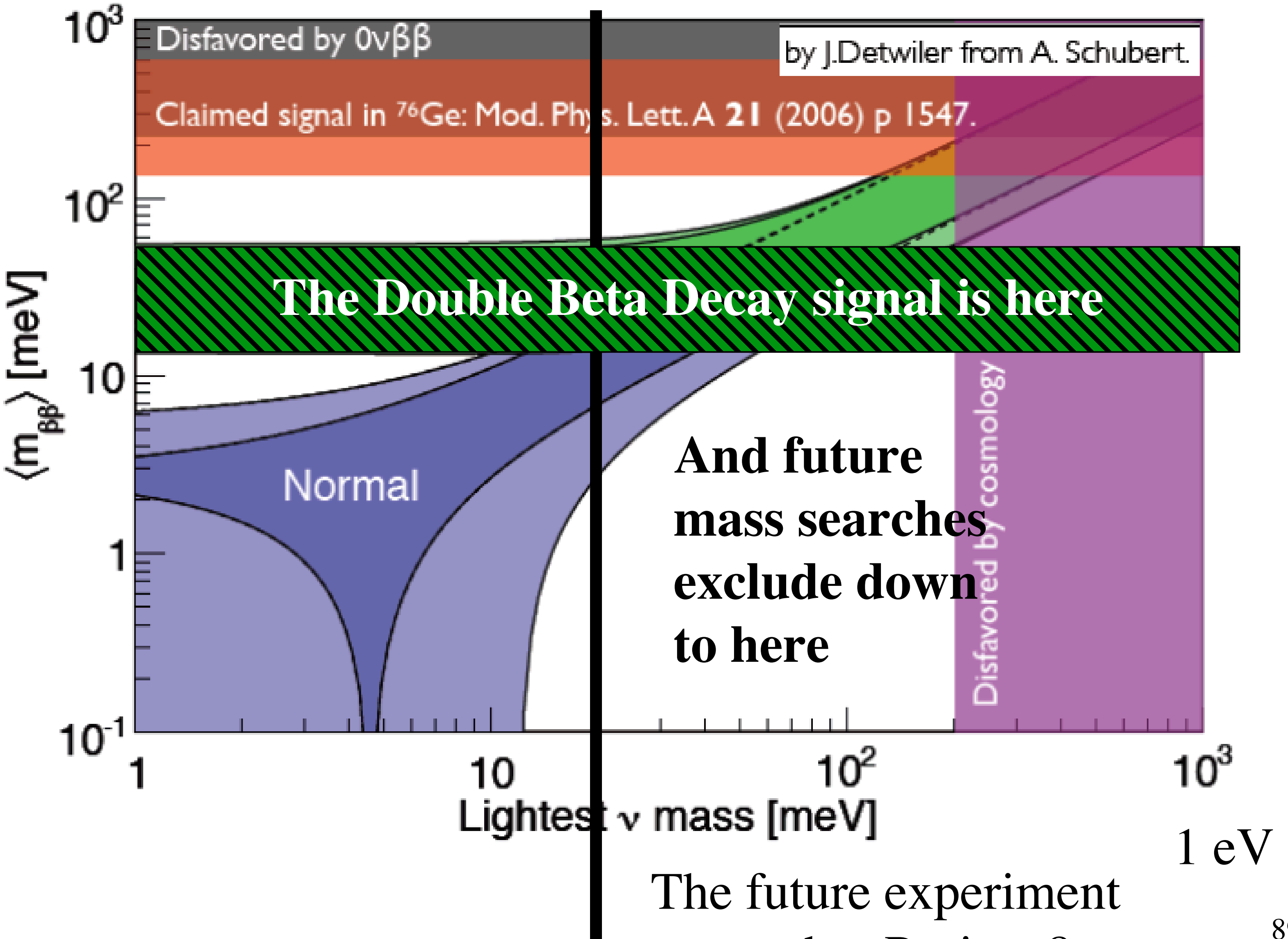


Majorana: Ge detector in a cryostat

…BUT WAIT! THERE'S MORE!!!
TOO MANY TO LIST!


Disfavored by 0νββ
by J.Detwiler from A. Schubert.
Claimed signal in 76Ge: Mod. Phys. Lett. A 21 (2006) p 1547.
Soon!
by 2020
Inverted
Normal
Disfavored by cosmology
⟨mββ⟩ [meV]
Lightest ν mass [meV]
1 eV
Katrin

We can know neutrinos are inverted heirarchy if…



The future experiment to watch: Project 8

Final Thought For This Lecture

My theme:

If I were a graduating student or recent postdoc, and considering working in neutrino physics, what would I consider working on?

This lecture has pointed out a lot of the theortical issues
(Is there a meaning to the mixing matrix?
to the mass hierarchy? Are there sterile nu's?…
and some neat neutrino-but-not-oscillation experiments…
(Solar, Neutrino mass, Double Beta Decay…)

All of these have great prospects for interesting results soon!

Next lecture: more about oscillation experiments.

-- end of Part I --