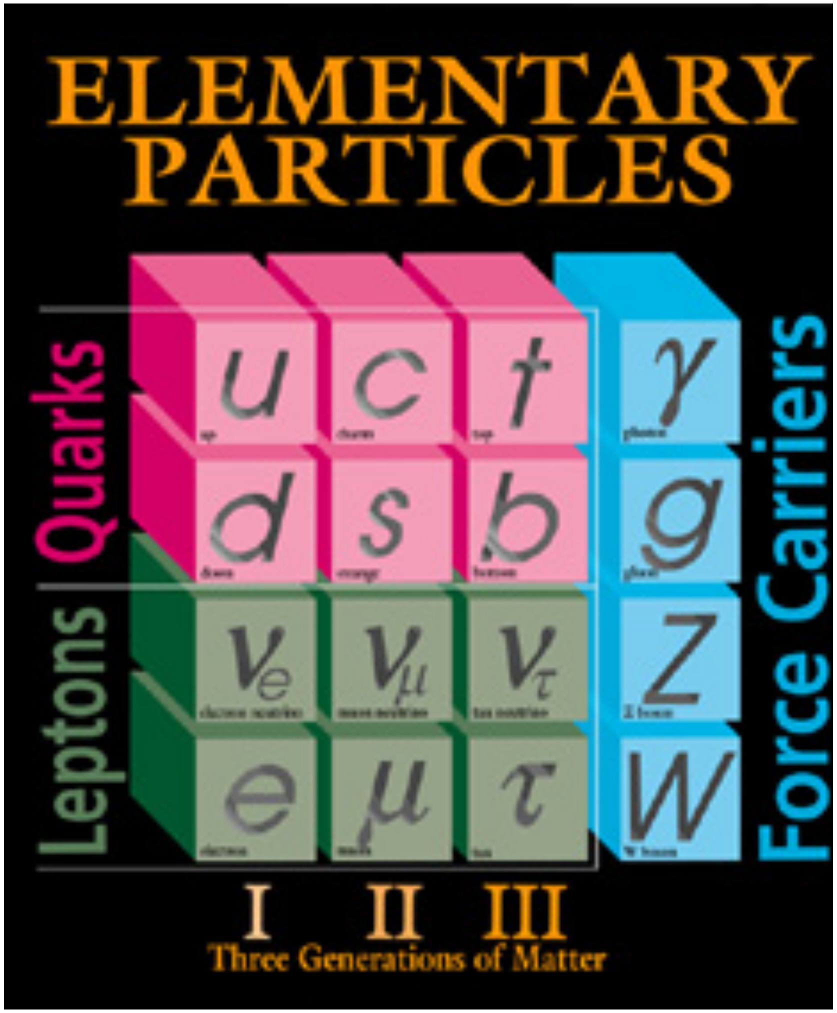
CYCLOTRONS:

New Sources for Neutrino Physics

Janet Conrad,
MIT
June 14, 2012

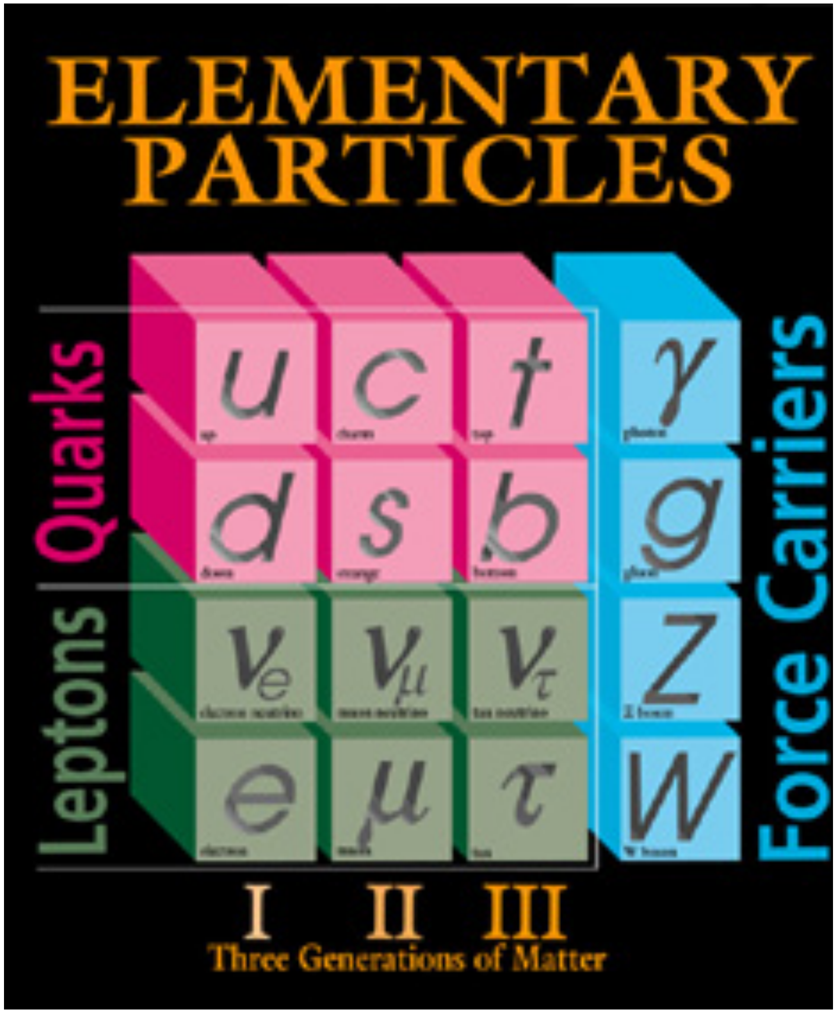
1. General motivation
2. About neutrino oscillations
3. Neutrino physics with Cyclotrons
    - The DAEdALUS Project
    - The IsoDAR Project

The motivation…

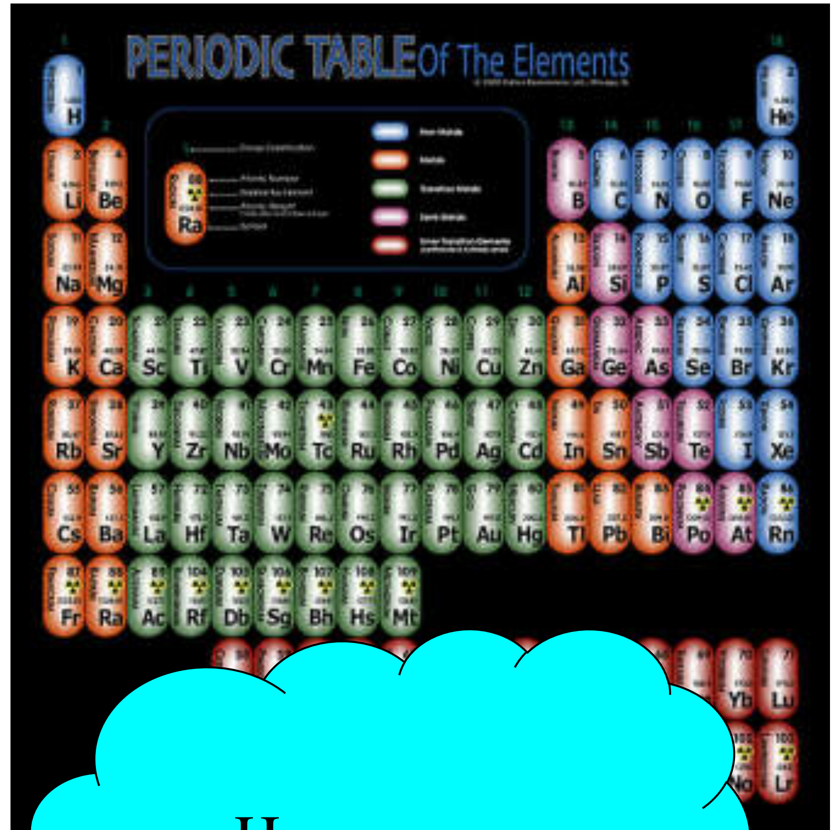


Understanding the
"The Standard Model"

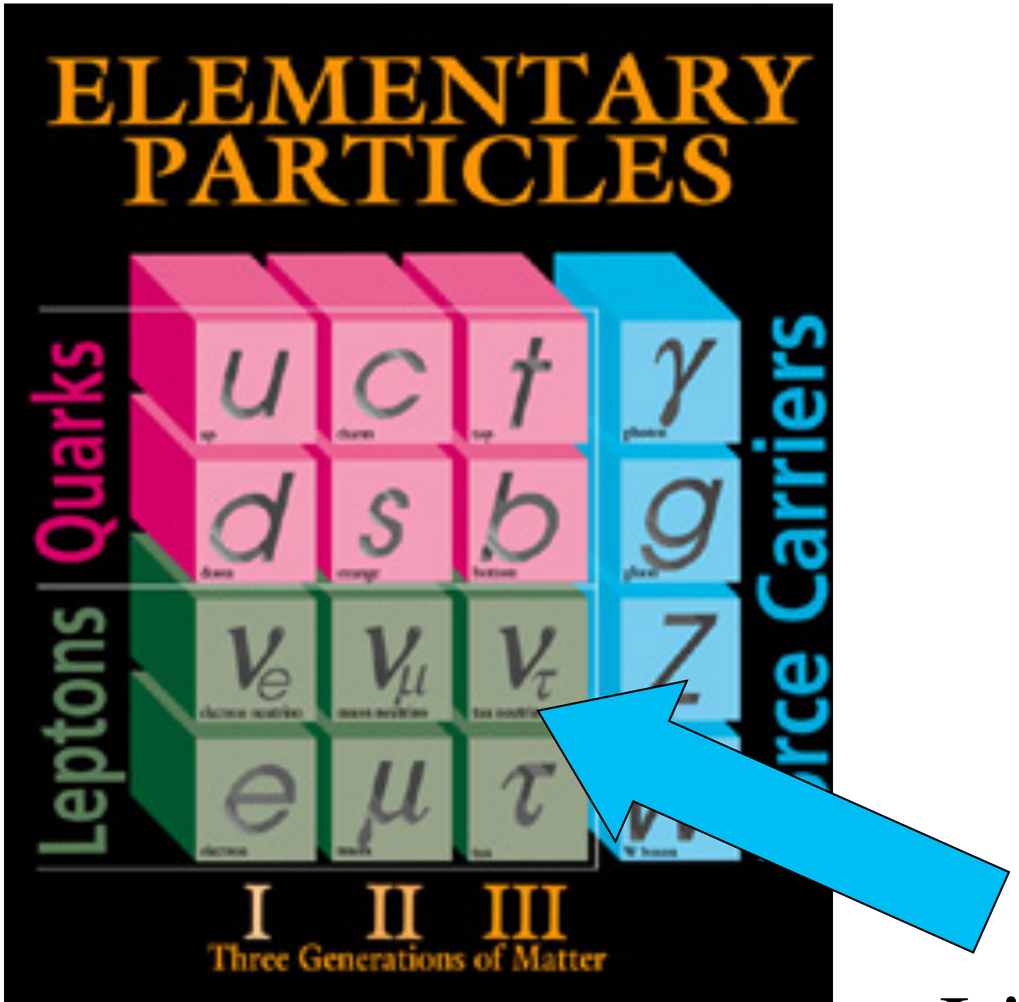
"The Standard Model"



Looks a lot like…



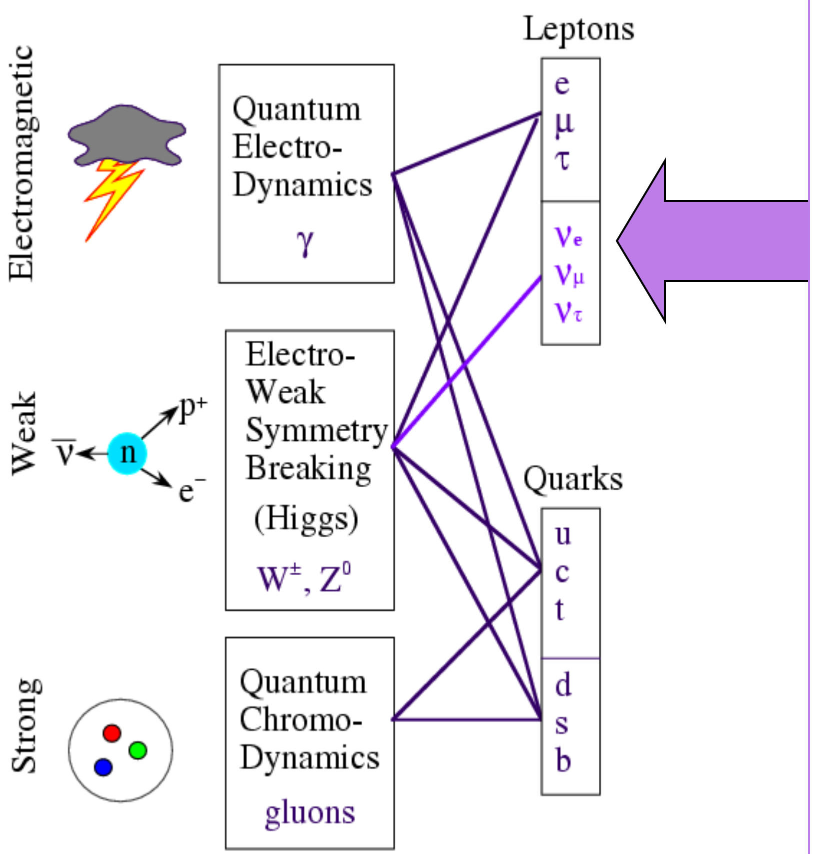
Hmmm…



Our first clue
To Beyond
Standard
Model
Physics

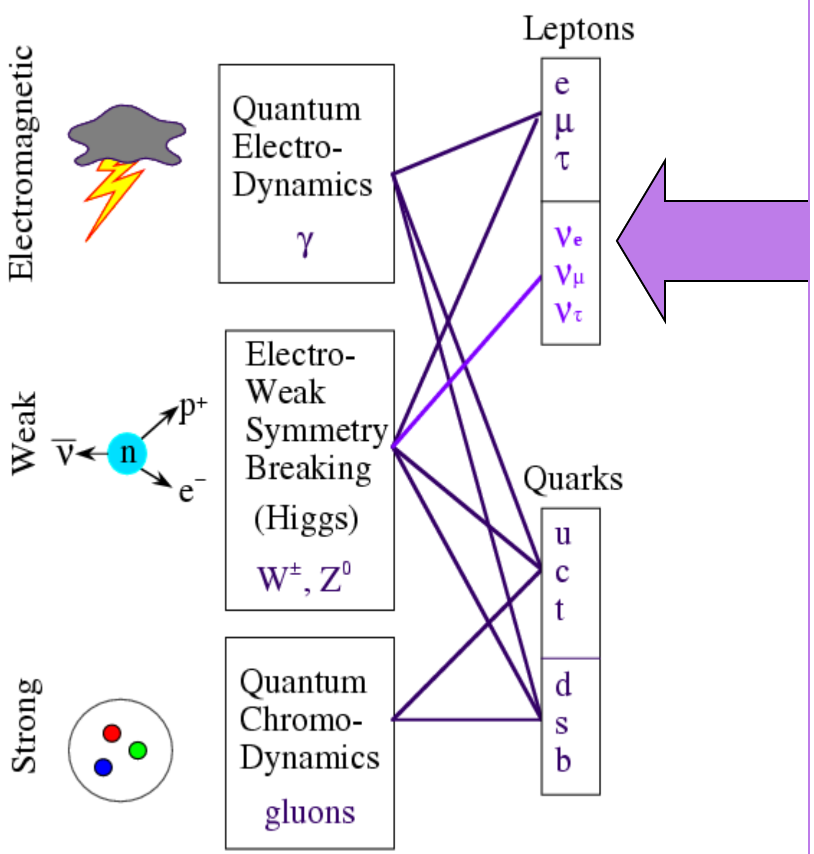
“Neutrinos”
Little Neutral Ones

The Standard Model



- Only interact via the "weak force"
- Interact through 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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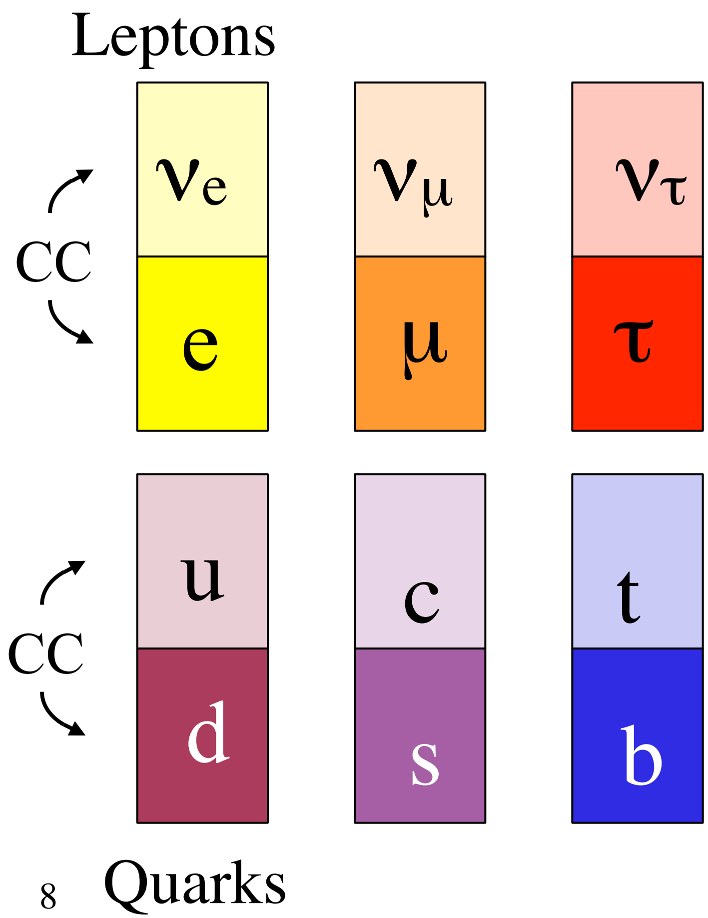
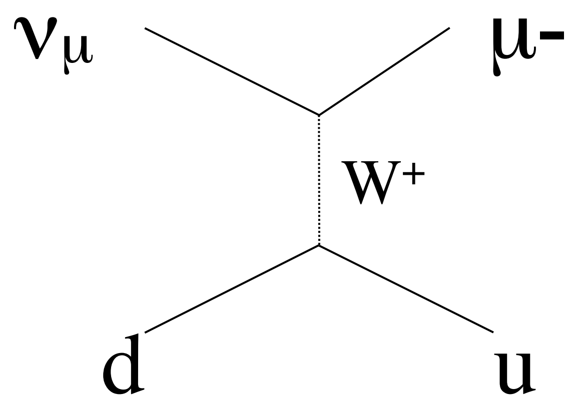
In the Standard Model,
Neutrinos are part of the lepton "weak doublets"



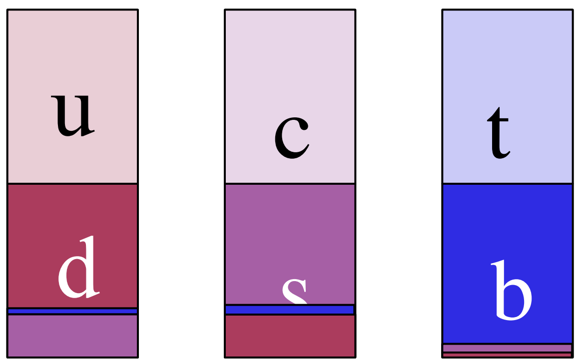


For a CC interaction to occur
you need enough energy
to produce the massive
final state particles

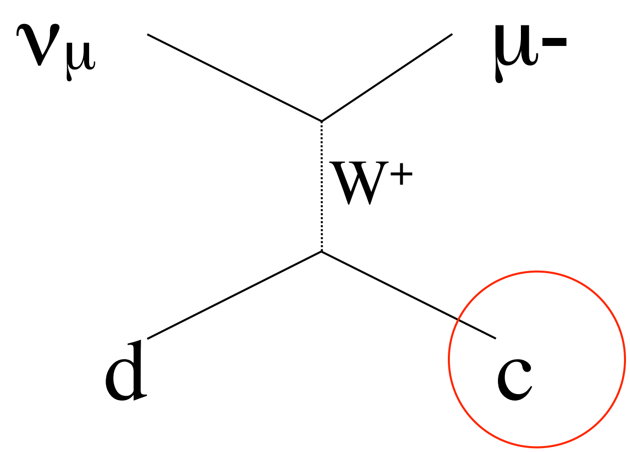
The quarks also form weak doublets…

In the quark sector, we have "mixing"

quark mass eigenstates $\neq$ quark weak eigenstates



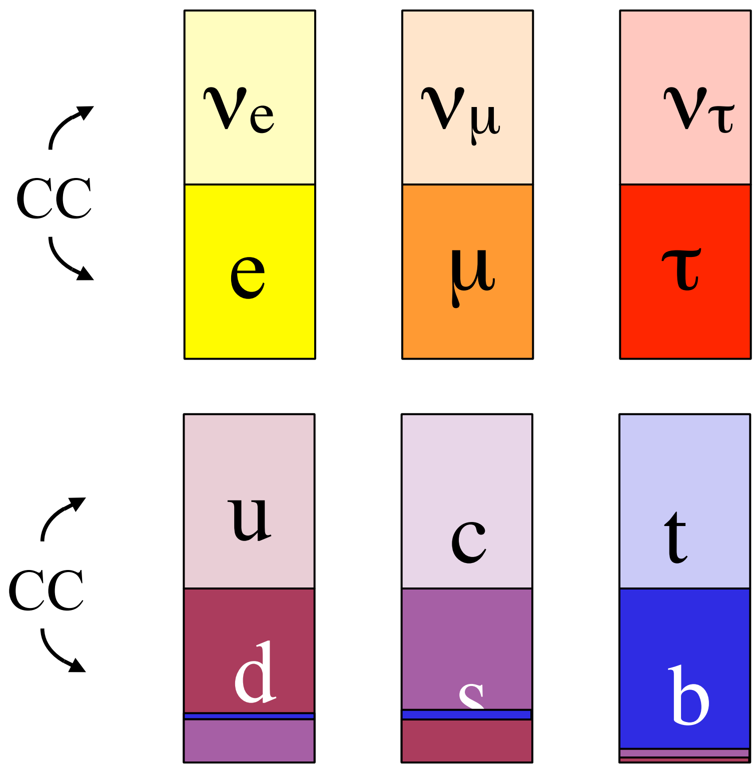
Small effect,
but clearly
seen in weak
interactions...



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

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

But within the Standard Model,
there is no mixing in the lepton sector



Which looks
a little strange,
doesn't it?

Of the three flavors of neutrinos…

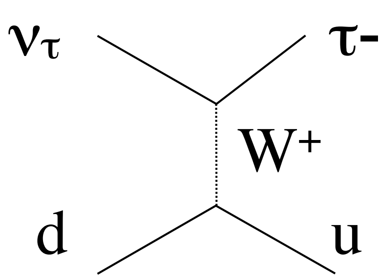
ν_τ	ν_μ	ν_e

Of the three flavors of neutrinos…

ν_τ ν_μ ν_e

Most difficult to work with

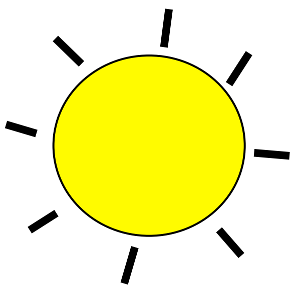
Production & observation are suppressed by The high τ mass ~ 2 GeV!



We won't discuss tau neutrinos further

Of the three flavors of neutrinos…

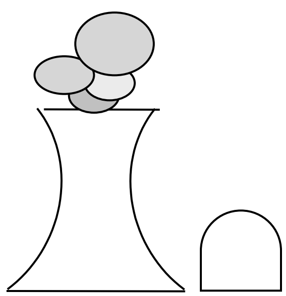
ν_τ ν_μ ν_e



electron neutrinos

(< 15 MeV)

Not so hard!



electron antineutrinos

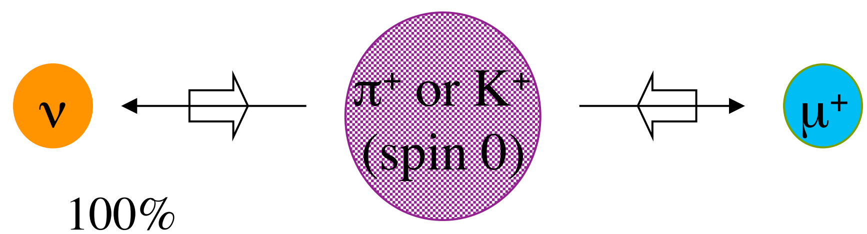
(< 10 MeV)

We will use
Beta decay
As our example
In this talk

There are three flavors of neutrinos

ν_τ ν_μ ν_e

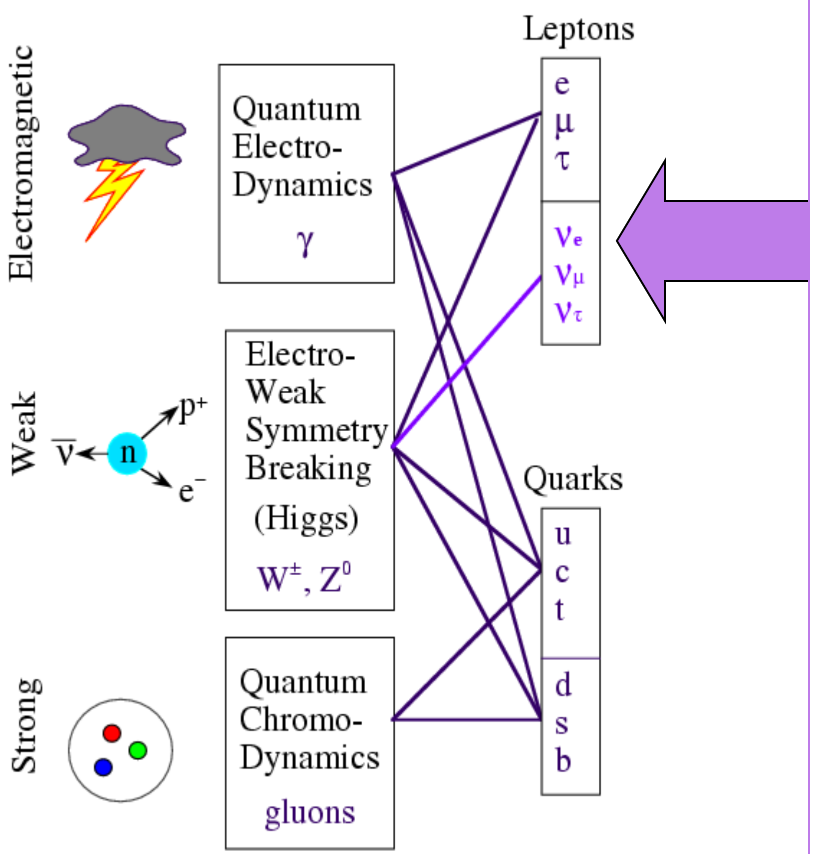
Most popular with physicists who make neutrino beams



100%
Left-Handed
(Parity Violation)

In this talk we will
Discuss pion decay.

The Standard Model



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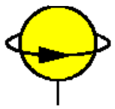
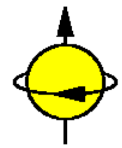
A quick reminder about parity violation...

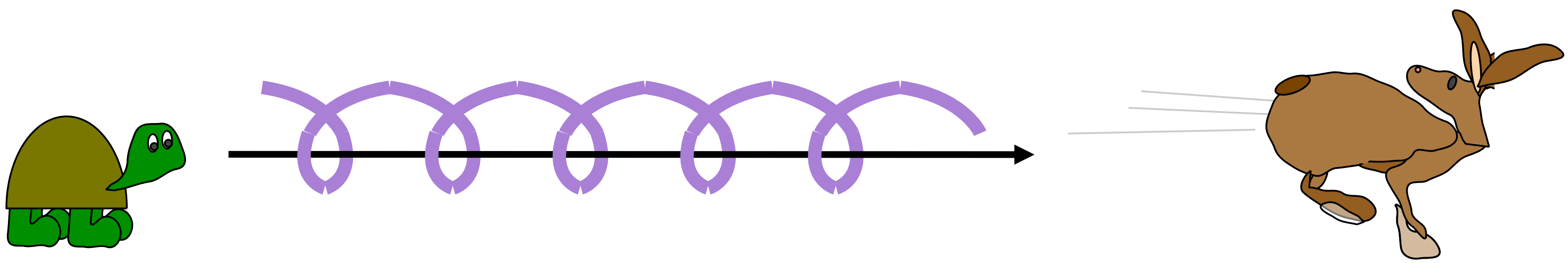
All spin 1/2 particles have "helicity"

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)

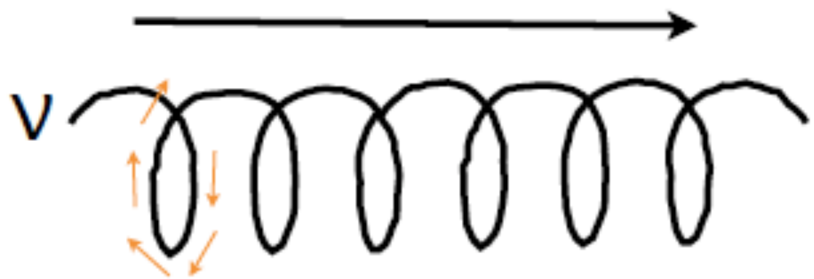


Handedness (or chirality) is the Lorentz-invariant counterpart

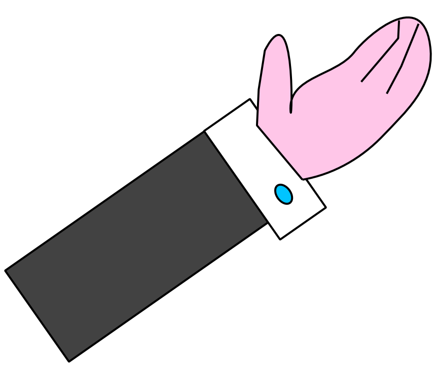
Identical to helicity for massless particles (standard model ν's)

Experimentally we have seen

Neutrinos are always left-handed

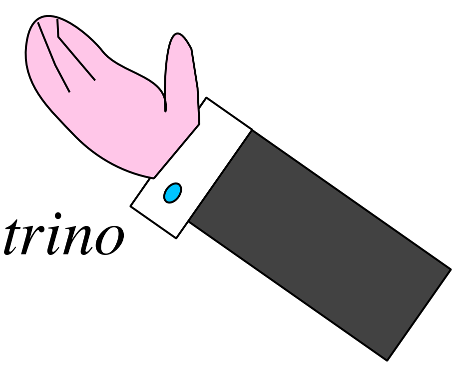


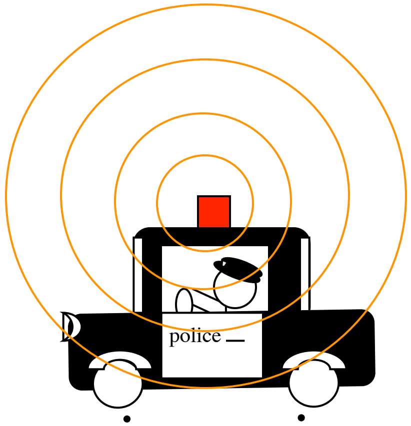
And antineutrinos are right-handed



Hello!
I’m a neutrino!

Hello!
I’m an antineutrino





How do you enforce the law of left-handedness?

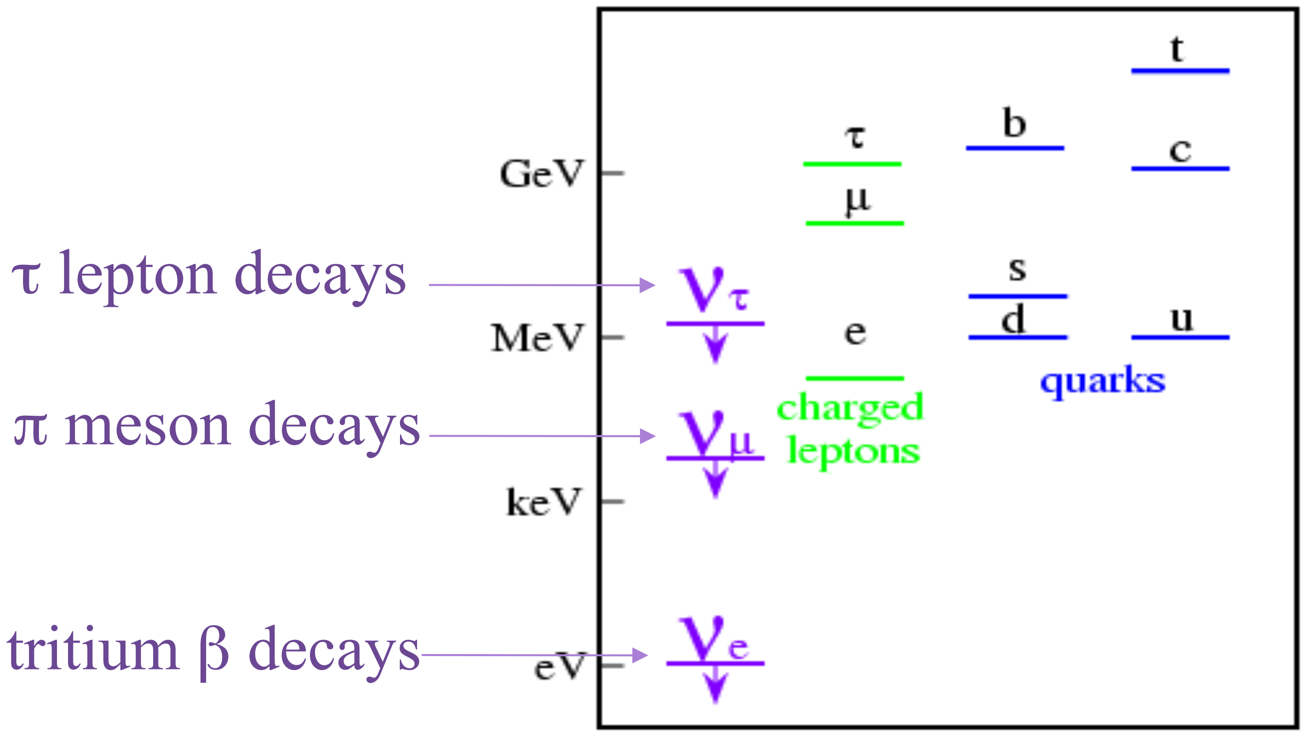
Well... what couples left-handed particles to right?

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!

It is the discovery of tiny neutrino mass
Through "Neutrino oscillations" that has lead us to realize

The Standard Model
has a big problem!

So lets discuss…

1. What are oscillations?

2. Are there more Beyond Standard Model Effects
   Beyond the ones we have seen?

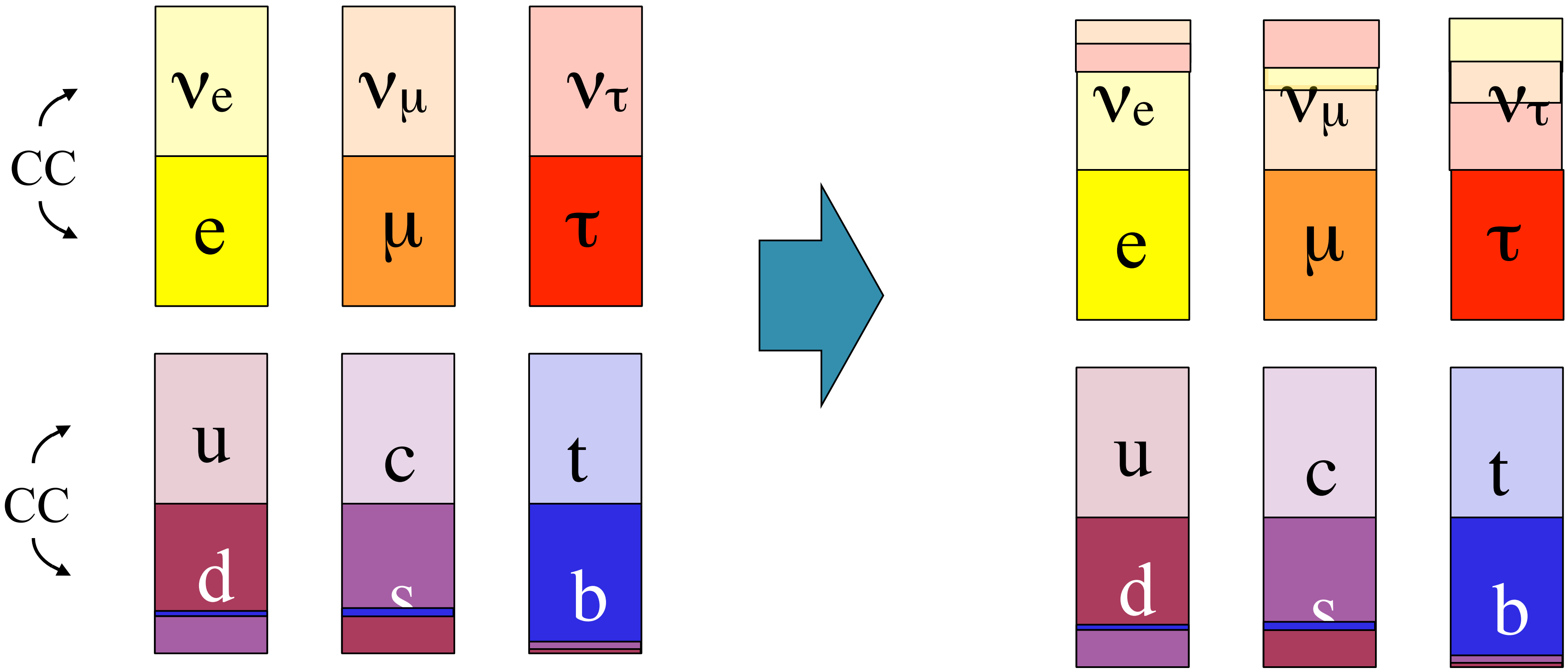
Here is where
The cyclotrons
help!

   * CP Violation
   * Sterile neutrinos

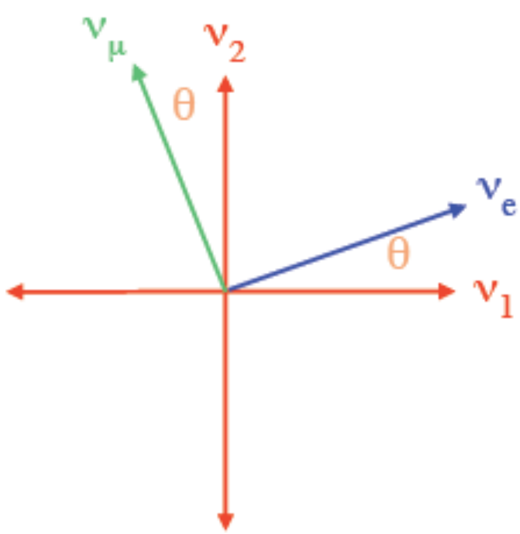
NEUTRINO

Oscillations

Neutrino oscillations assume that,
Like in the quark sector,
There is "mixing" in the lepton sector



It is simplest to think about 2 neutrinos…



Lets hypothesize:
Neutrinos have (tiny) masses
Mass states that are not
aligned with the flavor states
(as with the quarks)

For Two Neutrinos....

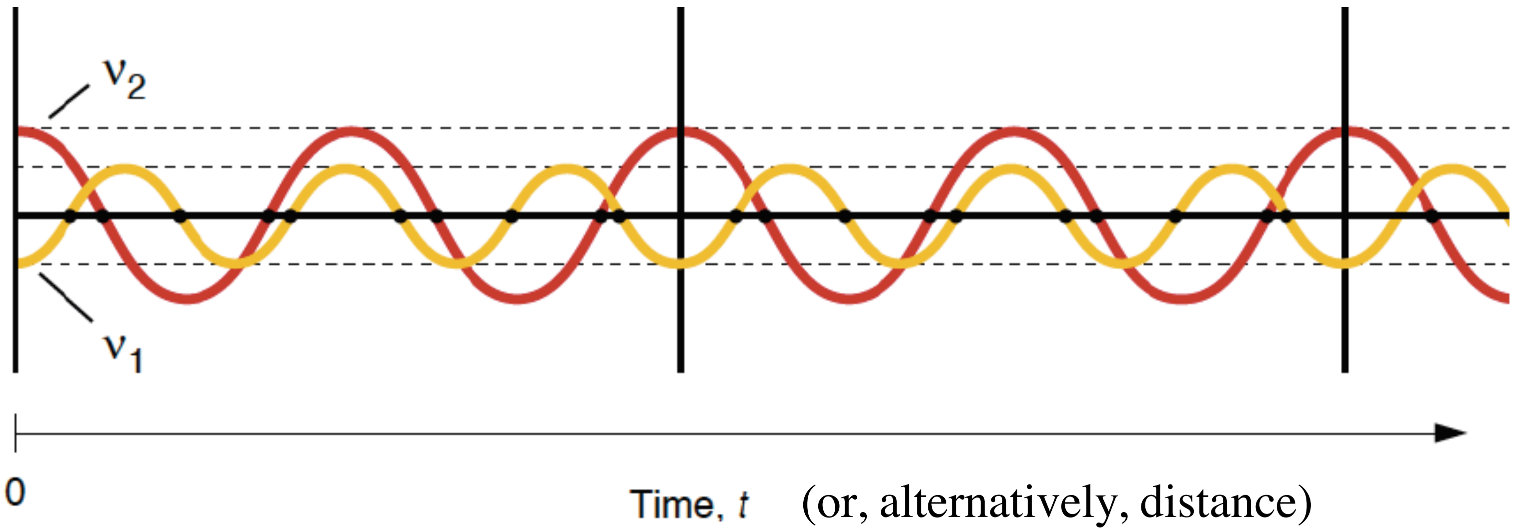
flavor | mass

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

A neutrino "born" as one flavor,
Is in a superposition of the mass states.

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

As the neutrino travels, the mass states propagate
with different frequency



(or, alternatively, distance)

The probability waves will interfere

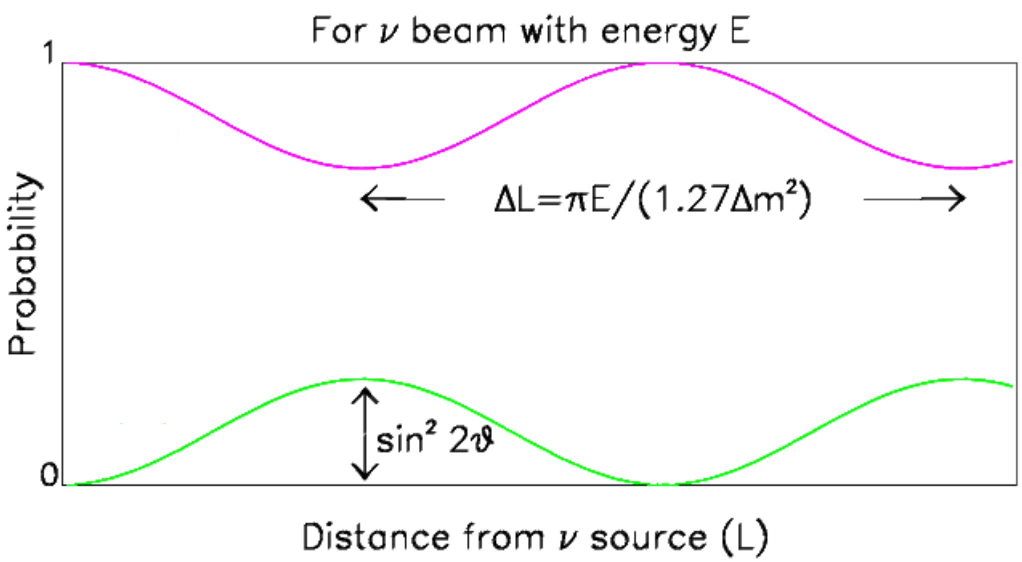
$$P_{osc} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

...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:

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

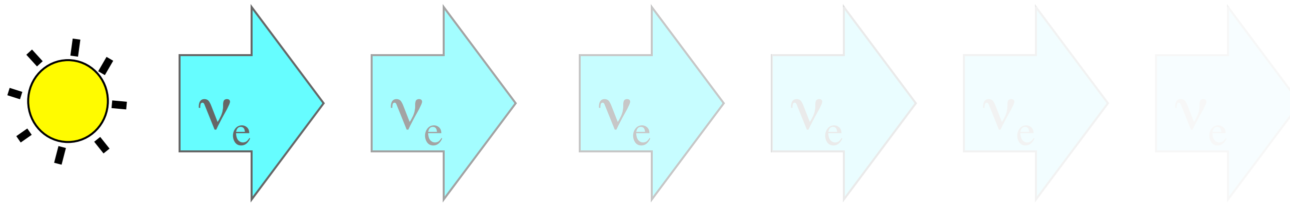


ν_e Disappearance

ν_μ Appearance

(assuming you can produce and see μ's)

The initial surprise was the solar neutrino deficit



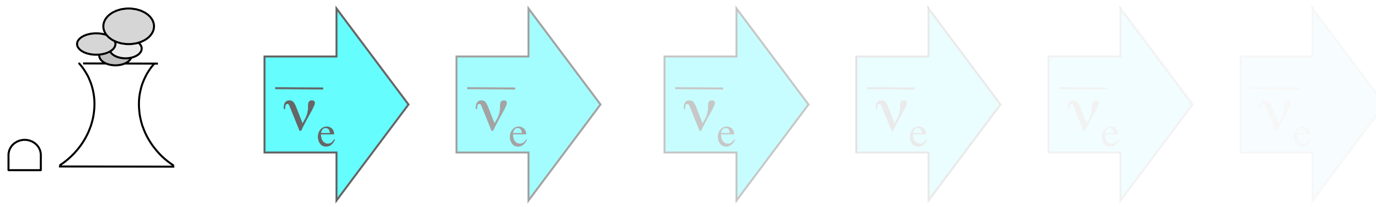
The observed ν_e rate was about 1/3 of prediction

Was it a problem with the predicted rate?
Or with the detector efficiency?

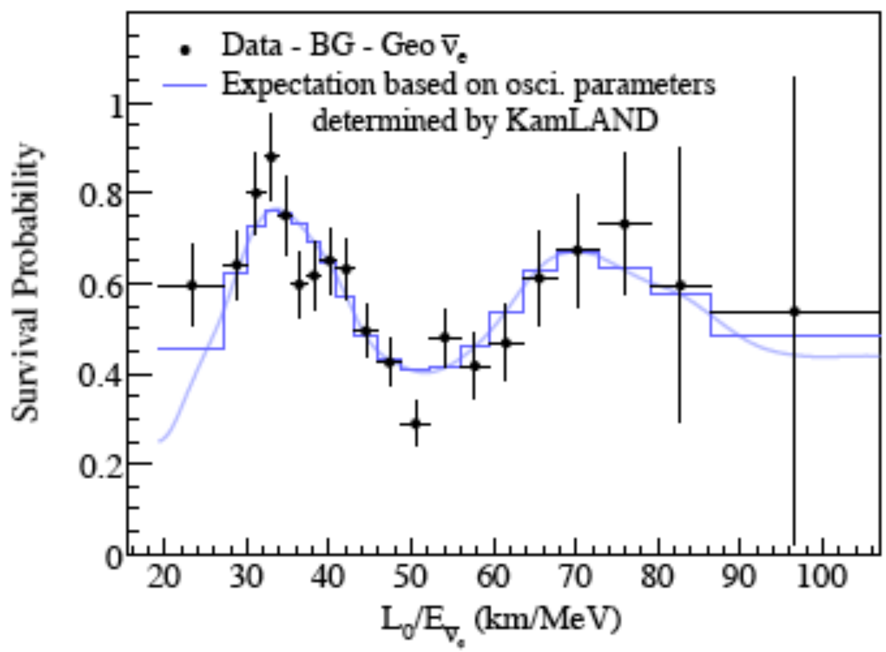
… Or were the neutrinos "disappearing" on the way?

This pointed us to the discovery of Neutrino Oscillations

The prettiest example comes from reactor neutrinos!



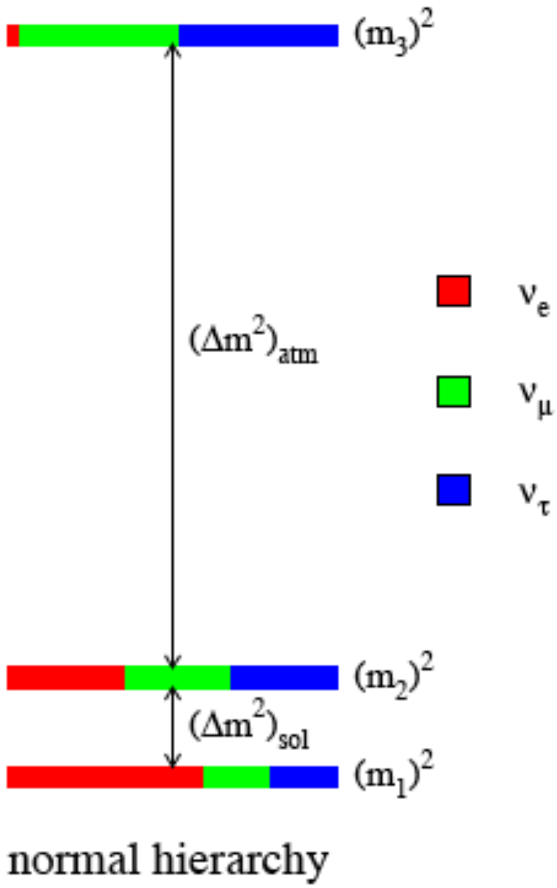
KamLAND!



Because you really see the oscillation "wiggle"

Really we have three neutrinos…

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



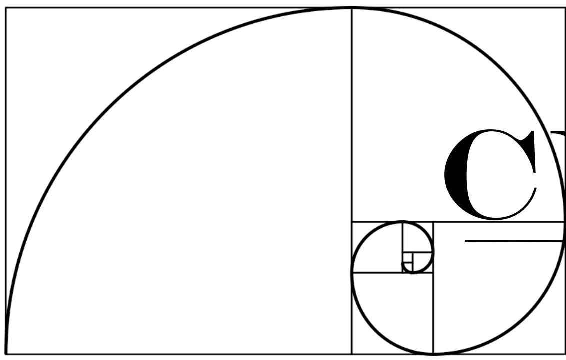
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"mixing" between neutrinos is parameterized by three "mixing angles"

$\theta_{12}, \theta_{13}, \theta_{23}$

This is a remarkable accomplishment.

It was the major focus of the conference I just attended



CYCLOTRONS

Where they come into the picture

Are there more signs of Beyond Standard Model Physics?

1. Are neutrino oscillations the same as antineutrino oscillations? (CP violation)

2. Are there partners to active neutrinos (sterile neutrinos)

The mixing matrix we know about now looks like this…

A 3×3 unitary matrix with

3 associated free parameters (Euler angles)

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

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

You can introduce an extra parameter into this…
a complex phase

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

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

In the quark sector, we definitely see CP violation
It shows up as a difference in decays of
Mesons vs. antimesons.

Does the lepton sector show similar phenomena?

If not, *Why Not*?

If so,

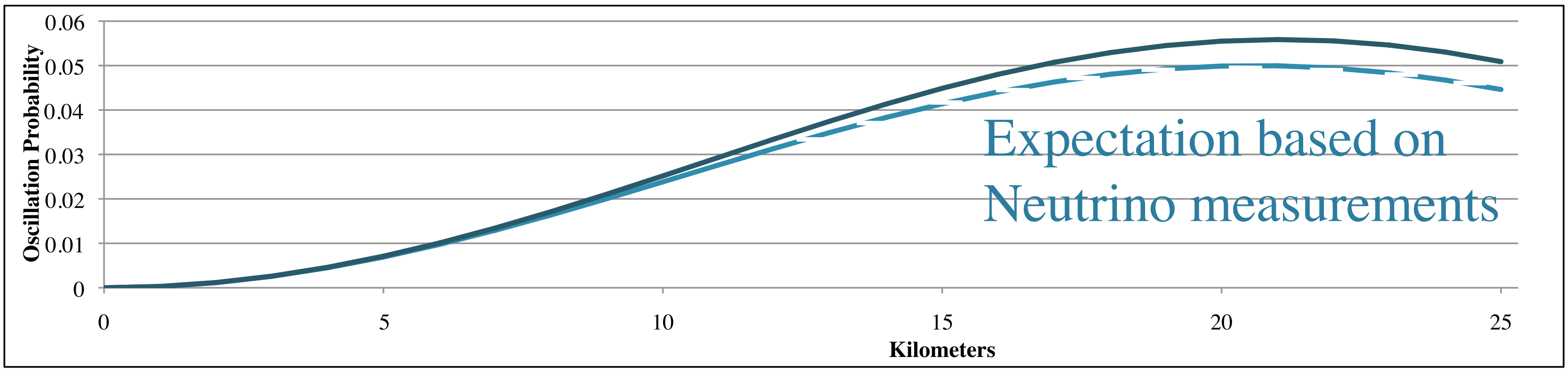
how similar is it to the quark sector? and what are the implications?

Can it explain the matter vs antimatter aymmetry
in the universe?

What would CP violation look like in the neutrino sector?

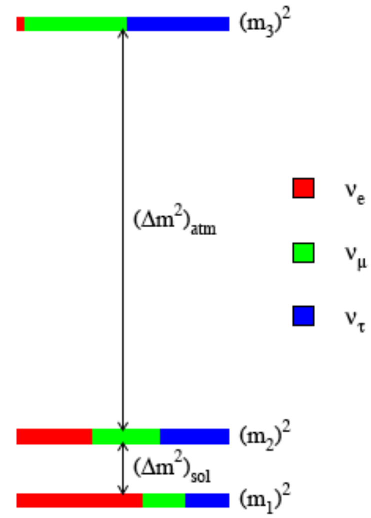
The antineutrino oscillation wave would look different
From the neutrino wave

Deviation you might see



To look for CP violation,
You want to trace the oscillation wave.

The oscillation of muon-flavor to electron-flavor
at the atmospheric Δm^2
may show CP-violation dependence!



in a vacuum…

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

We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

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

DAEδALUS

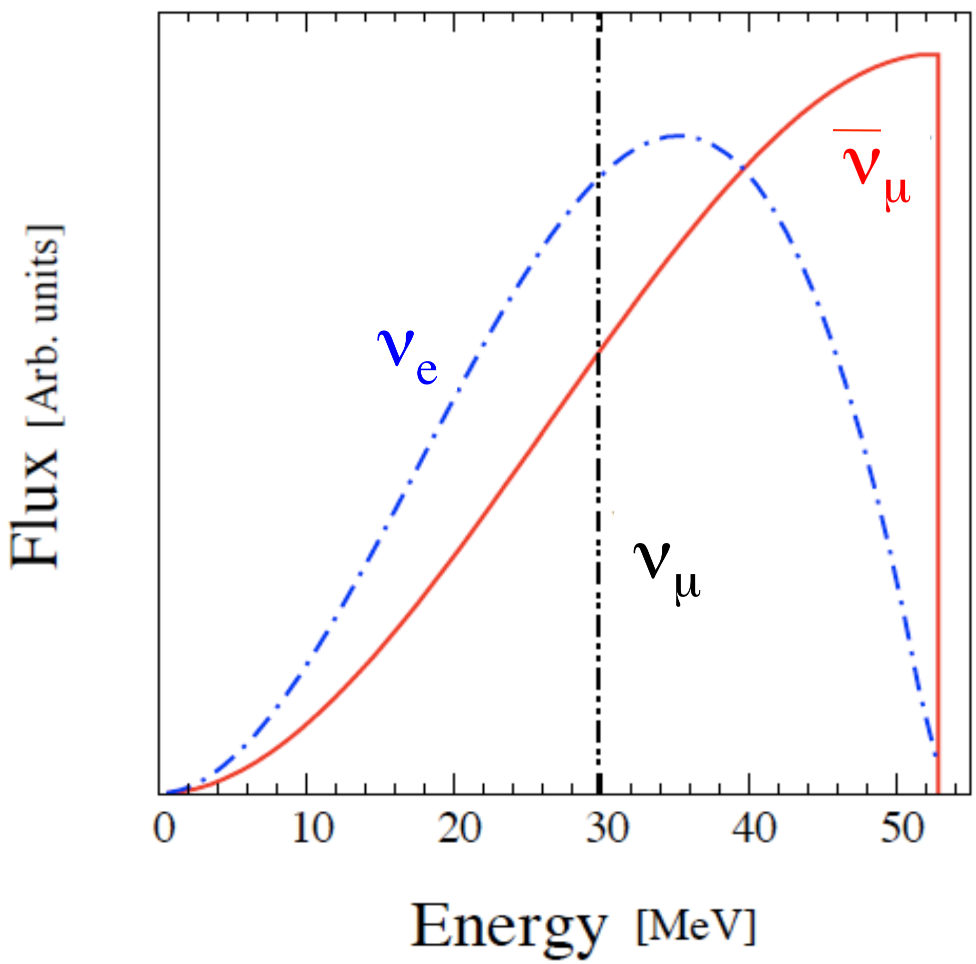
Decay
At rest
Experiment
for δ_{cp} studies
At the
Laboratory for
Underground
Science

Use *decay-at-rest neutrino beams*,
and one of the planned ultra-large
detectors
with free protons (H_2O, oil)
to search for CP violation in the neutrino sector

A really nice low-energy beam

A π^+ decay at rest beam:

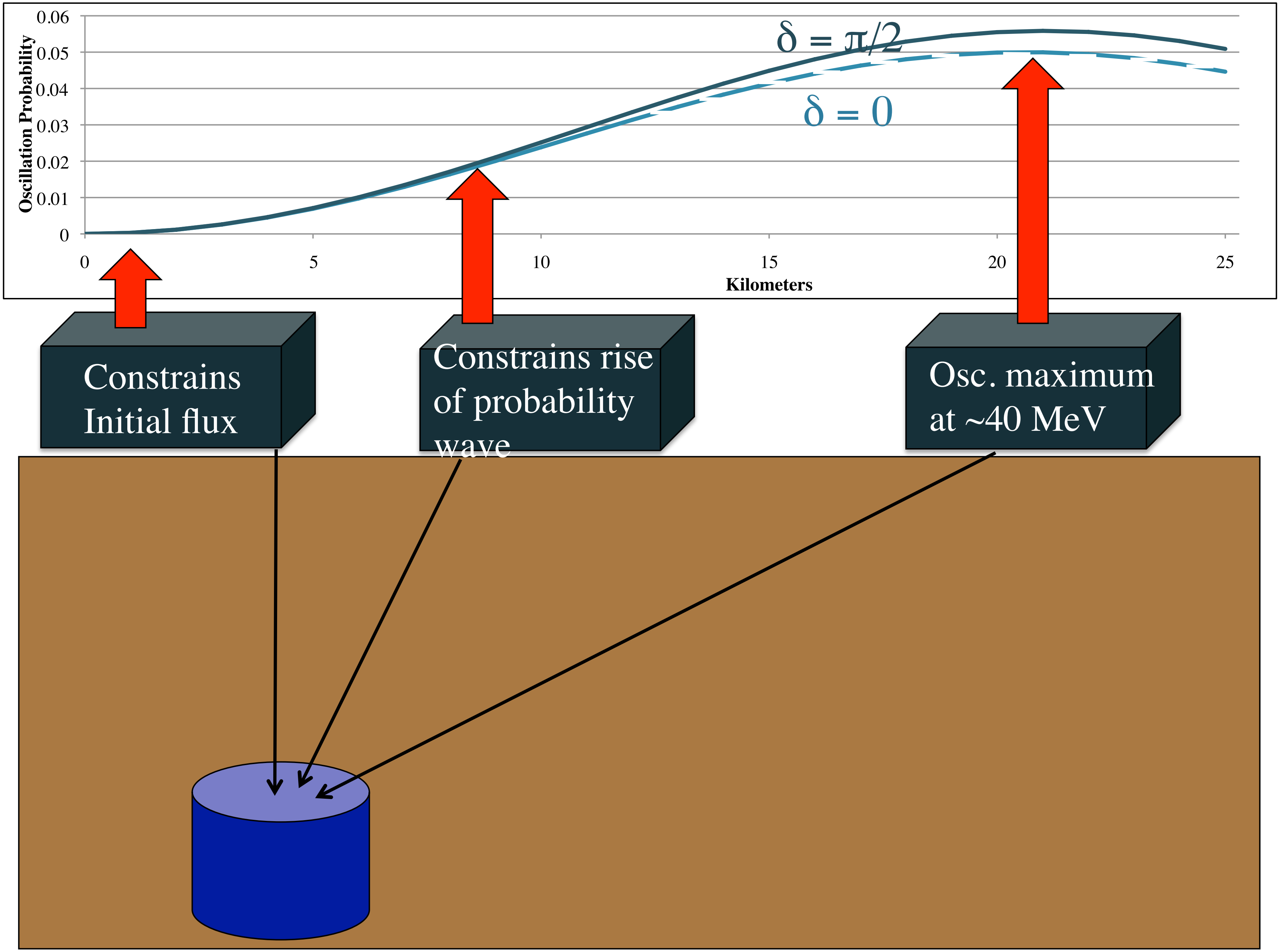
$$p+C \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e,$$



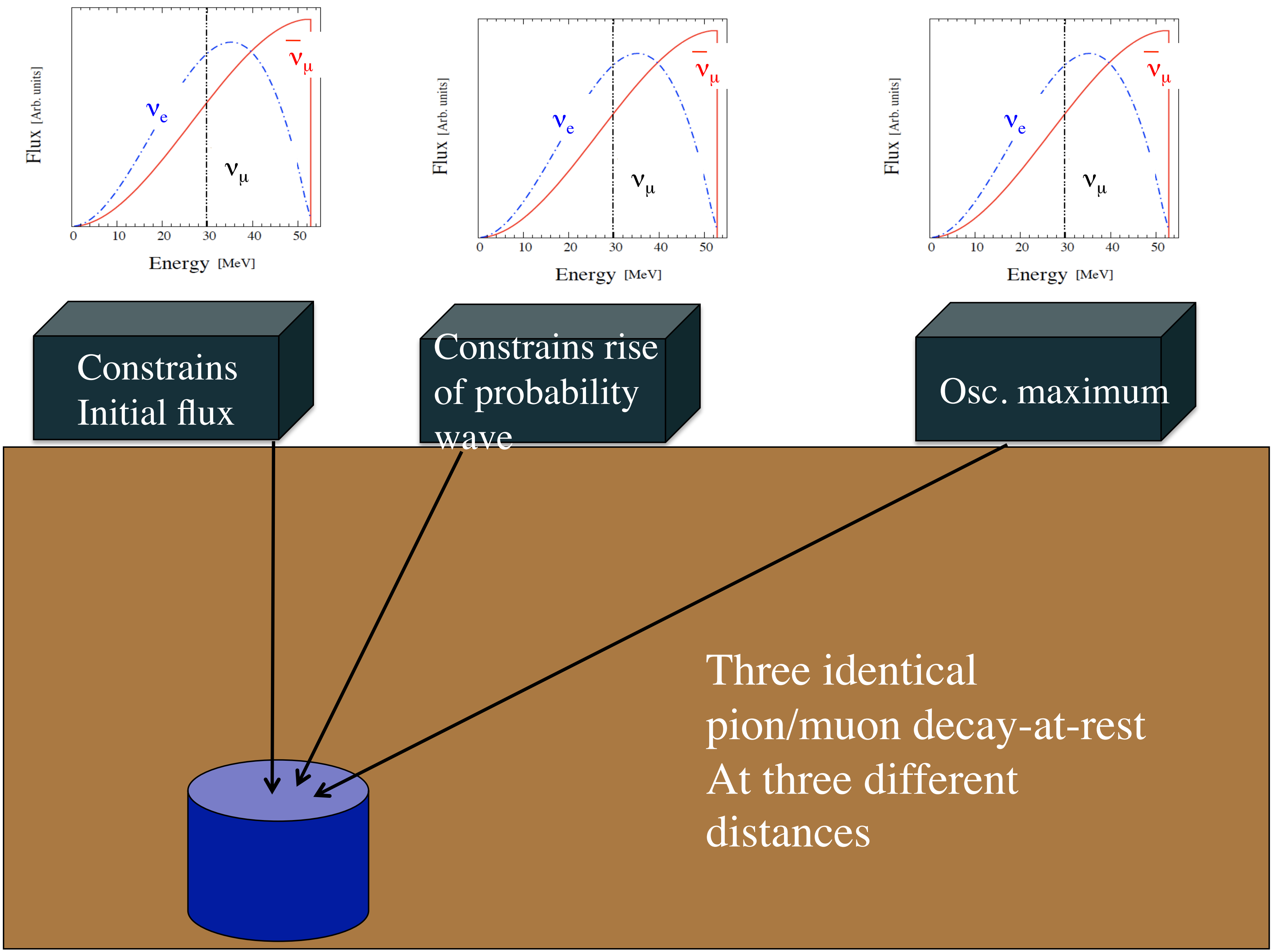
Shape driven by nature!

Only the normalization varies from beam to beam

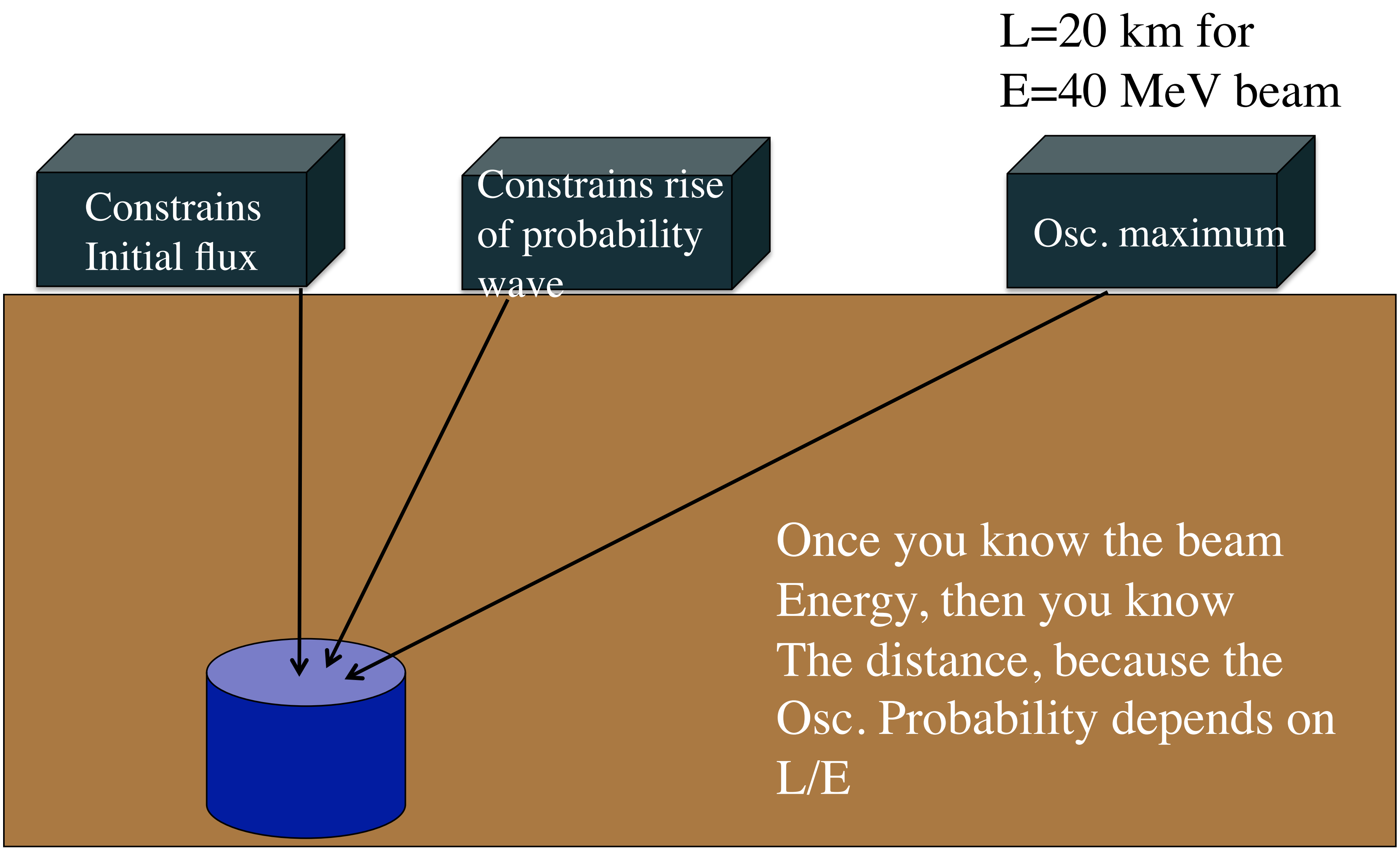
No "intrinsic" $\bar{\nu}_e$
So perfect for
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches



0.06
0.05
0.04
0.03
0.02
0.01
0
Oscillation Probability
0
5
10
15
20
25
Kilometers
δ = π/2
δ = 0
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum at ~40 MeV


Flux [Arb. units]
Energy [MeV]
0 10 20 30 40 50
ν_e
ν_μ
$\bar{\nu}_\mu$
Flux [Arb. units]
Energy [MeV]
0 10 20 30 40 50
ν_e
ν_μ
$\bar{\nu}_\mu$
Flux [Arb. units]
Energy [MeV]
0 10 20 30 40 50
ν_e
ν_μ
$\bar{\nu}_\mu$
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum
Three identical pion/muon decay-at-rest At three different distances

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



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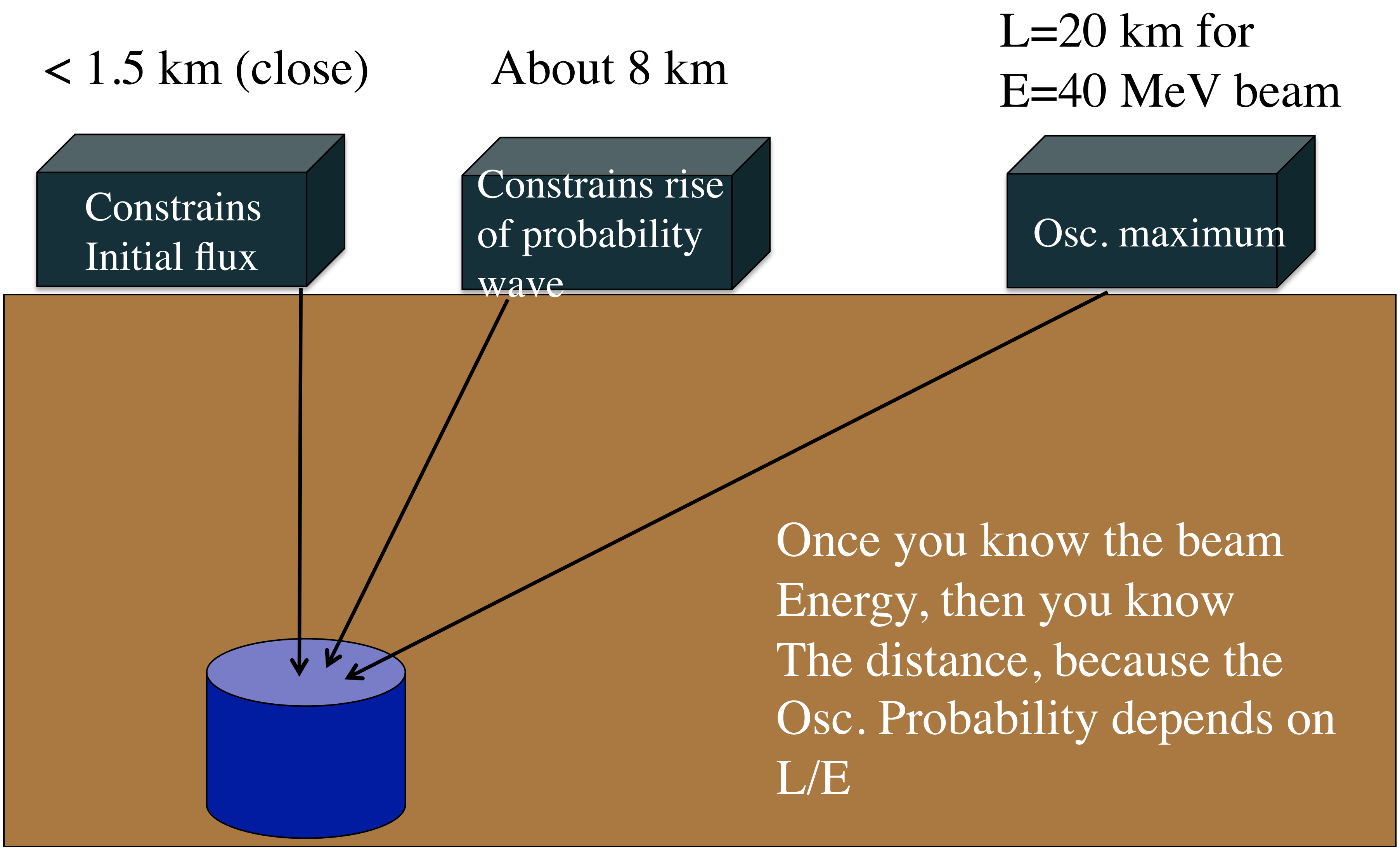
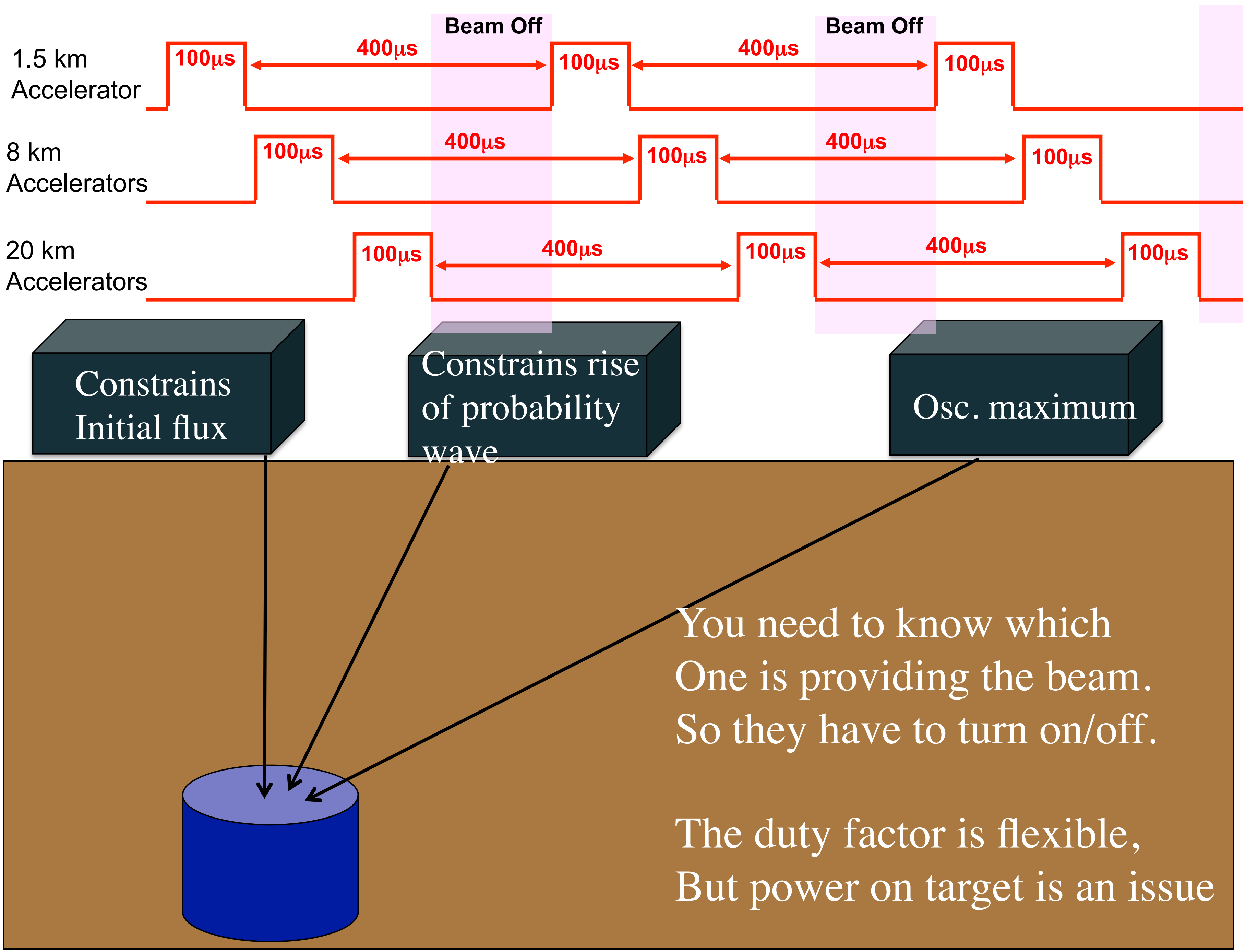
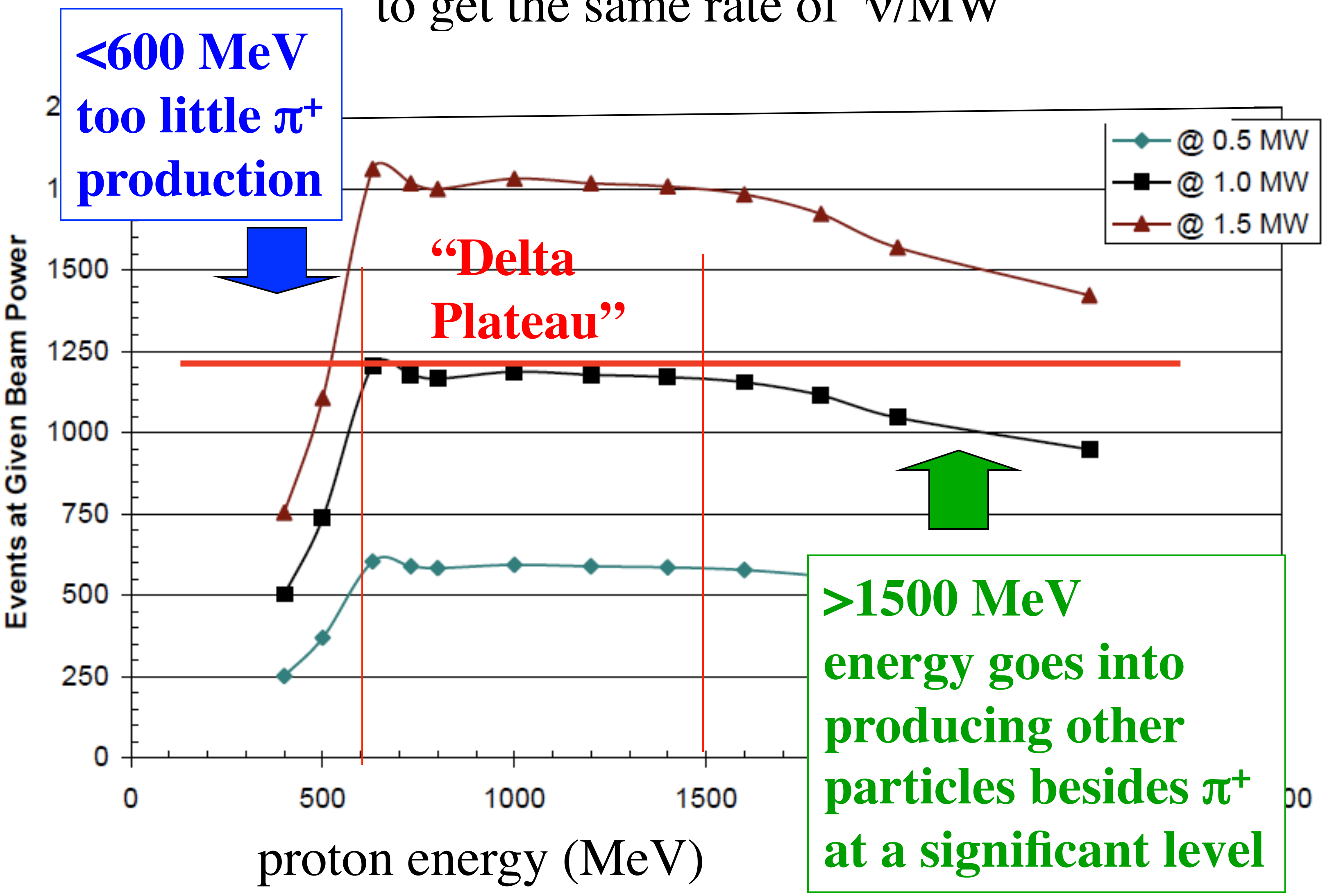


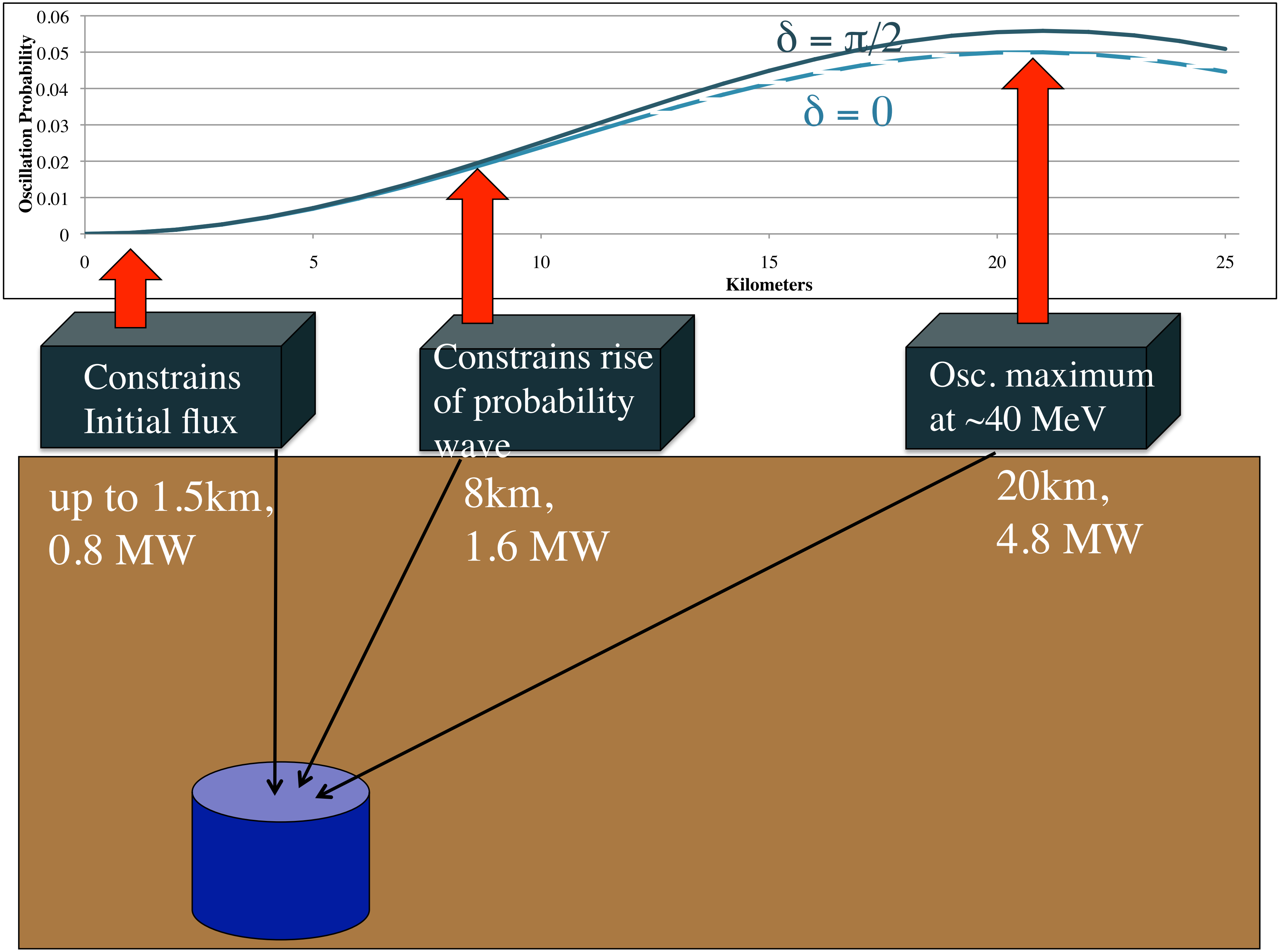


Beam Off
Beam Off
1.5 km Accelerator
8 km Accelerators
20 km Accelerators
100μs
400μs
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum
You need to know which One is providing the beam. So they have to turn on/off.
The duty factor is flexible, But power on target is an issue

What proton energy is required?

There is a "Delta plateau" where you can trade energy for current to get the same rate of ν/MW





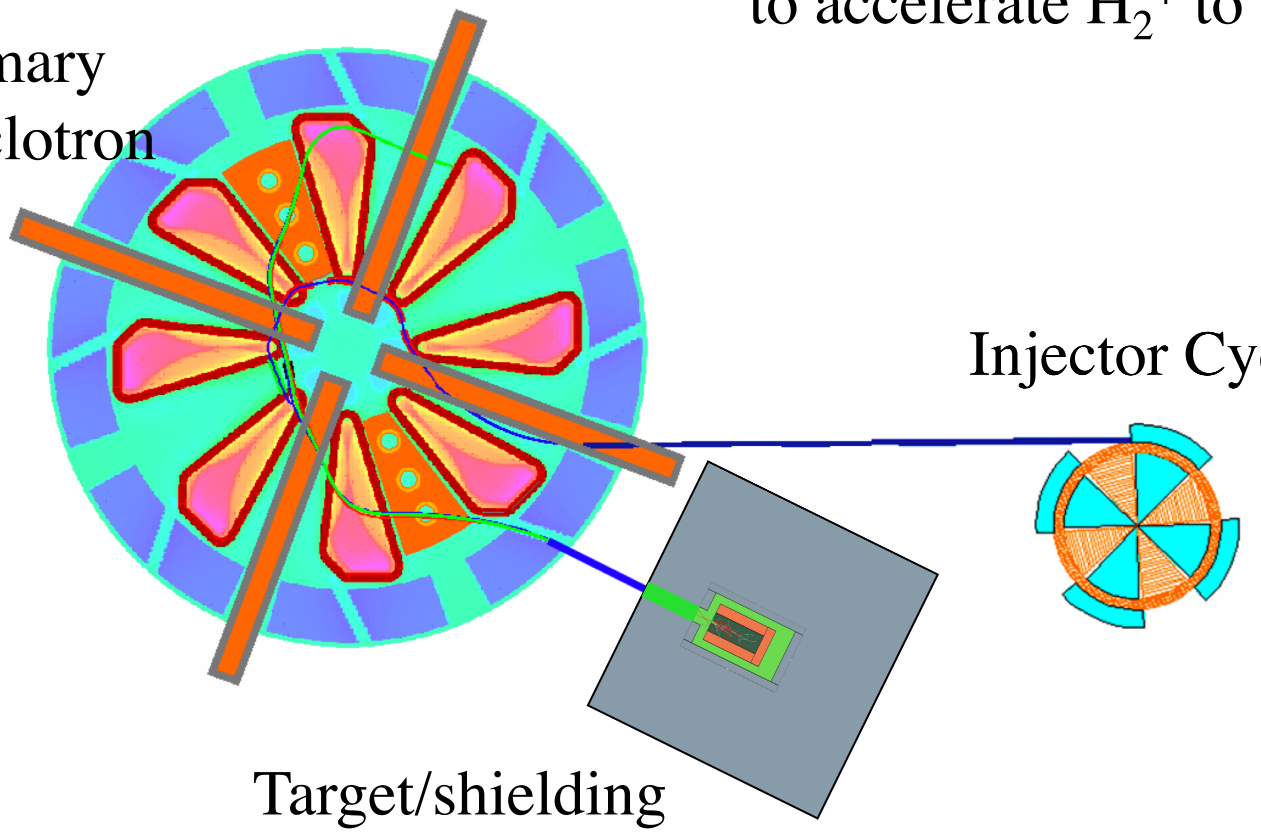
0.06
0.05
0.04
0.03
0.02
0.01
0
Oscillation Probability
0
5
10
15
20
25
Kilometers
δ = π/2
δ = 0
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum at ~40 MeV
up to 1.5km, 0.8 MW
8km, 1.6 MW
20km, 4.8 MW

The machines…

1. 800 MeV protons on target
2. No strict requirement on duty factor, but must turn on/off
3. High power
4. Relatively compact
5. Low cost

This led us to look at cyclotrons

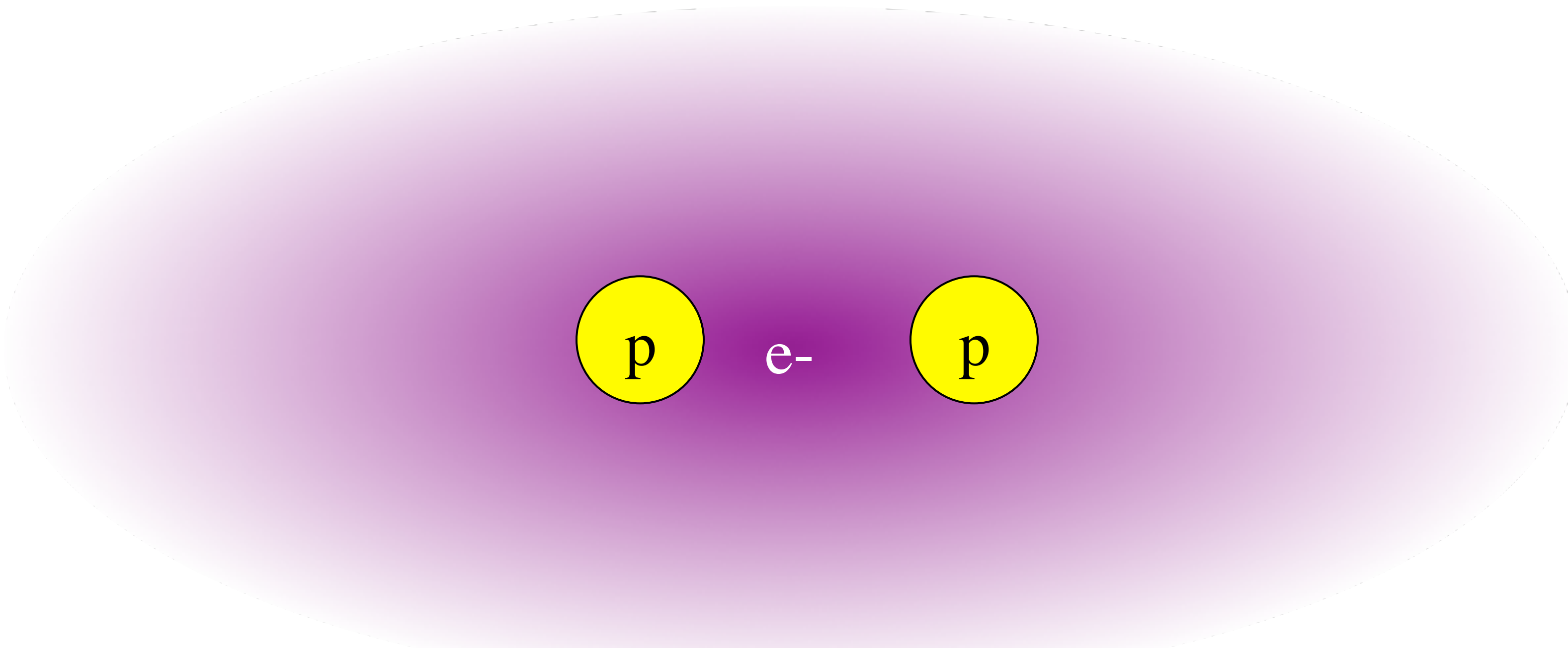
Uses Multiple "Accelerator Units"
constructed of cyclotrons
to accelerate H_2^+ to 800 MeV



The result is a decay-at-rest-flux
That can be used for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches

Why H_2+ ???

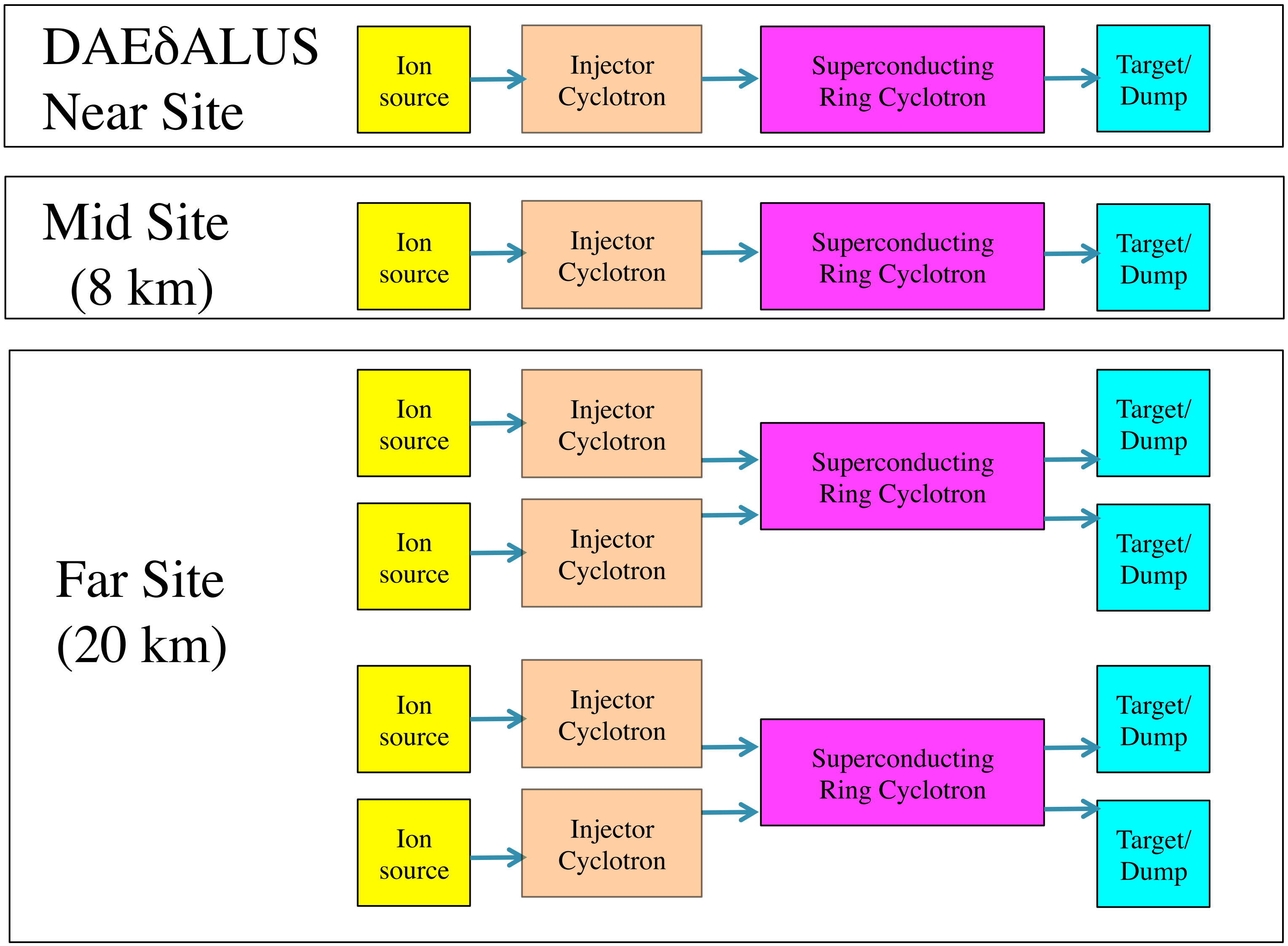
We need to reduce "space charge" at the start…



H_2+ gives you 2 protons out for 1 unit of +1 charge in!

Simple to extract! Just strip the electron w/ a foil

Design Principle: “Plug-and-play”



original design

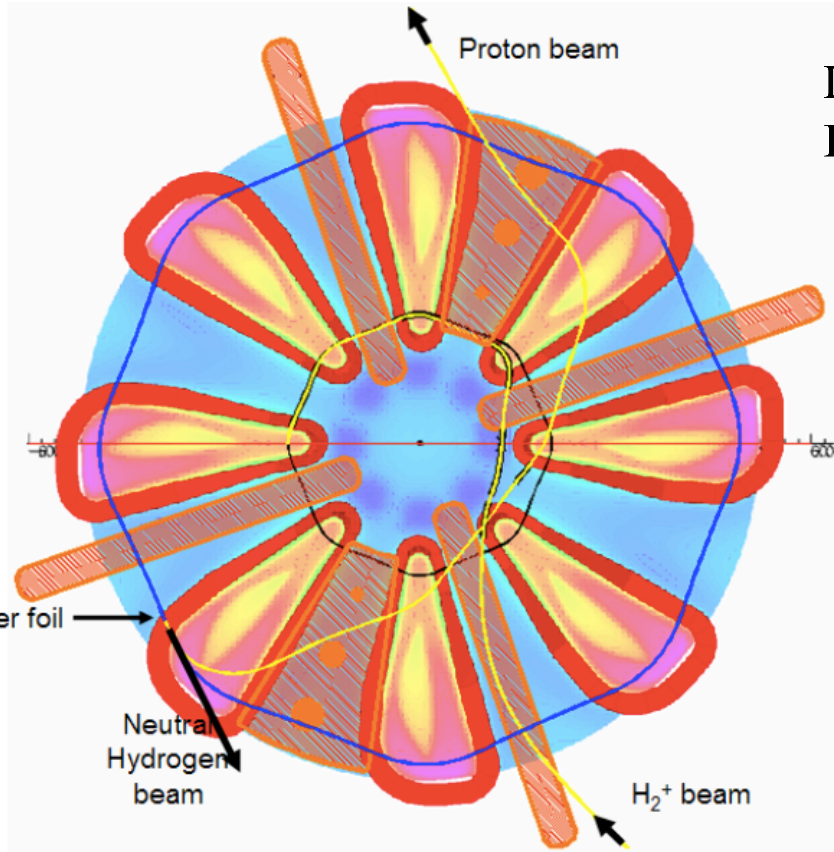
The most challenging aspect:
The Superconducting Ring Cyclotron

Multi Megawatt DAEδALUS Cyclotrons for Neutrino Physics

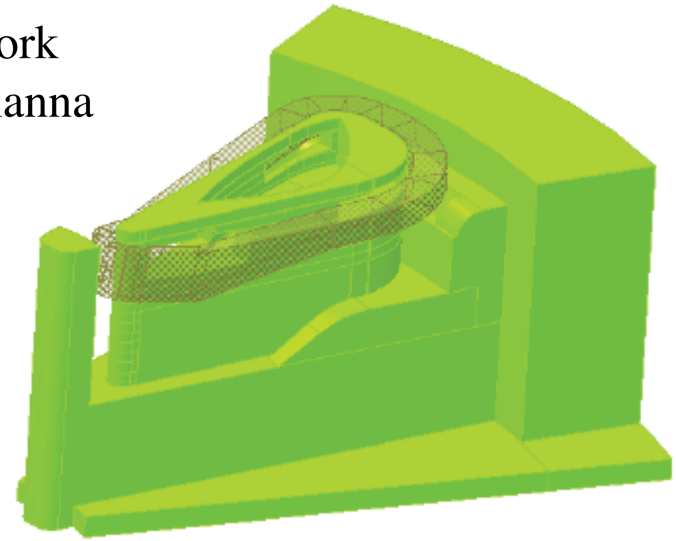
M. Abs[j], A. Adelmann[*,b], J.R. Alonso[c], W.A. Barletta[c], R. Barlow[h], L. Calabretta[f], A. Calanna[c], D. Campo[c], L. Celona[f], J. M. Conrad[c], S. Gammino[f], W. Kleeven[j], T. Koeth[a], M.Maggiore[e], H. Okuno[g], L.A.C. Piazza[e], M. Seidel[b], M. Shaevitz[d], L. Stingelin[b], J. J. Yang[c], J. Yeck[i]

[a]*Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland, 20742*
[b]*Paul Scherrer Institut, CH-5234 Villigen, Switzerland*
[c]*Department of Physics Massachusetts Institute of Technology*
[d]*Columbia University*
[e]*National Institute of Nuclear Physics - LNL*
[f]*National Institute of Nuclear Physics - LNS*
[g]*Riken*
[h]*Huddersfield University, Queensgate Campus, Huddersfield HD1 3DH, UK*
[i]*IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706*
[j]*IBA-Research*

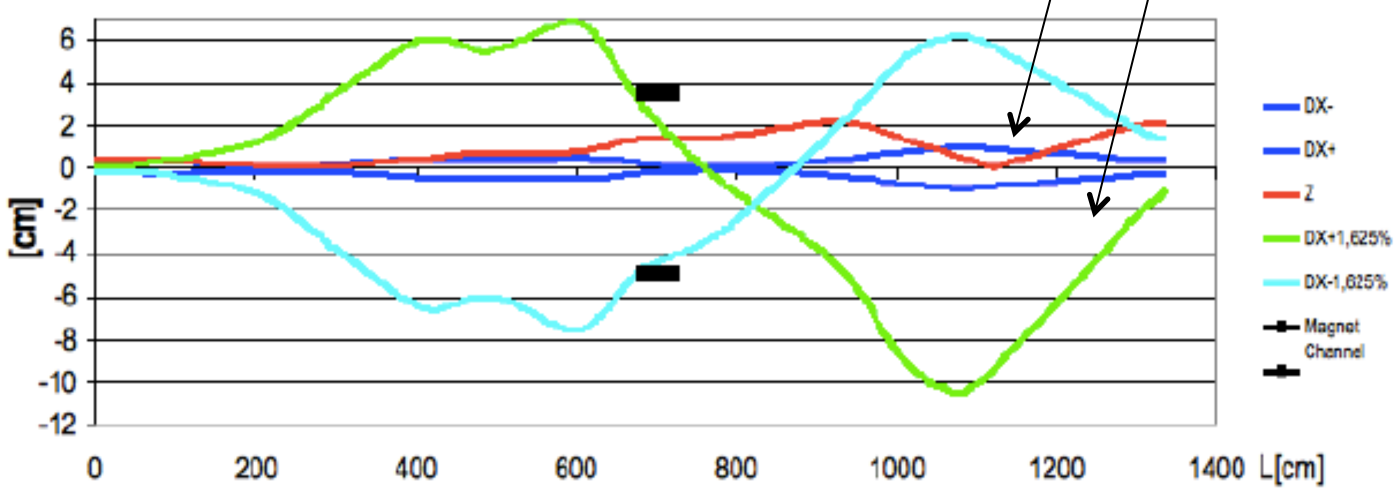
Paper in draft



Design work
By A. Calanna



Beam envelope,
No energy spread,
1% spread



The most challenging aspect:
The Superconducting Ring Cyclotron

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[f]*National Institute of Nuclear Physics - LNS*
[g]*Riken*
[h]*Huddersfield University, Queensgate Campus, Huddersfield HD1 3DH, UK*
[i]*IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706*
[j]*IBA-Research*

Paper in draft,
Will appear on arXiv soon

We can draw inspiration from the RIKEN-SRC!

Table 5: Comparison of main parameters for DSRC with those for RIKEN-SRC

Basic Parameters	**DSRC**	**RIKEN-SRC**	**Unit**
Maximum field on the hill	6.05	3.8	T
Maximum field on the coil	6.18	4.2	T
Stored Energy	280	235	MJ
Coil size	30× 24 or 15× 48	21× 28	cm^2
Coil Circumference	9.8	10.86	m
Magnetomotive force	4.9	4	MAtot/sector
Current density	34	34	A/mm^2
Height	5.6	6.0	m
Length	6.9	7.2	m
Weight	≦450	800	ton
Additional magnetic shield	0	3000	ton/total

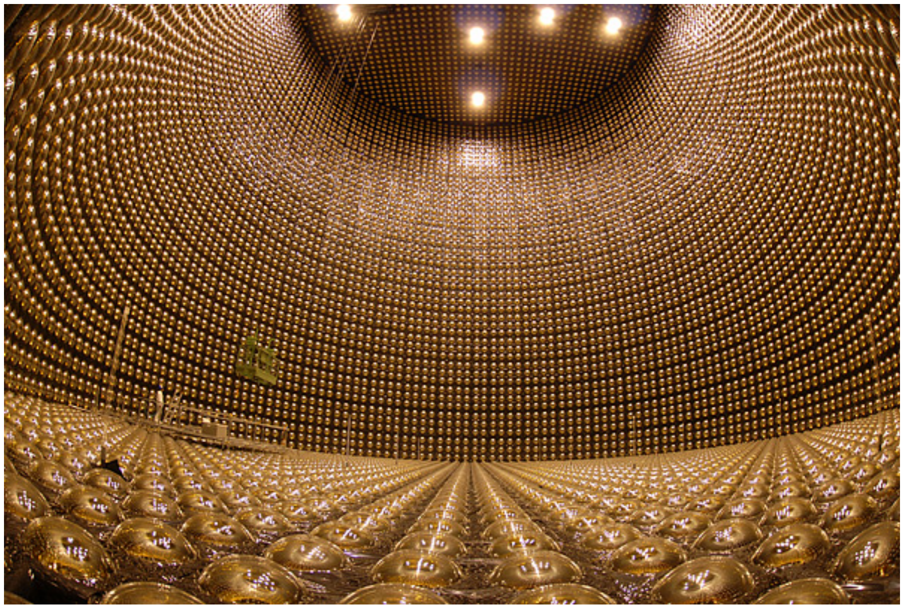
Magnetic Forces			
Expansion	1.87 or 1.8	2.6	MN/m
Vertical	3.7	3.3	MN
Radial shifting	2.7	0.36	MN
Azimuthal shifting	0.2	0	MN
Force on the pole	tbd	630	MN
Main Coil			
Operational current	5000	5000	A
Layer × turn	31×16	22×18	
Cooling	Bath cooling	Bath cooling	
Maddock Stabilized Current	6345	6665	A
Other Components			
SC trim	no	4	sets
NC trim× turn	no	22	pairs
Stray field in the SRC valley region	0.01	0.04	T
Gap for thermal insulation	40	90@min.	mm
Extraction method	Stripper foil	Electrostatic channel	

While there are some differences,
There are a lot of similarities!

And we are moving more toward Riken,
With a new 6-sector design…

Japan is a natural place to run this program.
It complements the JPARC program well.

We can pair our accelerators with…



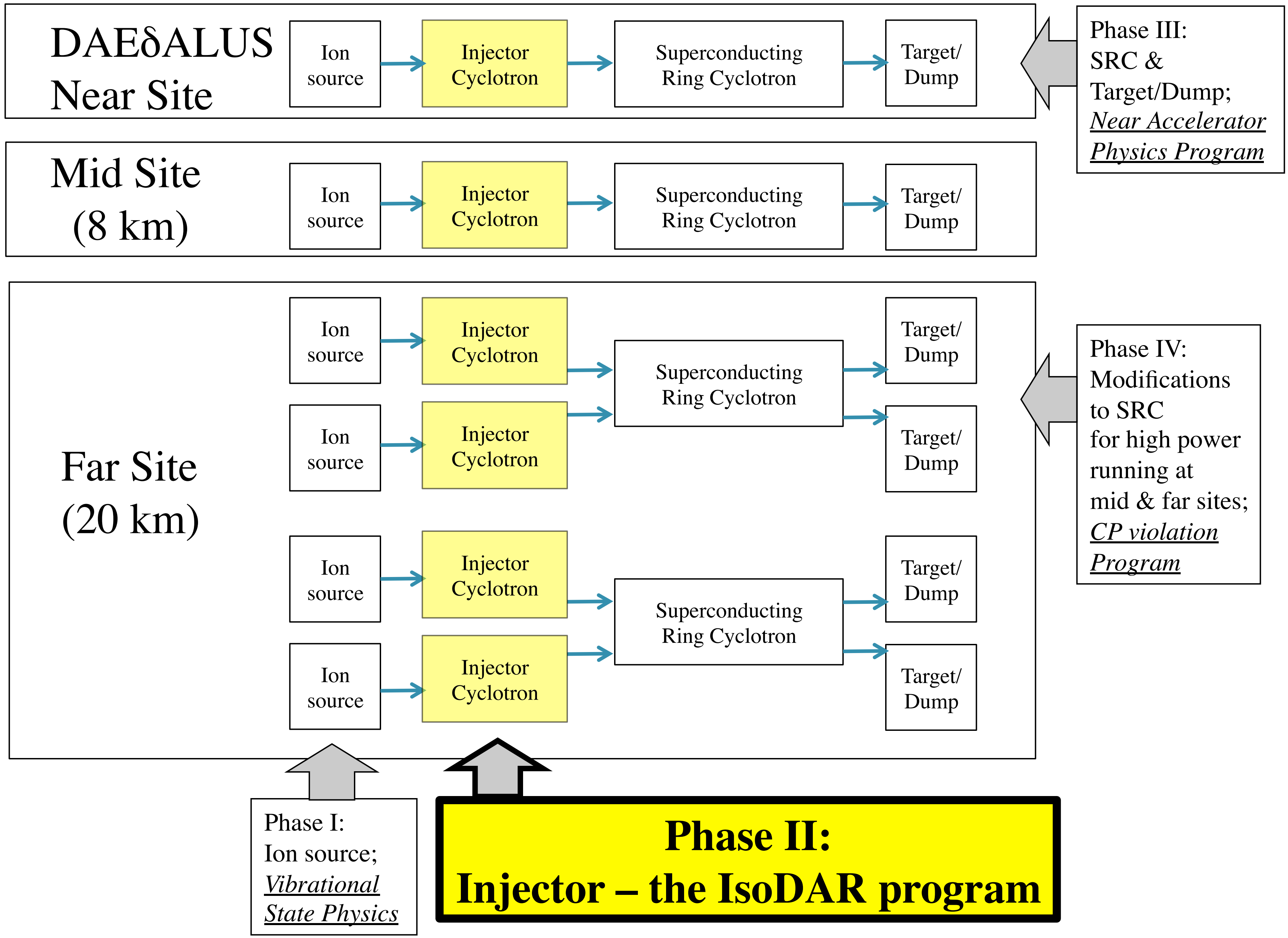
Super-K (running now)
And
Hyper-K (to be built
in the future)

Sites may be within 8 km
Of each other!

We are starting discussions…

Our goal is to start running in early 2020's

To do this, we need to think about how to move ahead with a phased plan…

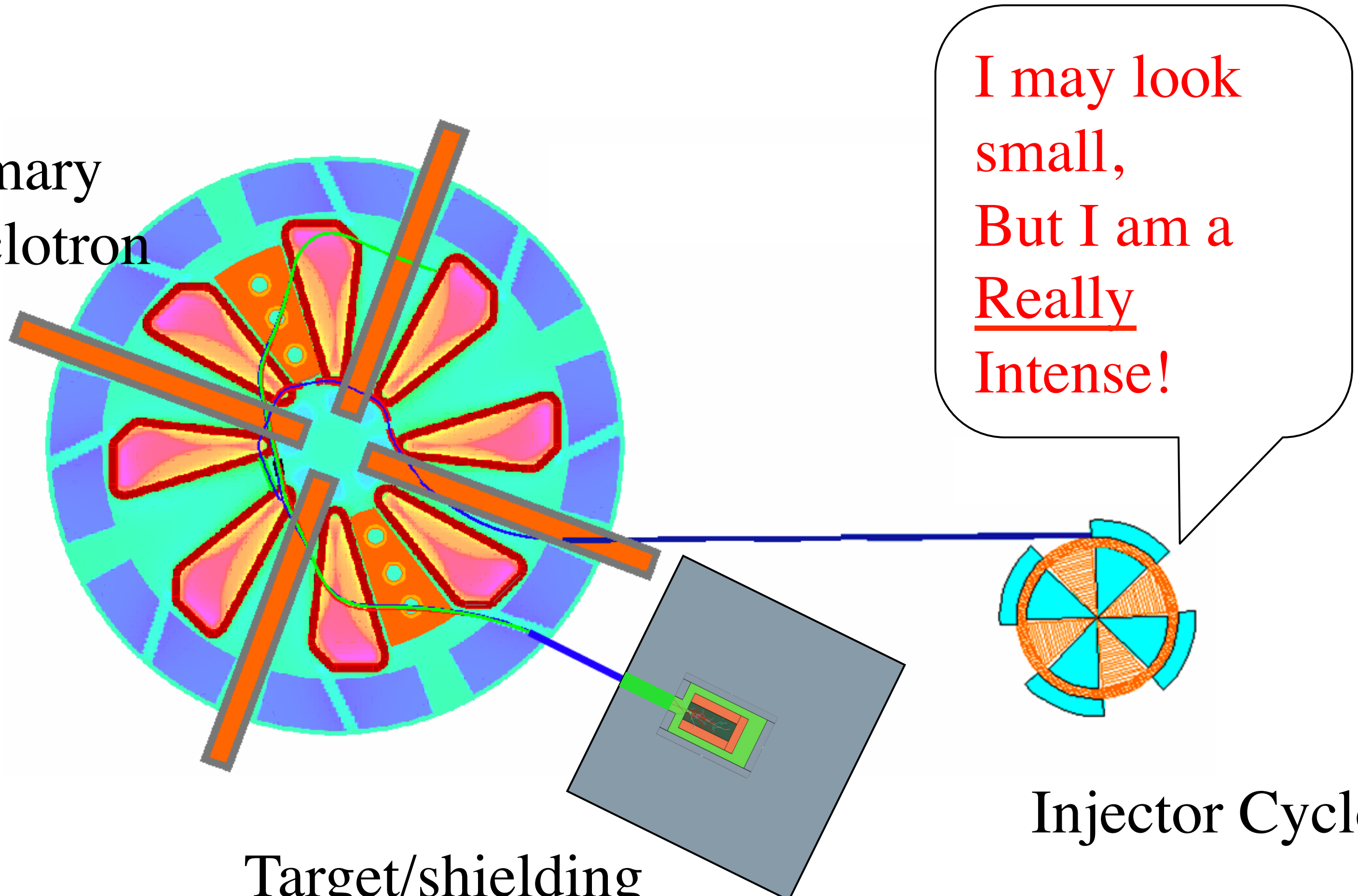


DAEδALUS Near Site
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Mid Site (8 km)
Far Site (20 km)
Phase III: SRC & Target/Dump; Near Accelerator Physics Program
Phase IV: Modifications to SRC for high power running at mid & far sites; CP violation Program
Phase I: Ion source; Vibrational State Physics
Phase II: Injector – the IsoDAR program

IsoDAR:

A Novel Isotope Decay at Rest Experiment

Do not be deceived…

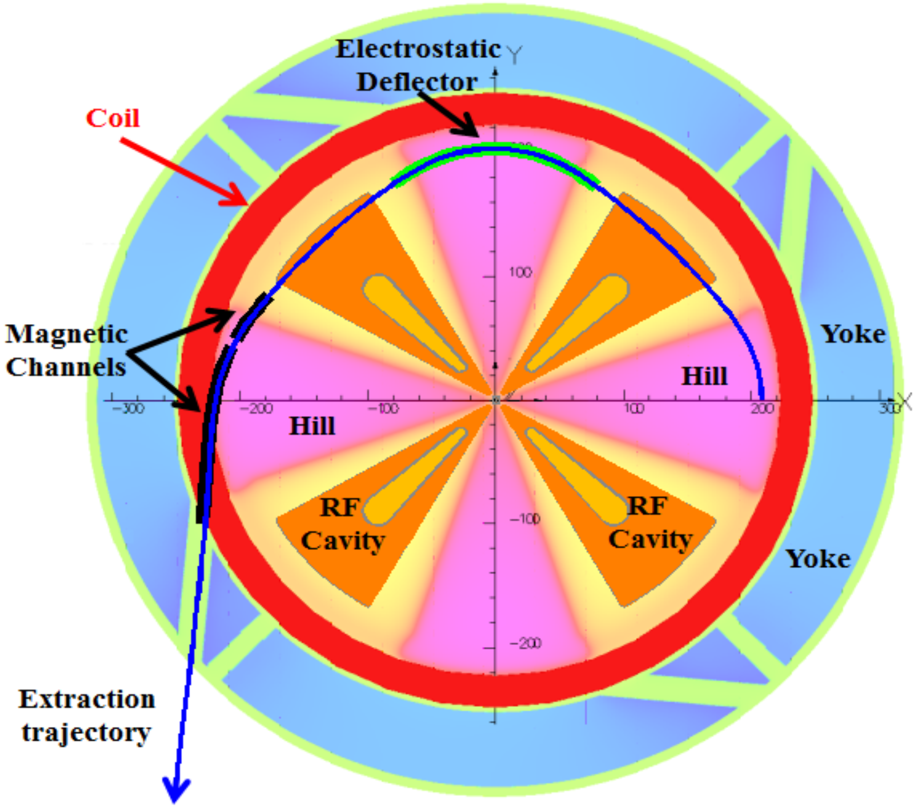


Lets get good physics
Out of this!

Designed for 5 mA of H2+ (10 mA of protons!)

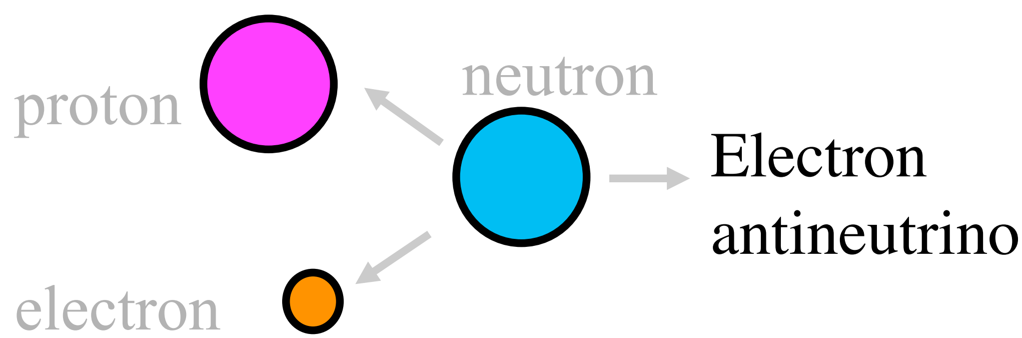
Table 3: Parameters of the DAEδALUS injector cyclotron

E_{max}	60 MeV/amu	E_{inj}	35 keV/amu
R_{ext}	1.99 m	R_{inj}	55 mm
$< B >$ @ R_{ext}	1.16 T	$< B >$ @ R_{inj}	0.97 T
Sectors	4	Hill width	28 - 40 deg
Valley gap	1800 mm	Pole gap	100 mm
Outer Diameter	6.2 m	Full height	2.7 m
Cavities	4	Cavity type	$\lambda/2$, double gap
Harmonic	6th	rf-frequency	49.2 MHz
Acc. Voltage	70 - 250 kV	Power/cavity	< 110 kW
ΔE/turn	1.3 MeV	Turns	107
ΔR /turn @ R_{ext}	20 mm	ΔR/turn @ R_{inj}	> 56 mm
Coil size	200x250 mm^2	Current density	3.1 A/mm^2
Iron weight	450 tons BIG!	Vacuum	$< 10^{-7}$ mbar



At 60 MeV/n,
We can use this to
Make isotopes
That beta decay
At rest…

This can produce
A lot of beam!



Returning to the list of questions…

So what would we like to learn next?

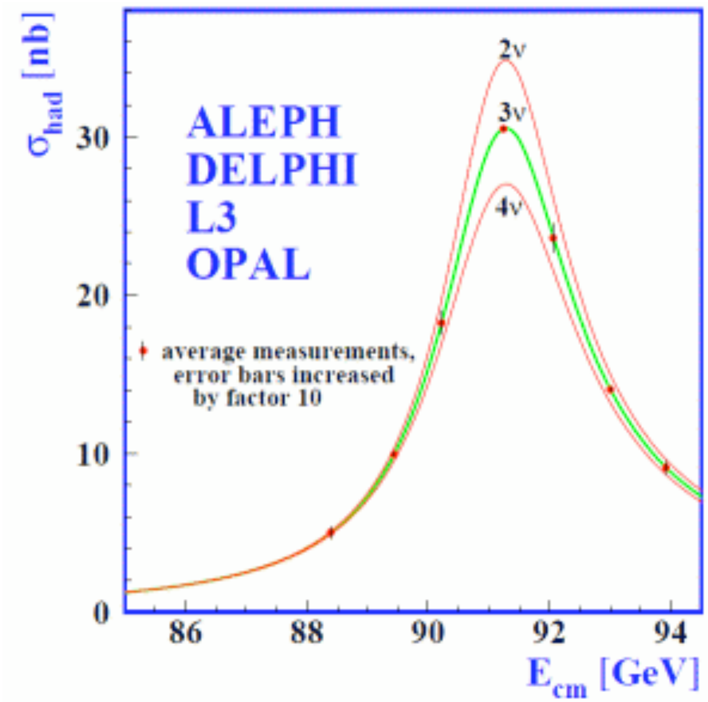
1. **Are neutrino oscillations the same as antineutrino oscillations? (CP violation)**

2. **Are there partners to active neutrinos (sterile neutrinos)**

This is the goal of "IsoDAR"

What kind of “partners” might be out there?

Light partners to the neutrino have to be non-interacting



Or we would have already seen them!

There is a lot of interest in the idea of sterile neutrinos!

arXiv.org > hep-ph > arXiv:1204.5379

Search or Article-id

High Energy Physics – Phenomenology

Light Sterile Neutrinos: A White Paper

K. N. Abazajian, M. A. Acero, S. K. Agarwalla, A. A. Aguilar-Arevalo, C. H. Albright, S. Antusch, C. A. Arguelles, A. B. Balantekin, G. Barenboim, V. Barger, P. Bernardini, F. Bezrukov, O. E. Bjaelde, S. A. Bogacz, N. S. Bowden, A. Boyarsky, A. Bravar, D. Bravo Berguno, S. J. Brice, A. D. Bross, B. Caccianiga, F. Cavanna, E. J. Chun, B. T. Cleveland, A. P. Collin, P. Coloma, J. M. Conrad, M. Cribier, A. S. Cucoanes, J. C. D'Olivo, S. Das, A. de Gouvea, A. V. Derbin, R. Dharmapalan, J. S. Diaz, X. J. Ding, Z. Djurcic, A. Donini, D. Duchesneau, H. Ejiri, S. R. Elliott, D. J. Ernst, A. Esmaili, J. J. Evans, E. Fernandez-Martinez, E. Figueroa-Feliciano, B. T. Fleming, J. A. Formaggio, D. Franco, J. Gaffiot, R. Gandhi, Y. Gao, G. T. Garvey, V. N. Gavrin, P. Ghoshal, D. Gibin, C. Giunti, S. N. Gninenko, et al. (129 additional authors not shown)

(Submitted on 18 Apr 2012)

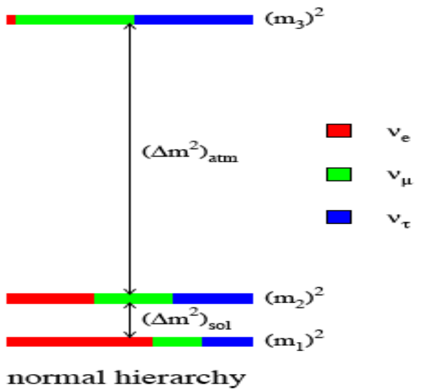
This white paper addresses the hypothesis of light sterile neutrinos based on recent anomalies observed in neutrino experiments and the latest astrophysical data.

New on
The arXiv
This spring!

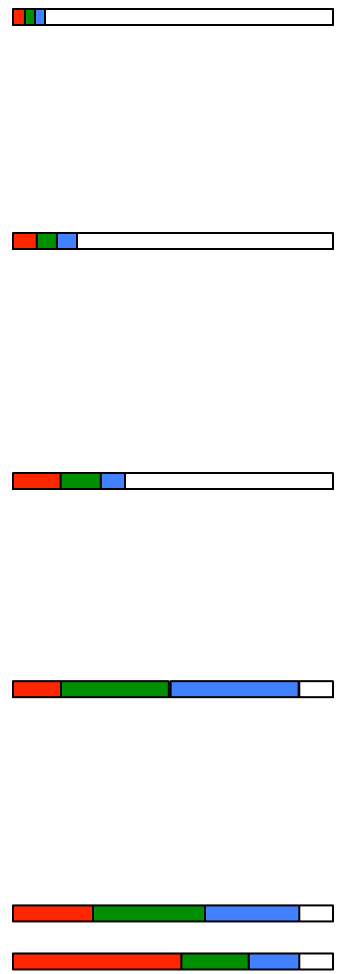
The most general phenomenological models have…
- 3 sterile partners
- Mixing between the sterile states and active states
- CP violation

This introduces 7 new parameters to the theory.
We can hope some parameters dominate over others,
Simplifying fits…

We are going from a model
That looks like this..



To one that looks like this:

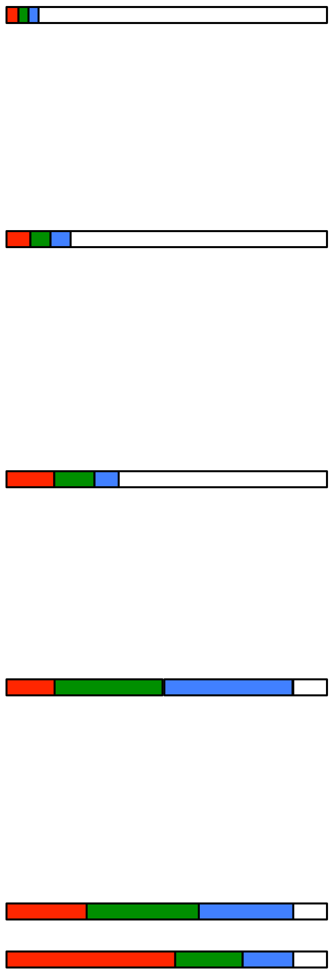


Introducing
3 sterile
Neutrinos
(white)
That mix
With the
3 flavors

This is a “3+3” model,
And it is clearly
Complicated!

We can hope that nature
Made one or two of the
States almost fully sterile,
So we can ignore them.

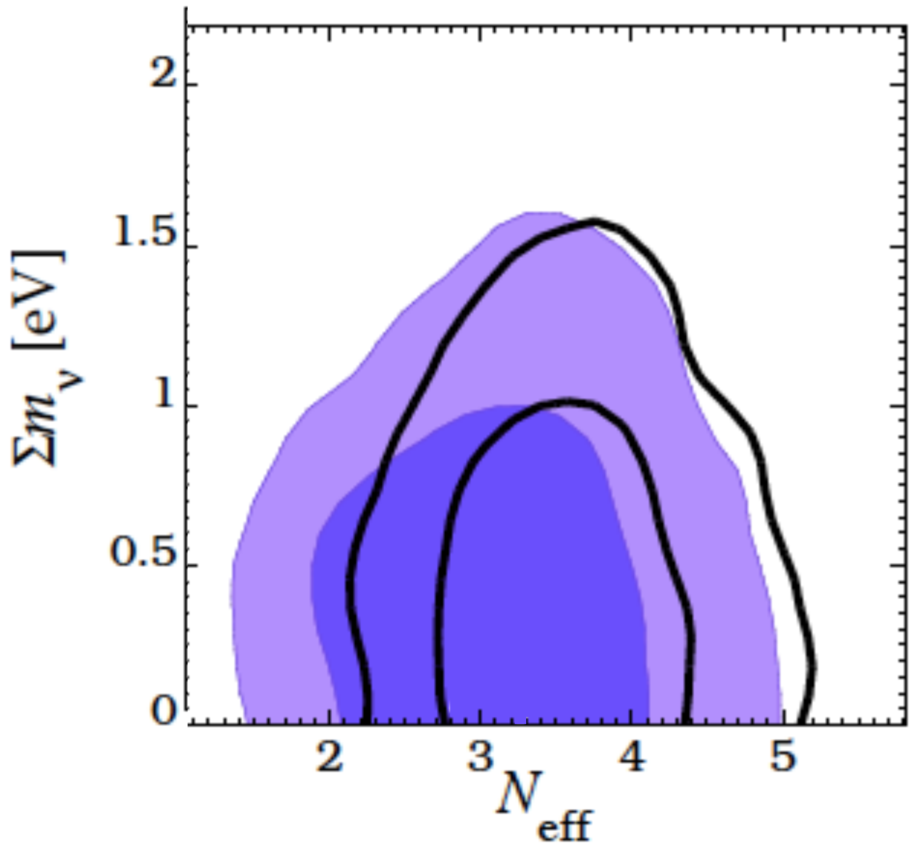
We can then look at
3+2 or 3+1 models



Introducing
3 sterile
Neutrinos
(white)
That mix
With the
3 flavors

Sterile neutrinos show up in cosmology…

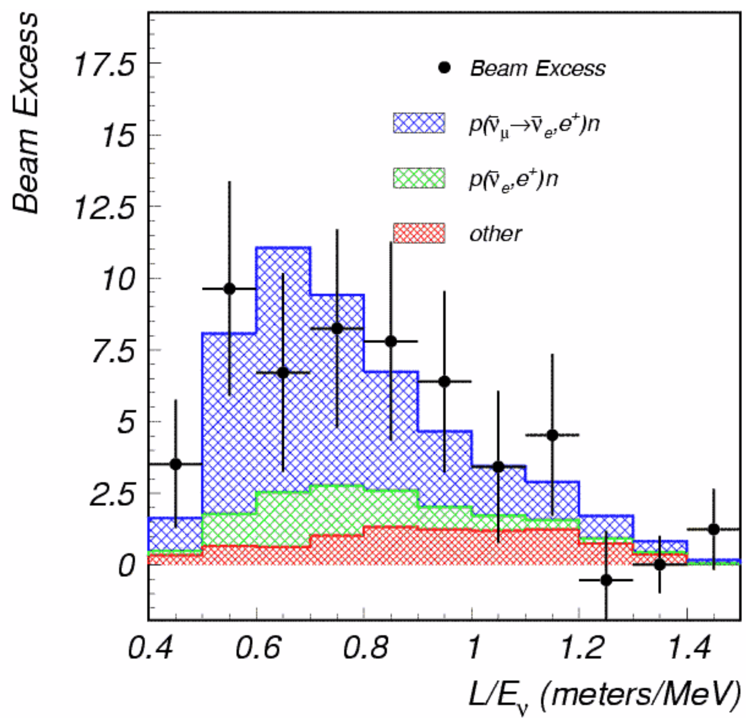
Fit to the number of effective neutrinos from WMAP (1202.0005)

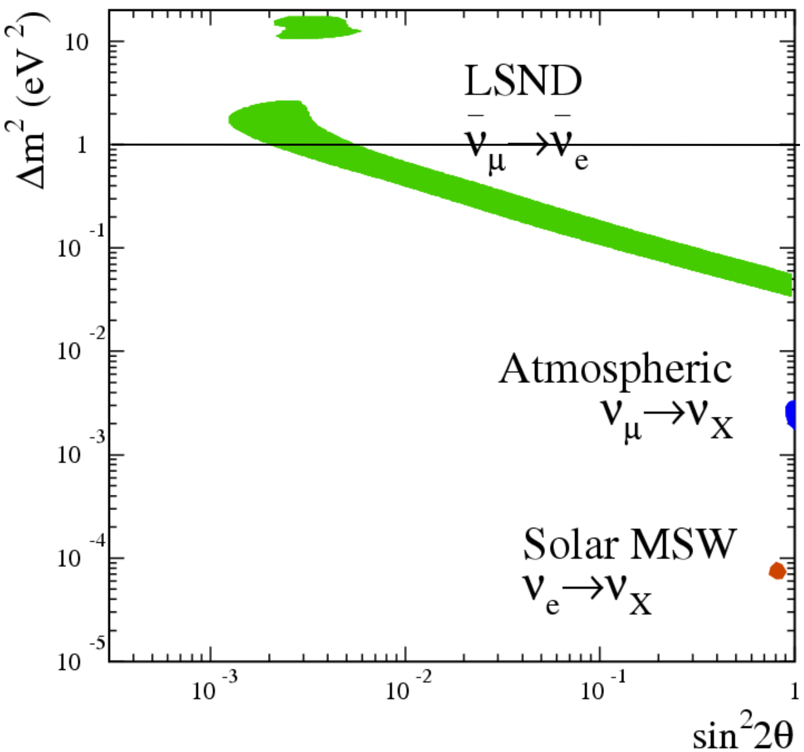


This is not a very Sensitive test, since Effects not included In the model can Significantly change N_{eff}

Still, it is a hint… there is room for a heavy "neutrino"

Consider muon electron flavor appearance



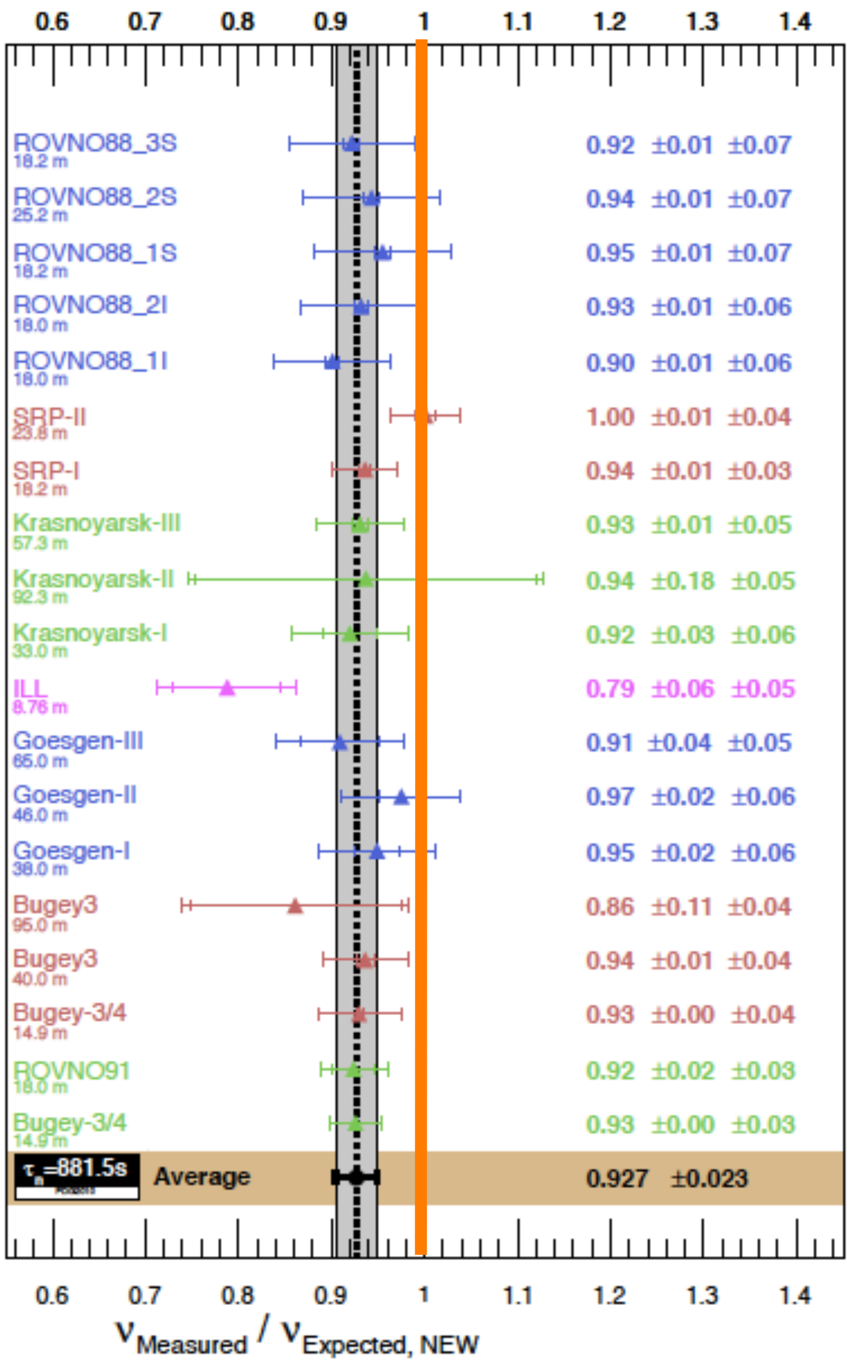


Unexpected excess in LSND, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

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

Higher Δm^2 than other signals, $\sim 1\ eV^2$

…Also seen by MiniBooNE



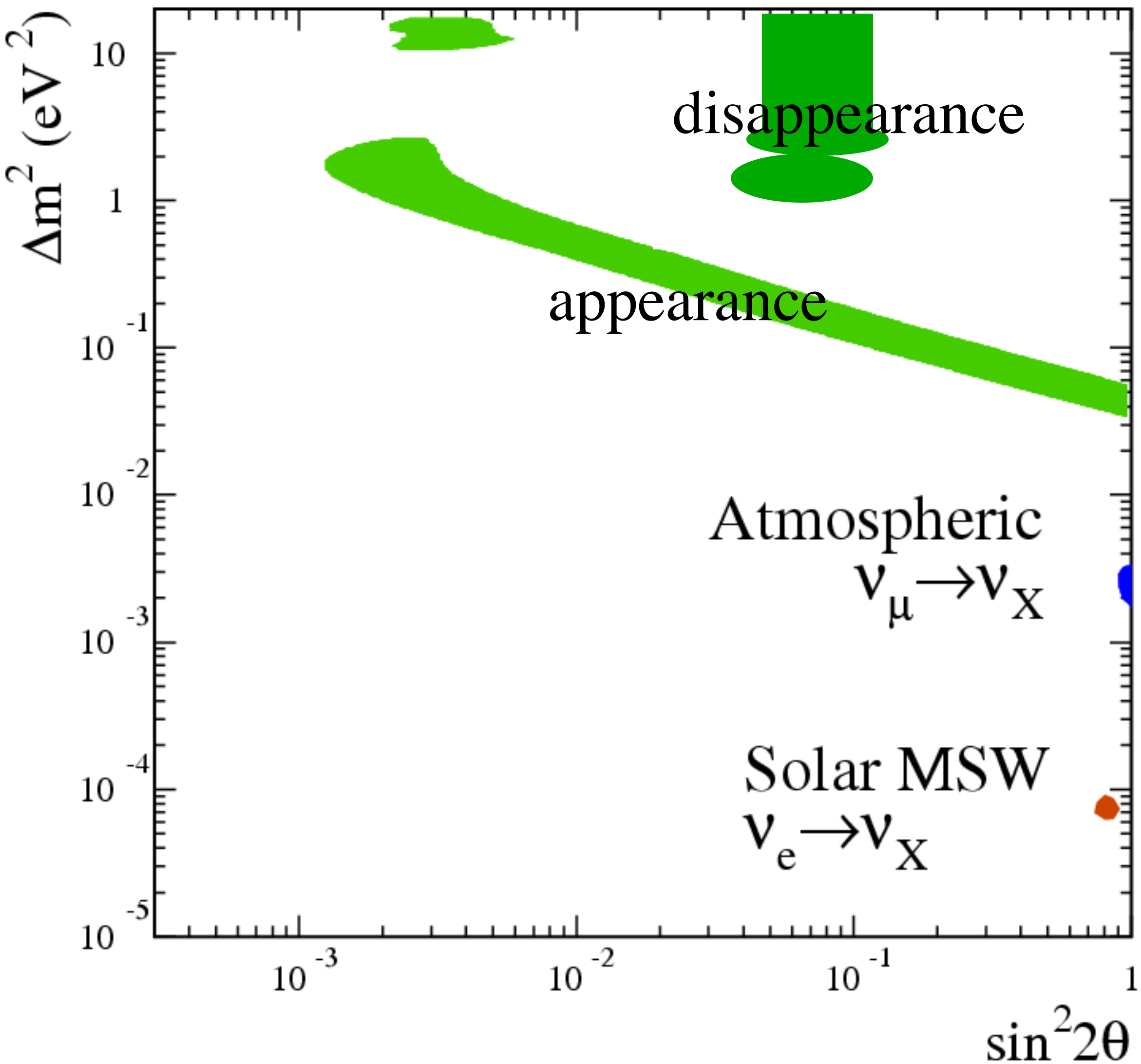
Also hints from ν_e disappearance

Signal from reactors

As well as calibration sources (SAGE/GALLEX)

Interpreted as oscillations…

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

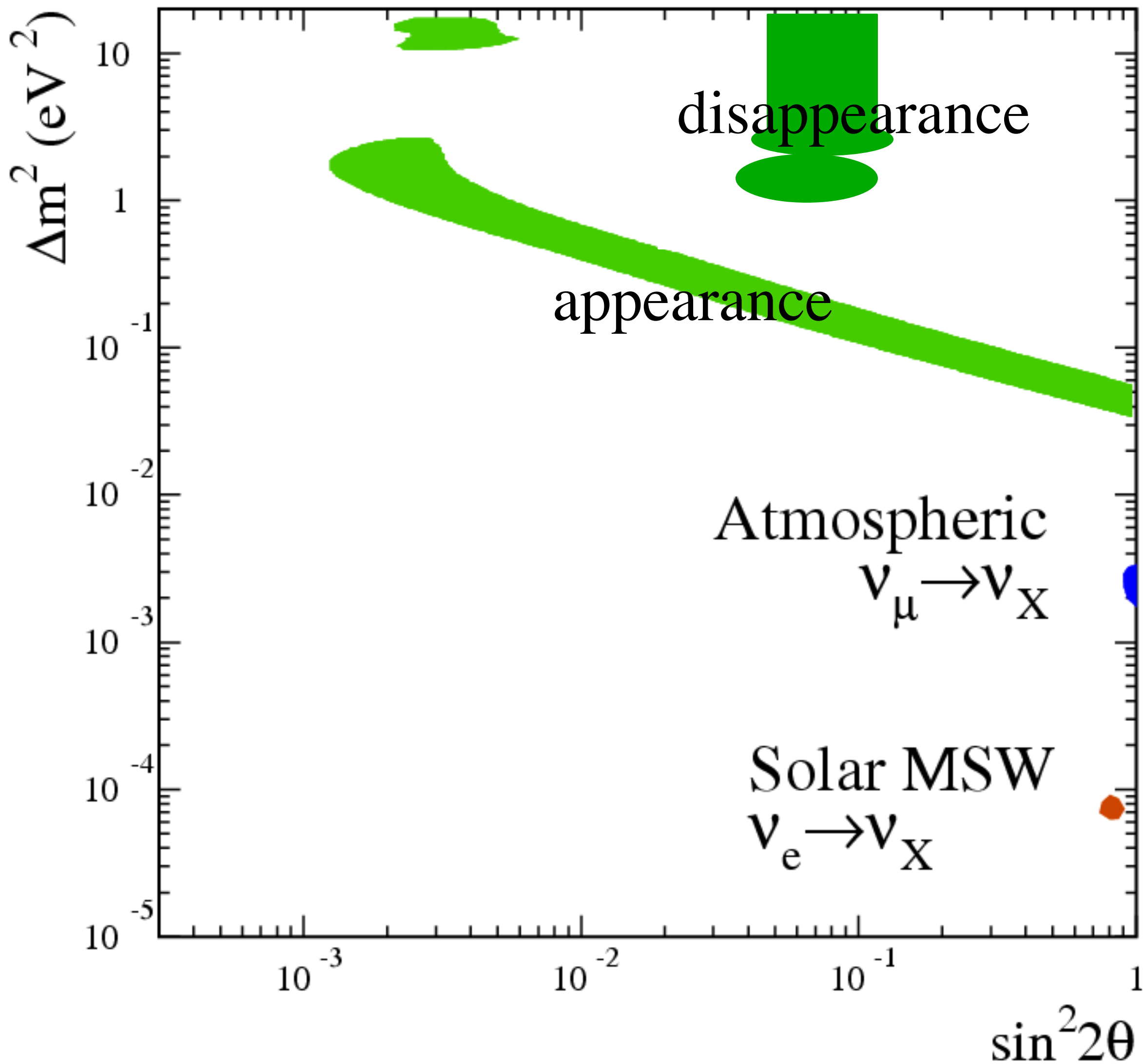


These are multiple Results, but all are at 3σ or less. Not decisive!

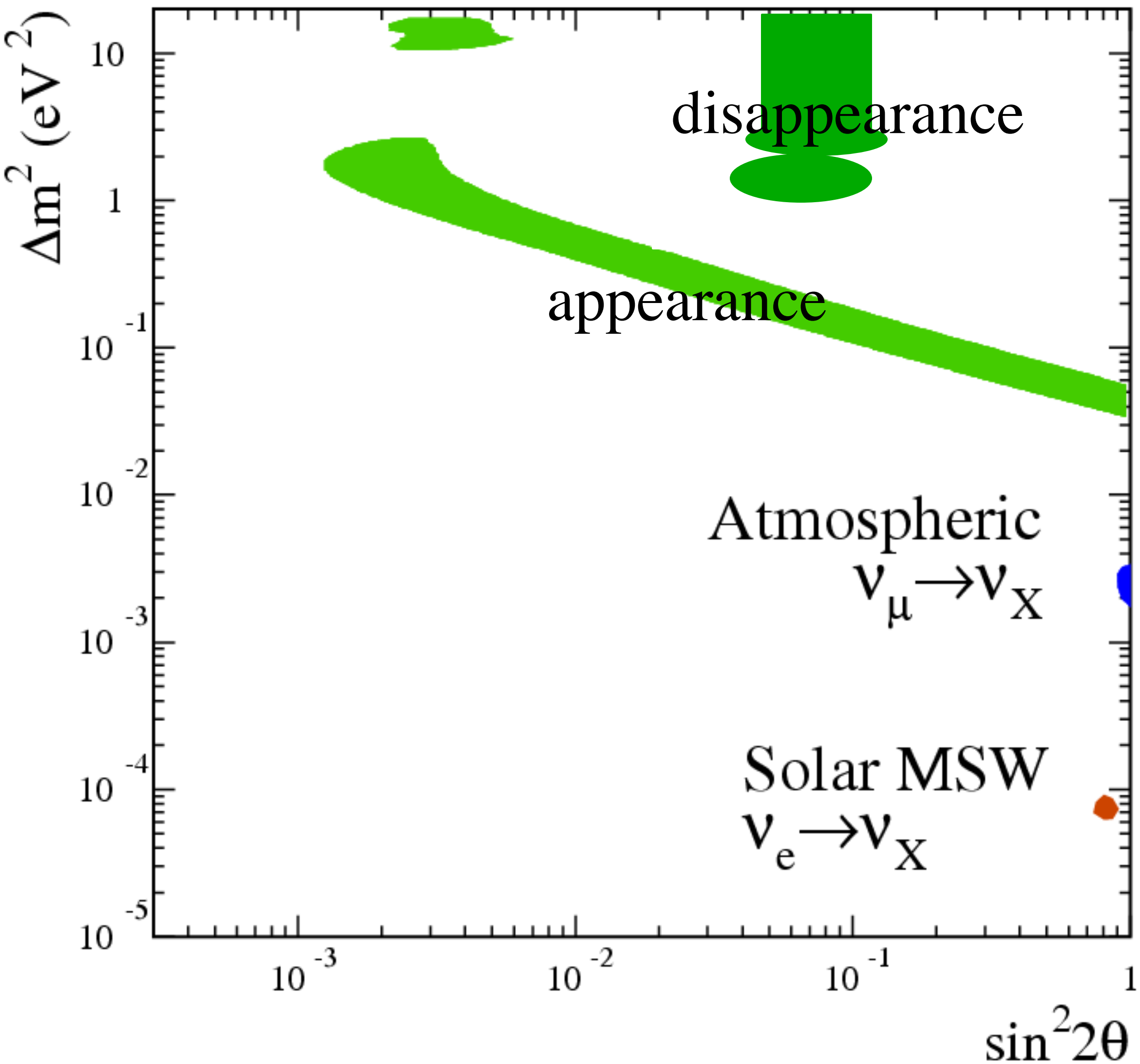
Be careful with This plot!

The "effective" mixing is not the same for each osc. mode

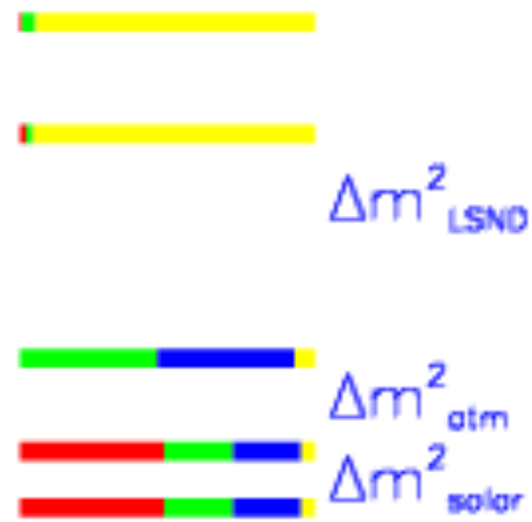
While not decisive, they are intriguing!



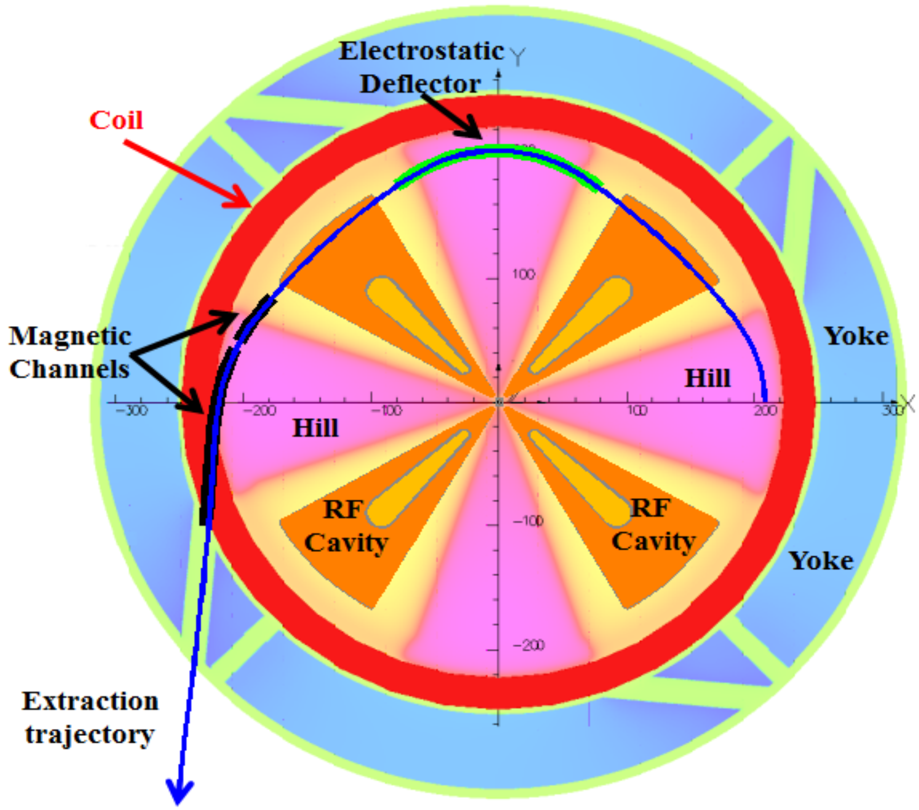
With only 3 Neutrinos, There are Only 2 Independent Δm^2 regions



You need extra
Sterile neutrinos
To solve the problem



We need a decisive experiment



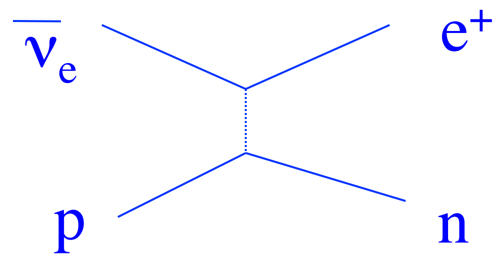
Use the injector to produce Isotopes which decay to Electron antineutrinos.

Detect these in a 1 kton Liquid scintillator detector

You can choose the experimental design,
Such that it will decisively address the sterile neutrino question

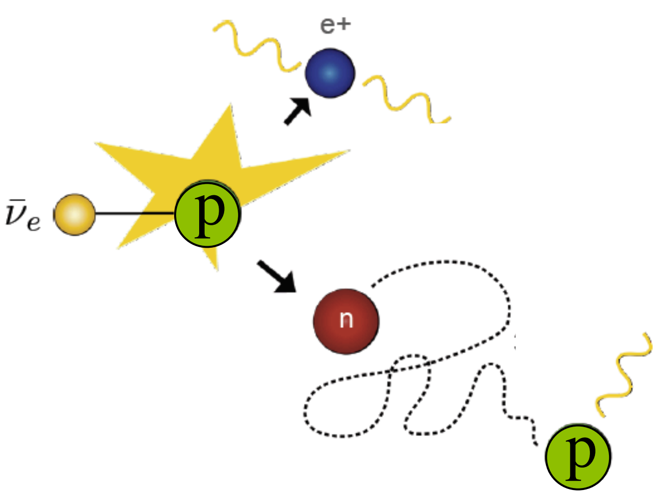
Why a liquid scintillator detector?

The signal:
inverse beta decay, IBD



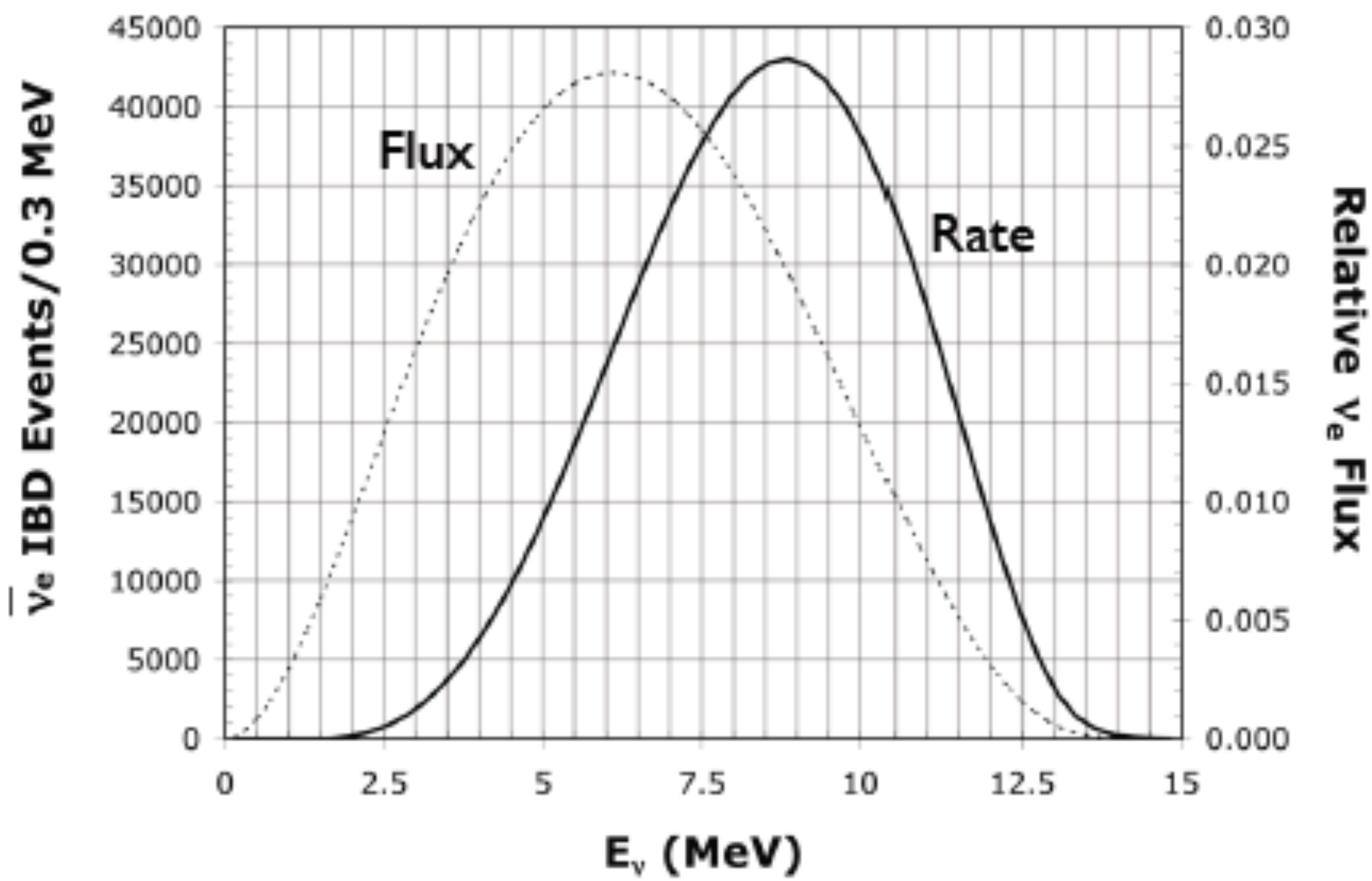
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

You can use a detector with scintillator = **free protons**!



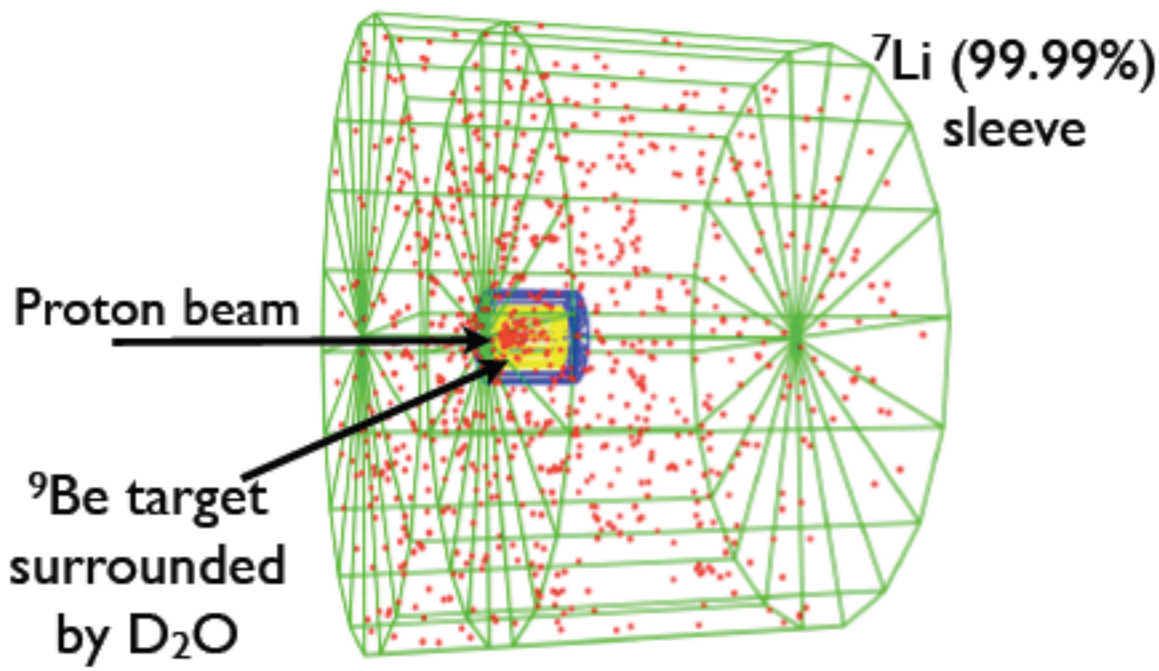
A coincidence signal:
- Positron
- Neutron capture

^{8}Li



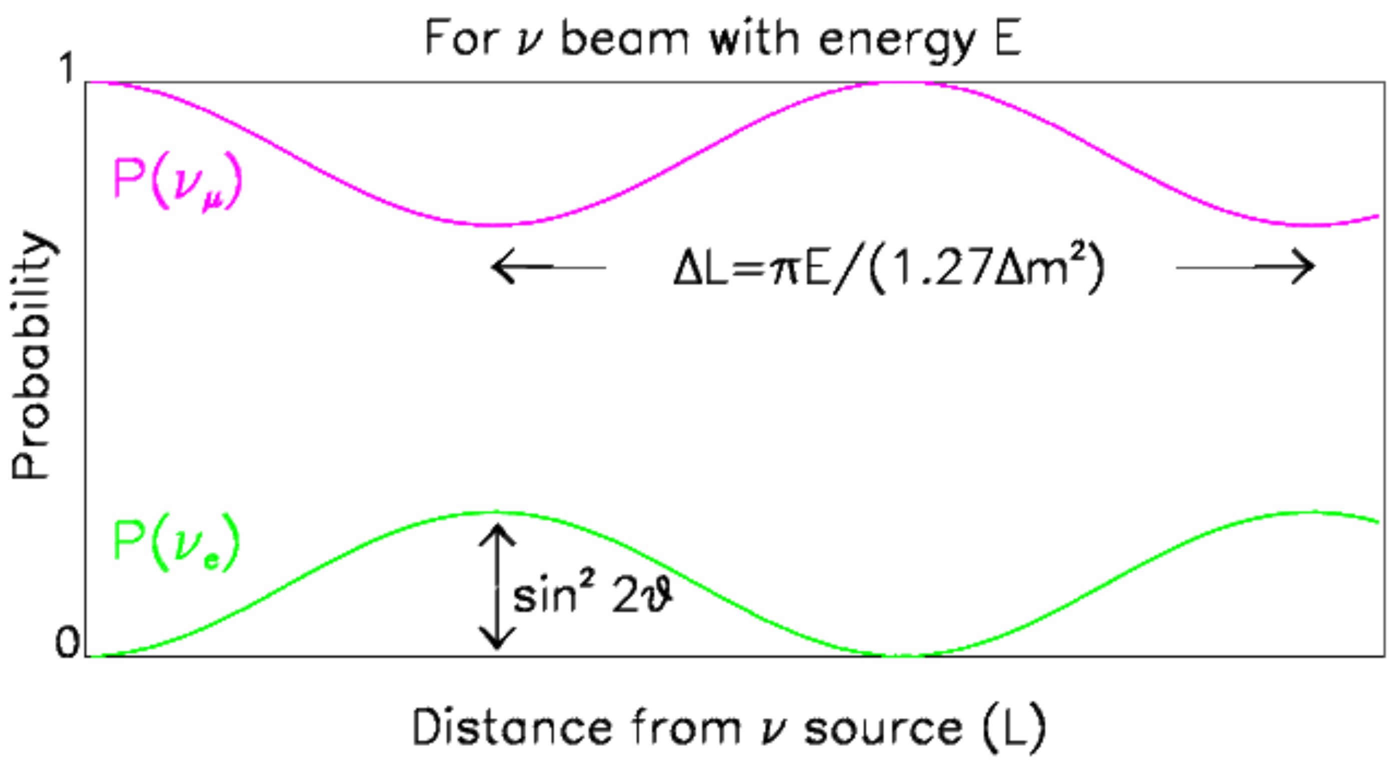
Flux
Rate
$\overline{\nu}_e$ IBD Events/0.3 MeV
Relative $\overline{\nu}_e$ Flux
E_ν (MeV)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0.030
0.025
0.020
0.015
0.010
0.005
0.000
0
2.5
5
7.5
10
12.5
15

How to produce a lot of ^{8}Li



Recall about oscillations…

If E ~ 8 MeV,
Then L~ 8 m will correspond to $\Delta m^2 \sim 1$ eV^2

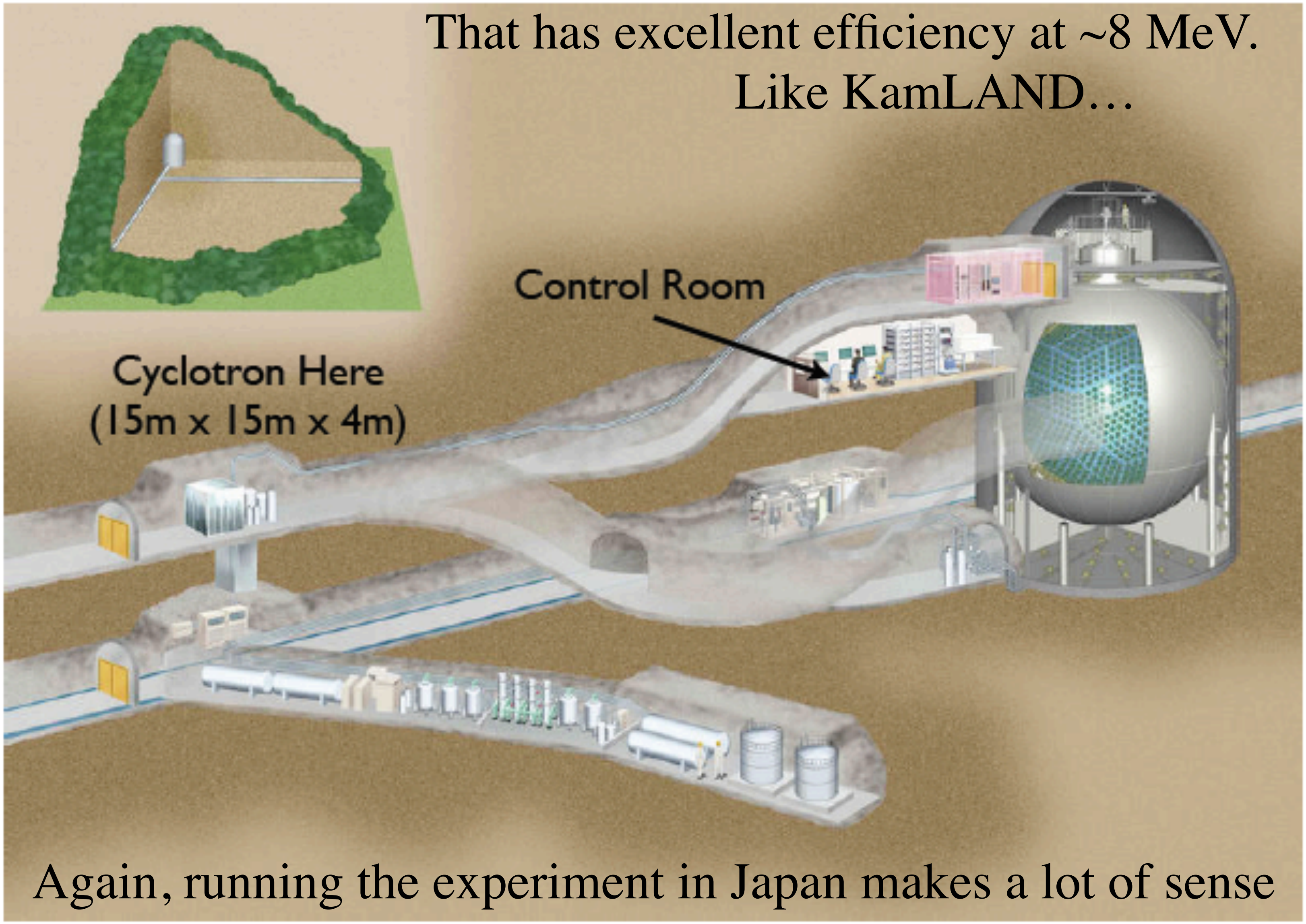


Where could we run this?

We need an existing big detector, full of free protons

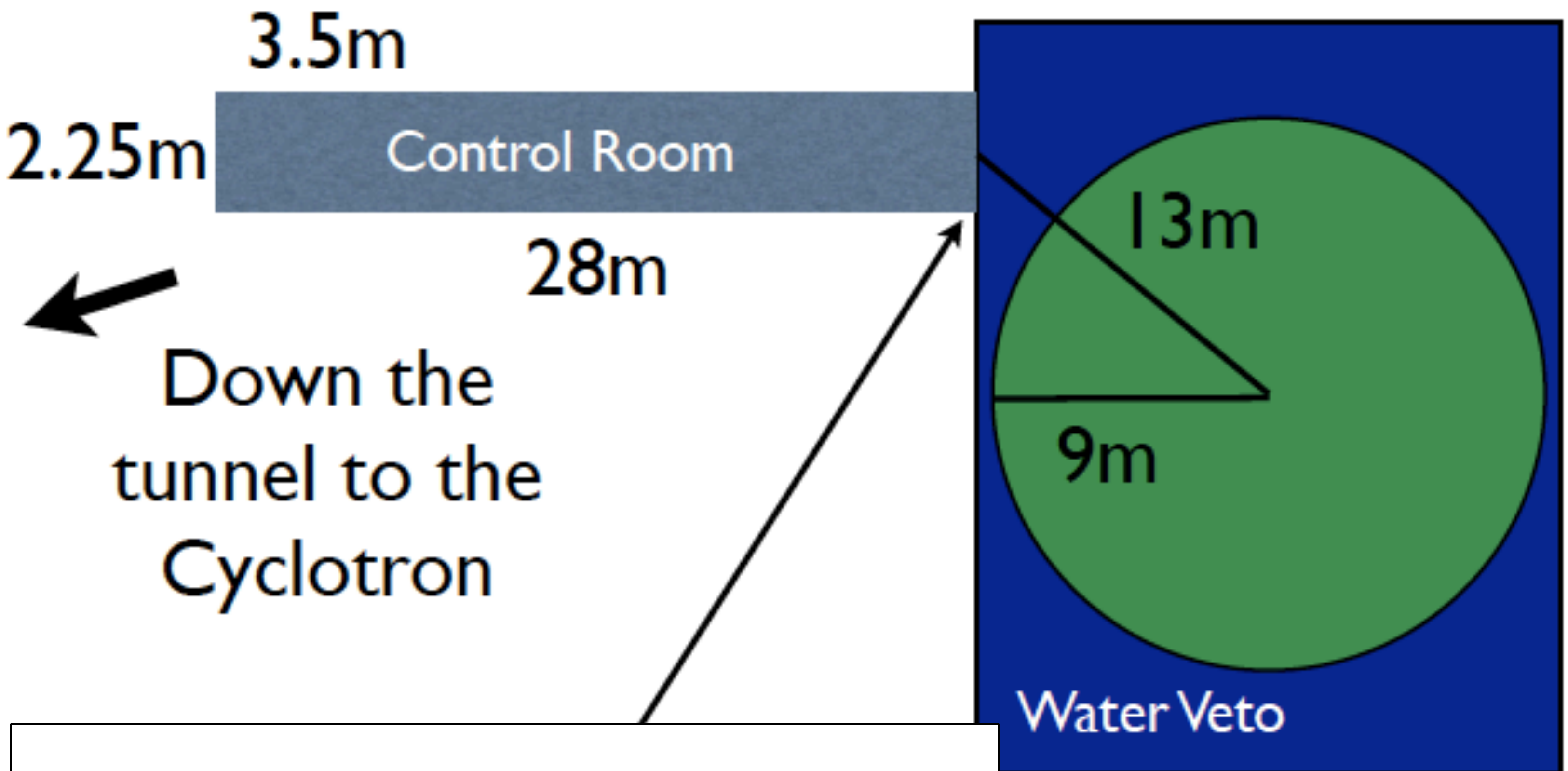
That has excellent efficiency at ~8 MeV.

Like KamLAND…



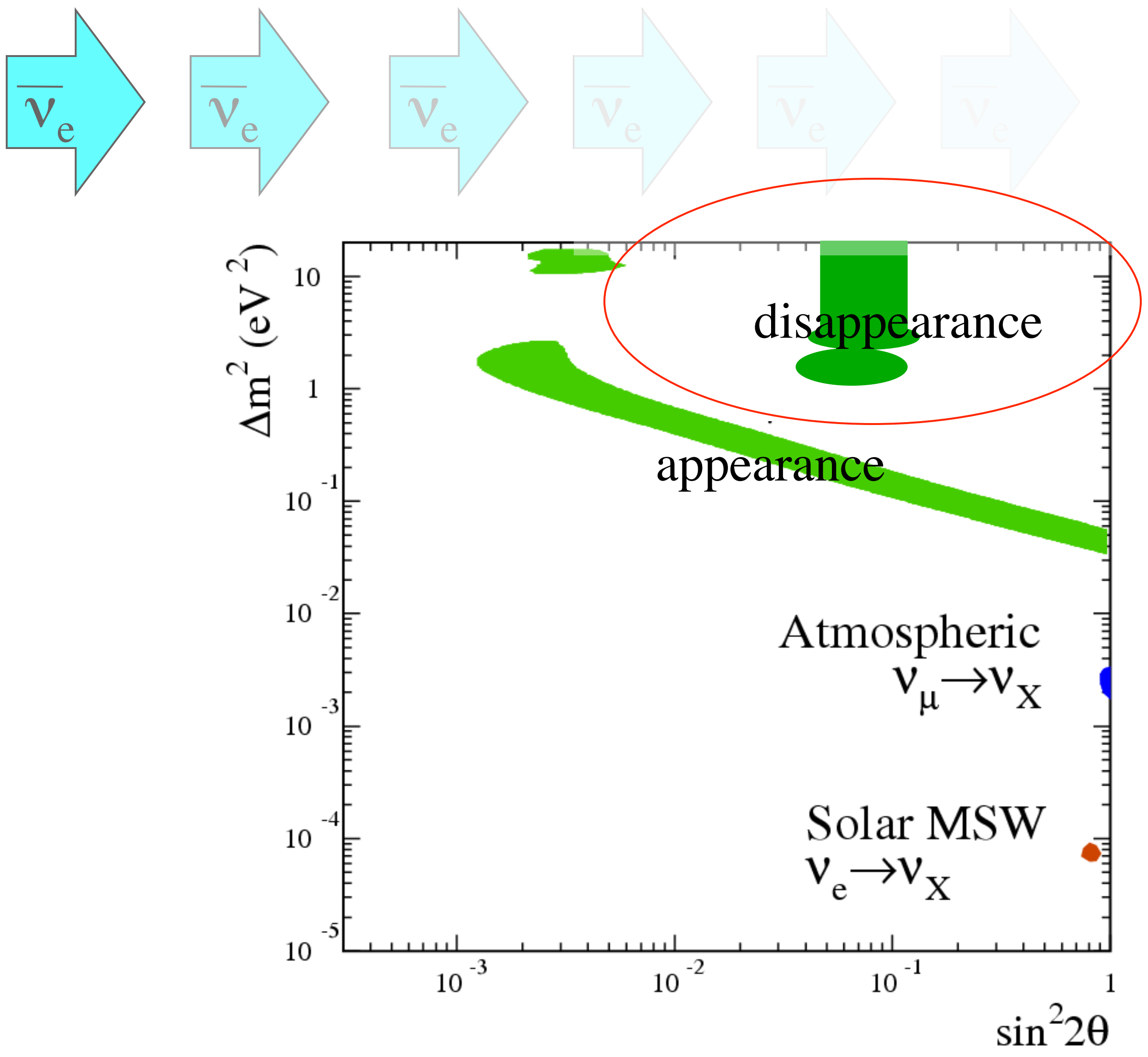
Again, running the experiment in Japan makes a lot of sense

We are discussing moving the control room and installing
The target/sleeve/shielding next to the wall

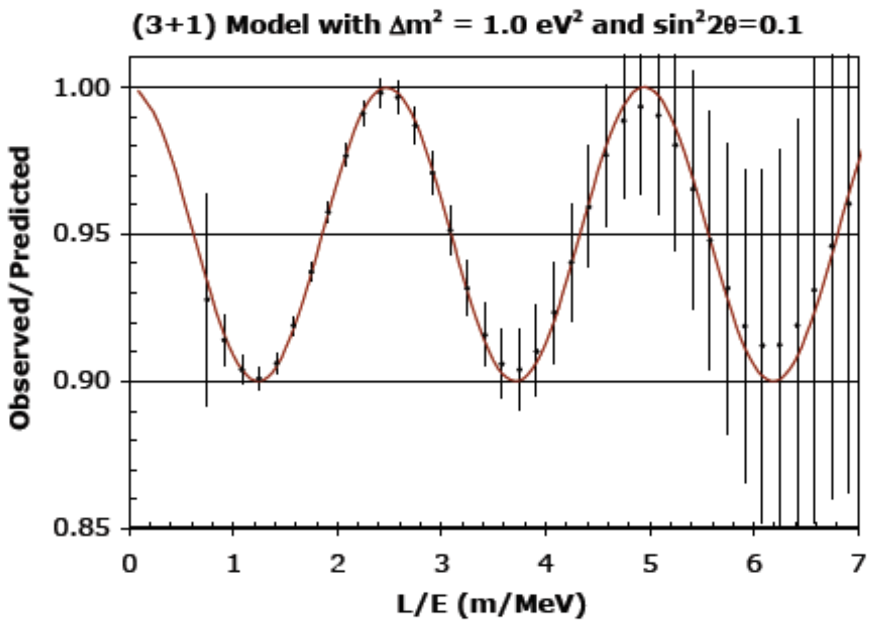


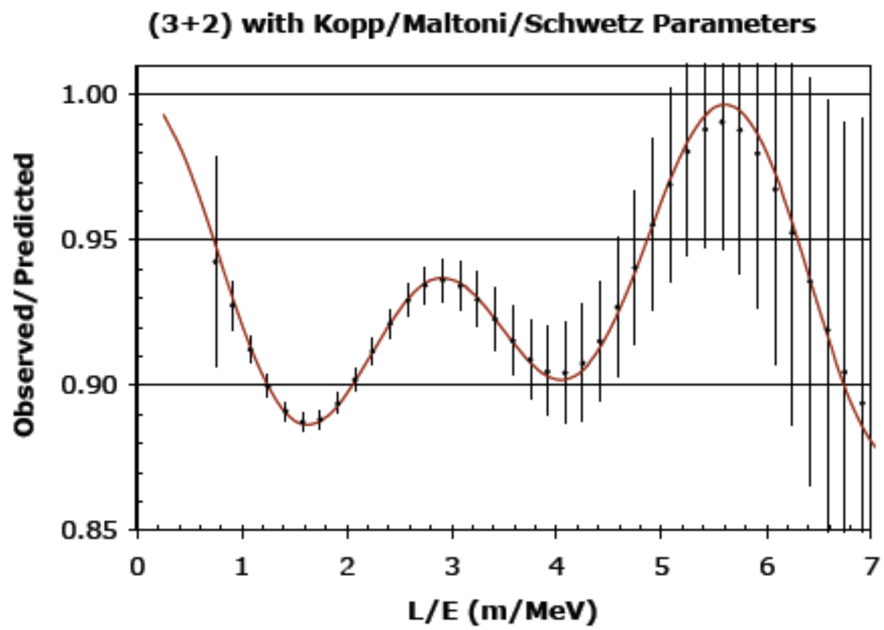
This places the target at 16.5 m
From the center of the detector

This allows us to address disappearance…



With 5 years statistics:

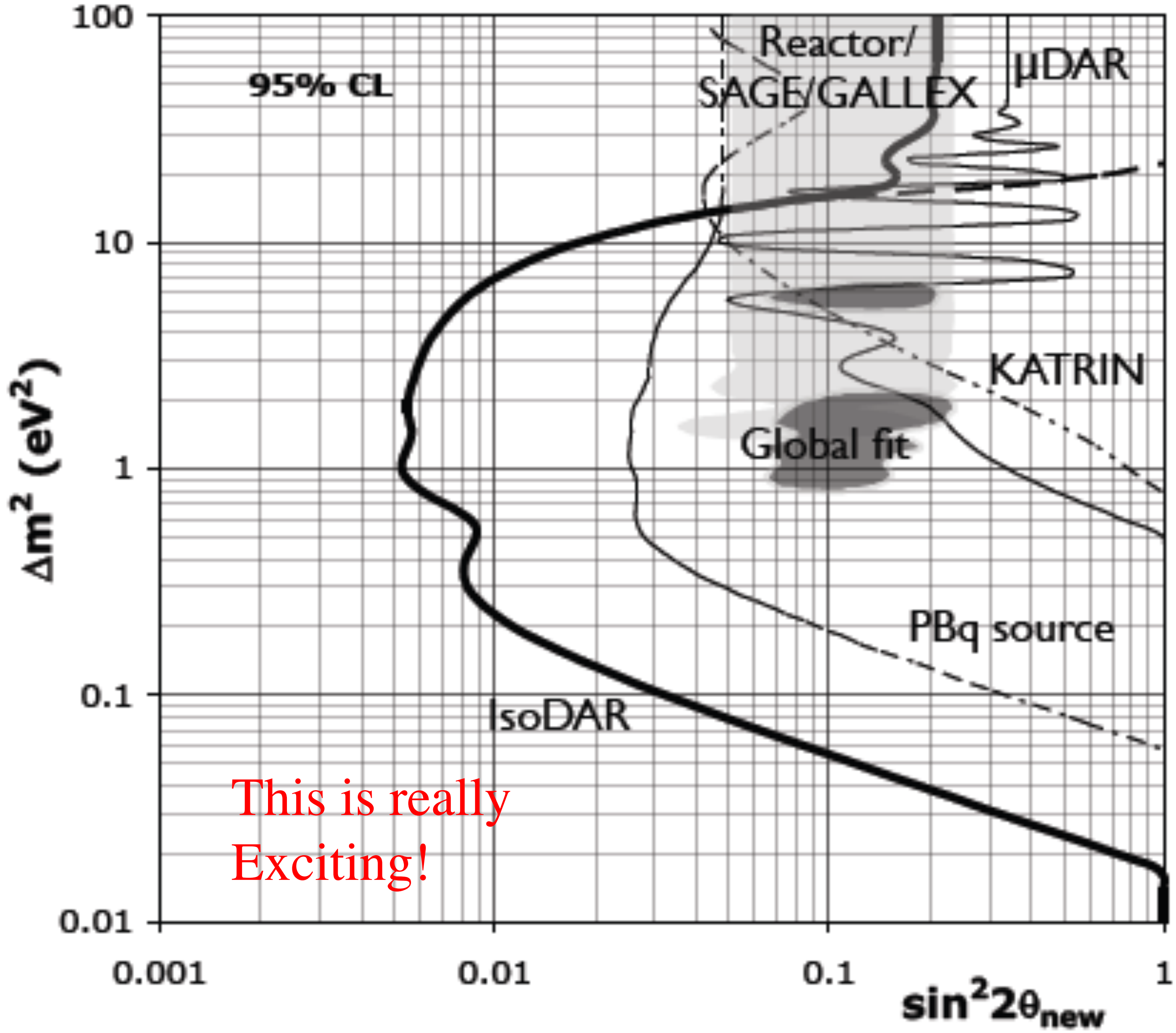




3+1

3+2

No other experiment that can be staged in the next 5 years
Can do this well!



This is really
Exciting!

5 mA H2+ beam = 10 mA protons on target

nearly an order of magnitude higher than any
exiting or designed cyclotron
(600 kW on target)

60 MeV/n -- typical of many medical isotope machines

Table 2: *Medical isotopes relevant to IsoDAR energues, from Ref. [29].*

Isotope	half-life	Use
^{52}Fe	8.3 h	The parent of the PET isotope ^{52}Mn and iron tracer for red-blood-cell formation and brain uptake studies.
^{122}Xe	20.1 h	The parent of PET isotope ^{122}I used to study blood brain-flow.
^{28}Mg	21 h	A tracer that can be used for bone studies, analogous to calcium
^{128}Ba	2.43 d	The parent of positron emitter ^{128}Cs. As a potassium analog, this is used for heart and blood-flow imaging.
^{97}Ru	2.79 d	A γ-emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ-emitter potentially useful for bone studies.
^{82}Sr	25.4 d	The parent of positron emitter ^{81}Rb, a potassium analogue This isotope is also directly used as a PET isotope for heart imaging.

Potentially very useful outside of neutrino physics

CONCLUSIONS

In the last 15 years,
neutrino physics has made amazing discoveries.

But there is still a lot
that we do not understand.

To take the next step,
we need smart new accelerators,
that are not highly expensive,
that can produce a lot of decay-at-rest neutrinos.

Cyclotrons are perfect for this.

I would like to see a cyclotron-based
Neutrino program develop in Japan.

This fits Japan’s existing neutrino resources
Very well!

I hope you are interested also.