ν_e

Neutrino Oscillation Experiments

ν_μ

National Nuclear Physics Summer School – MIT – July 29, 2016 – Janet Conrad

Introduction
to this class

What do I hope to do with this class?

- Paint a quick picture of how neutrino experiments are designed,
- Point out a few things we are working on now,
- Draw connections between Nuclear and Particle communities,
- And most importantly…

try to plant some ideas in your mind,
that could lead to interesting papers
and even interesting new experiments.

This will go by fast.
If you would like to learn more, I suggest you attend the annual Neutrino Summer School associated with the NuFact Conference.

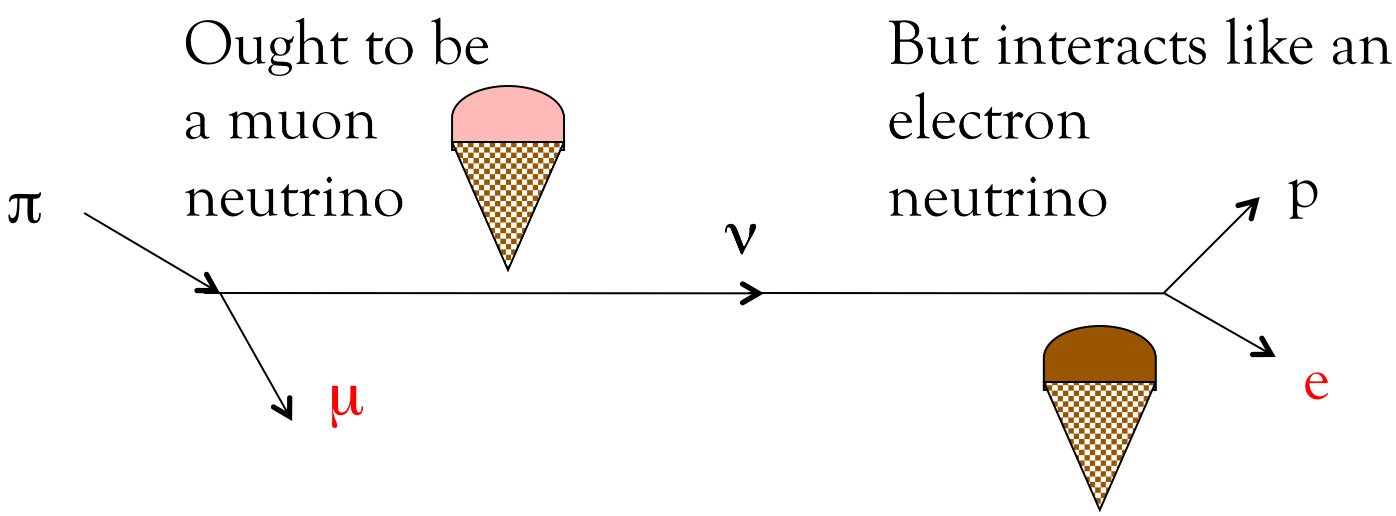
Properties of neutrinos that we use to explore for new physics…

	source dependent	detector dependent
Flavor	✔	✔
Energy	✔	✔
Distance (really, time)	✔	✔

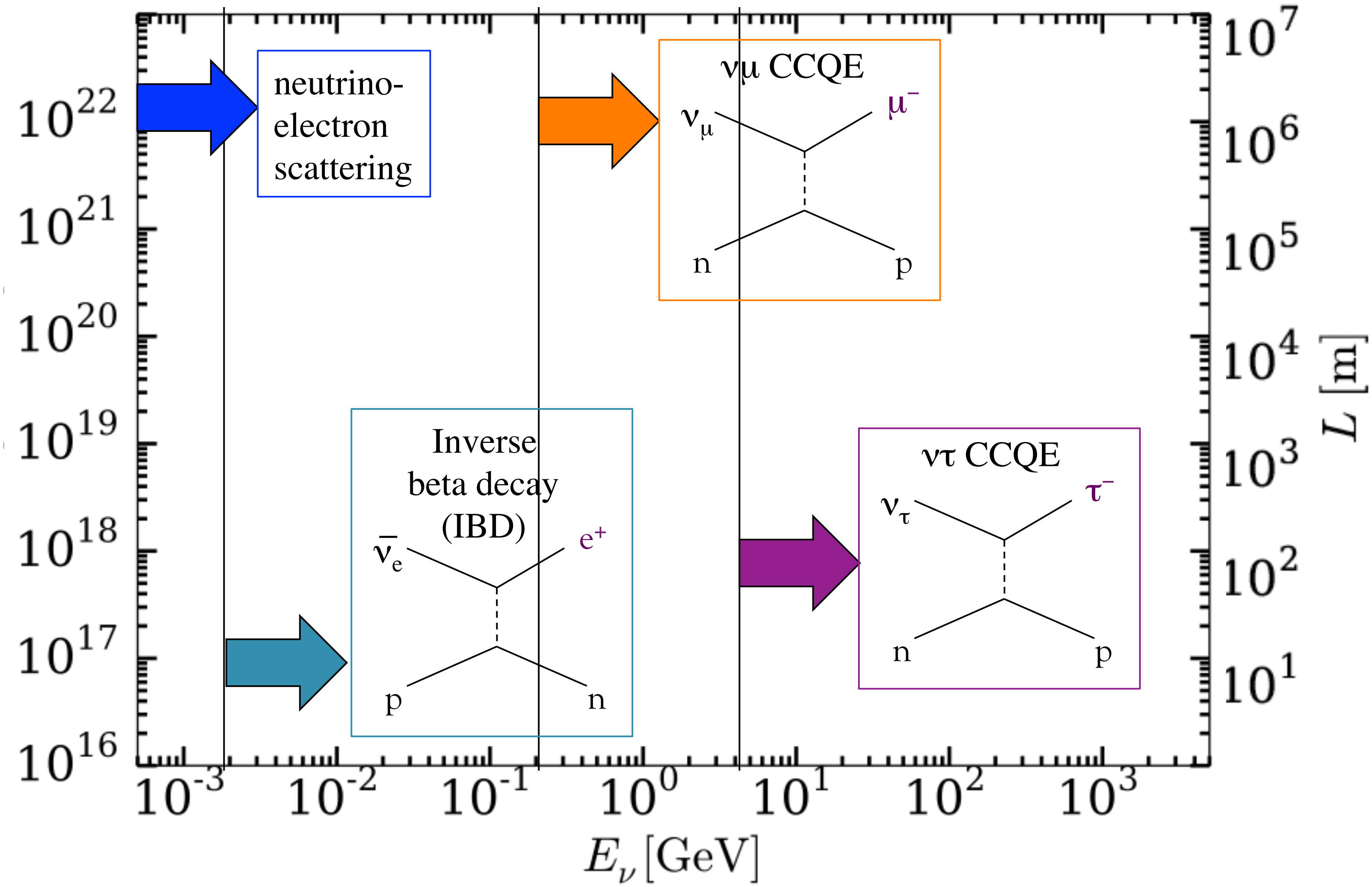
In an experiment…

Create a beam that is all one type of neutrino

Look downstream…

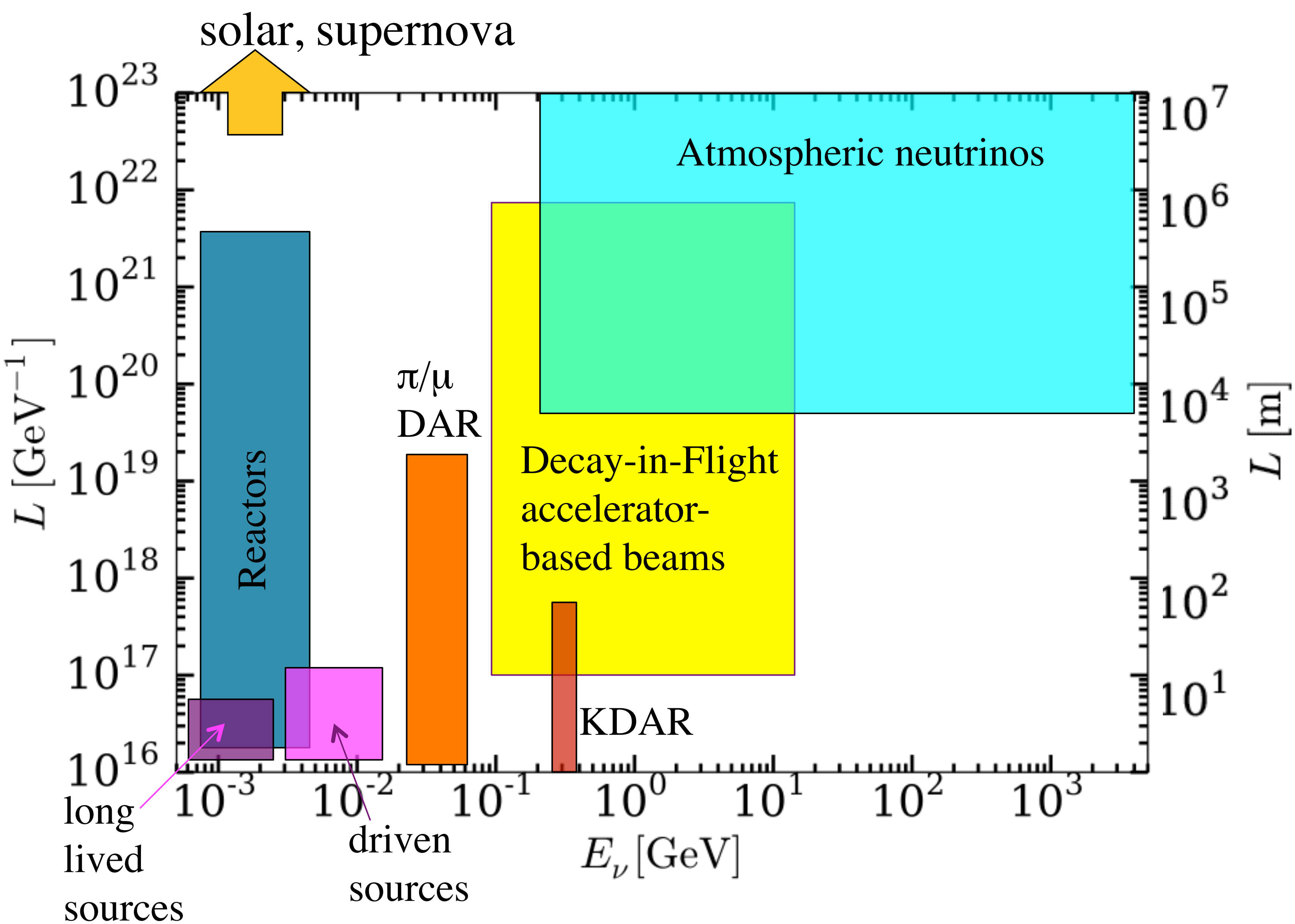


New flavor components may be too massive to produce in a CC interaction,
→ There are thresholds for CC interactions

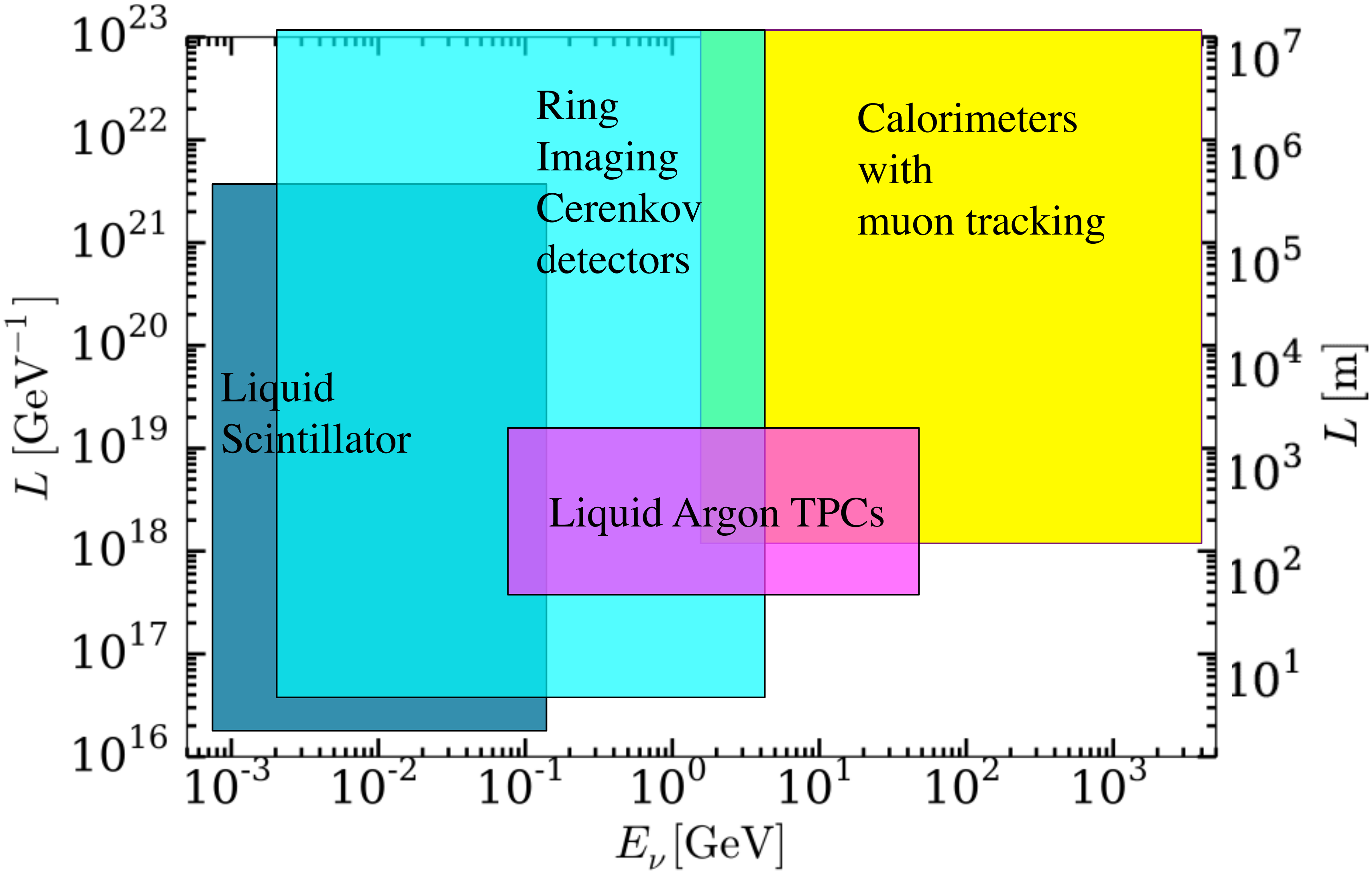


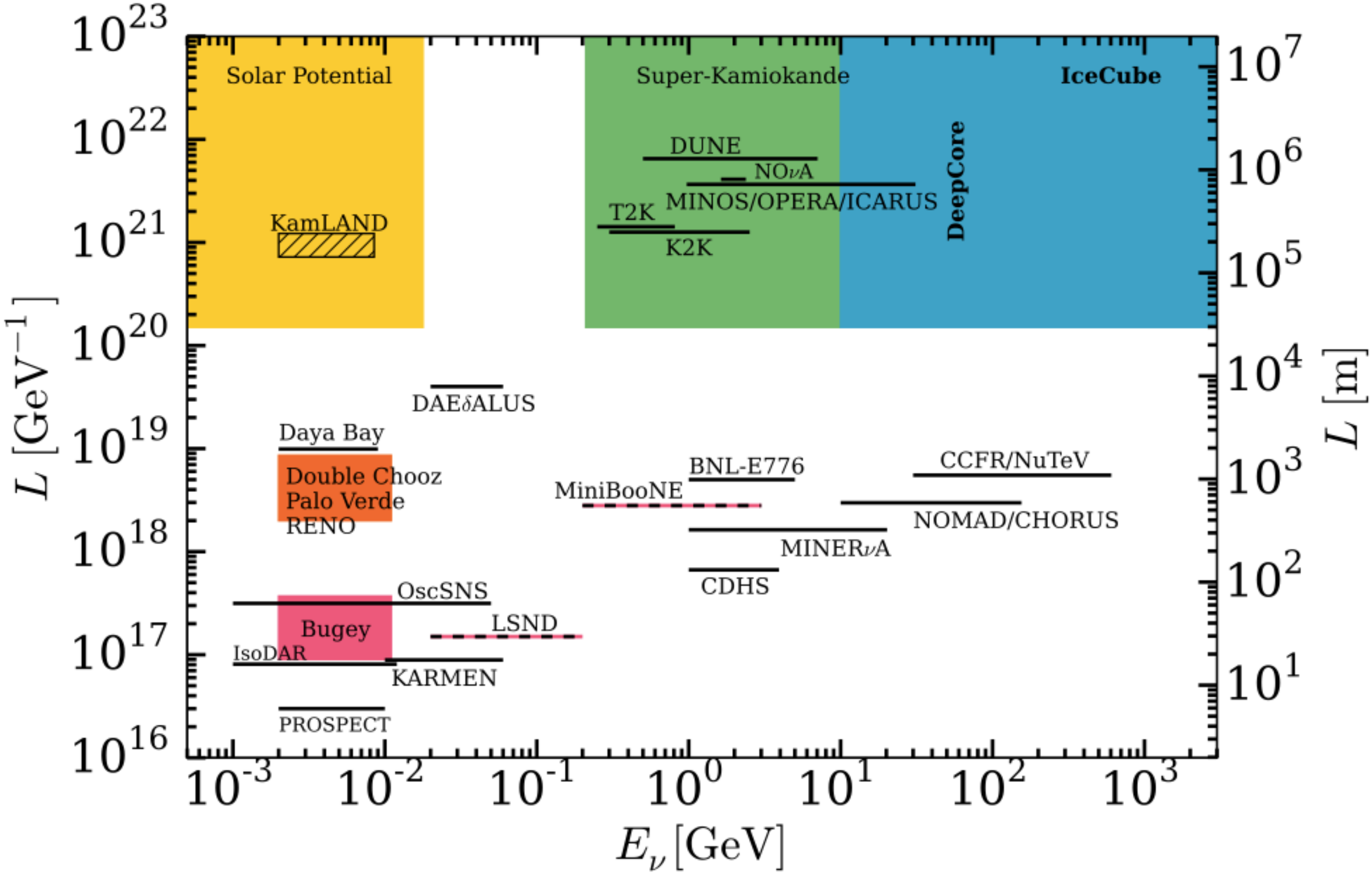
All neutrinos will have NC interactions

Neutrino sources…

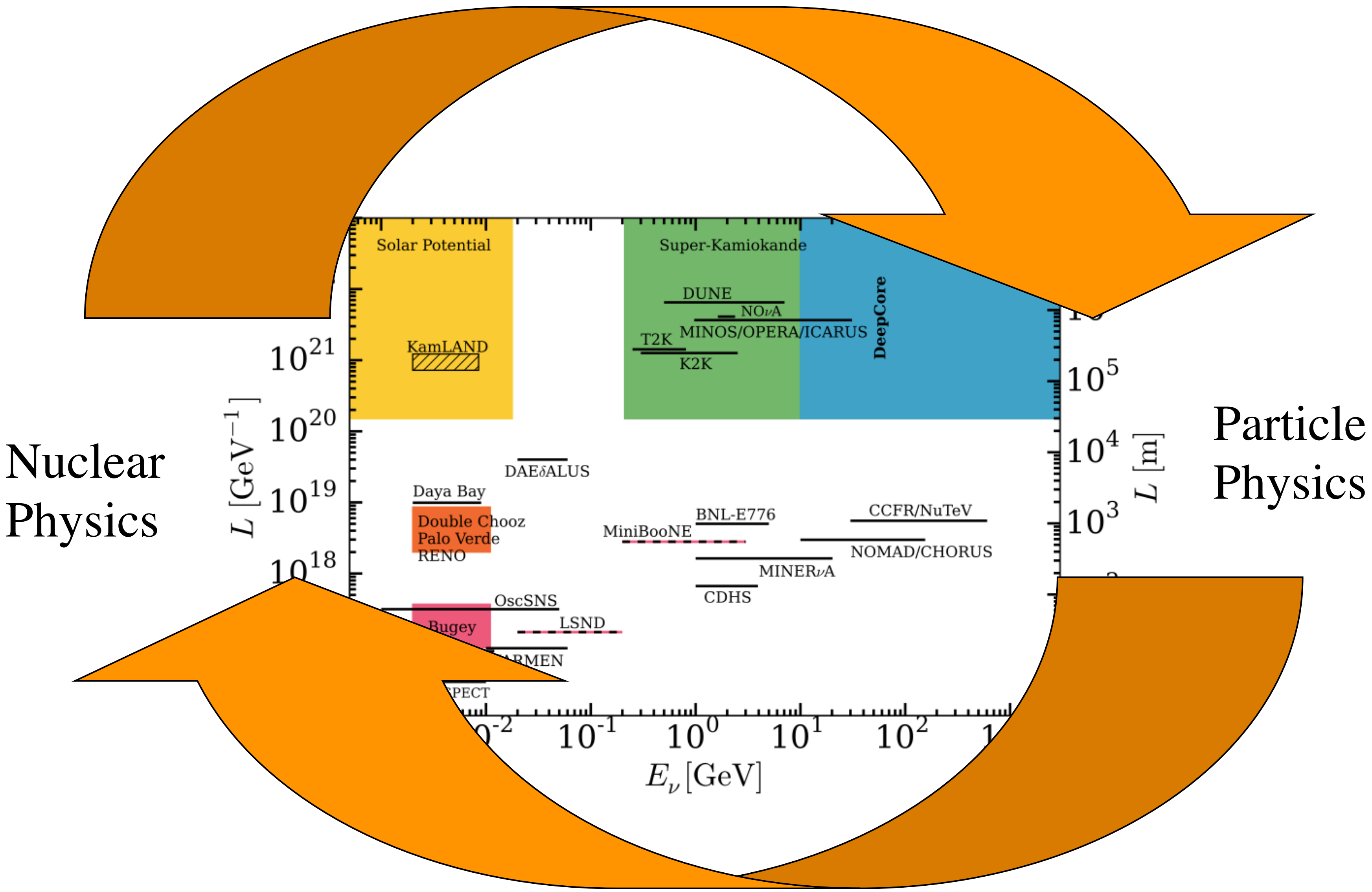


Neutrino detectors…





Solar Potential
KamLAND
Super-Kamiokande
IceCube
DeepCore
DUNE
NOνA
MINOS/OPERA/ICARUS
T2K
K2K
DAEδALUS
Daya Bay
Double Chooz
Palo Verde
RENO
MiniBooNE
BNL-E776
CCFR/NuTeV
NOMAD/CHORUS
MINERνA
CDHS
OscSNS
LSND
Bugey
IsoDAR
KARMEN
PROSPECT
L [GeV^{-1}]
L [m]
E_ν [GeV]



Nuclear Physics
Particle Physics
Solar Potential
KamLAND
Super-Kamiokande
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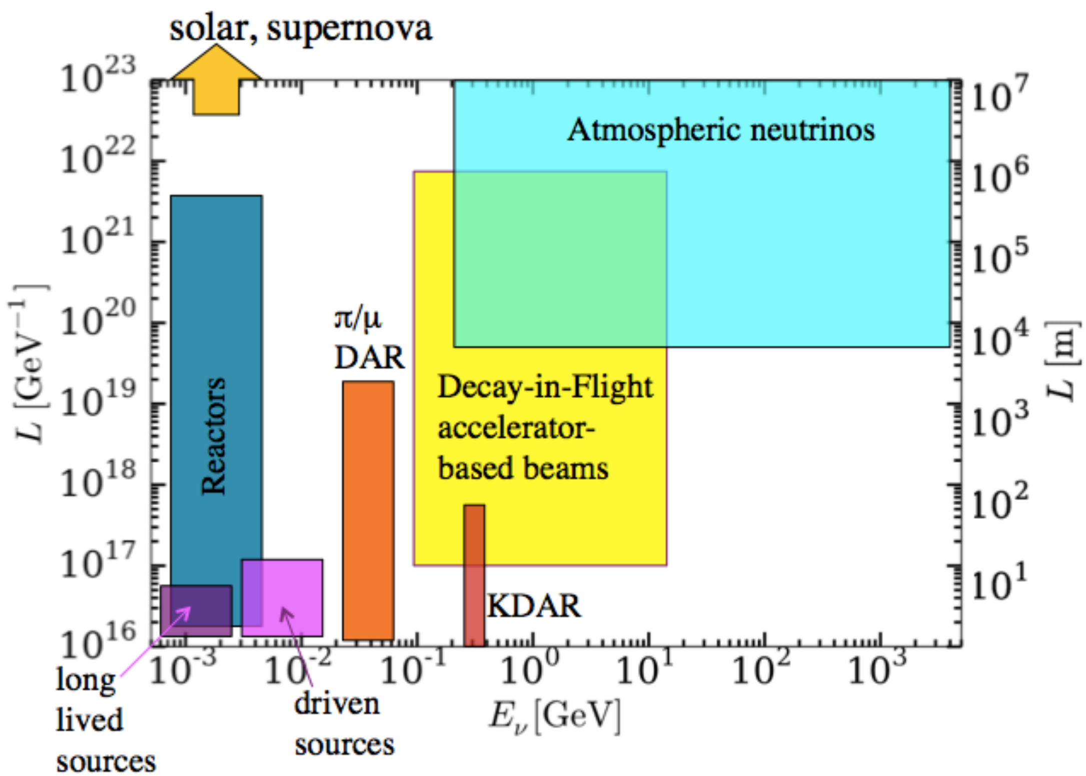
LSND
Bugey
L [GeV^{-1}]
L [m]
E_ν [GeV]

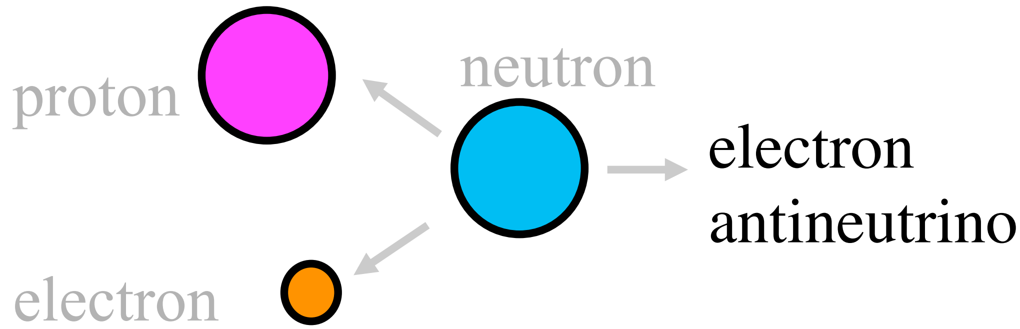
A closer look at available “tools”

Neutrino Sources



- Isotope Sources (long-lived and driven)
- Reactors
- meson/muon DAR
- DIF and the atmospheric flux

Isotope decay-at-rest

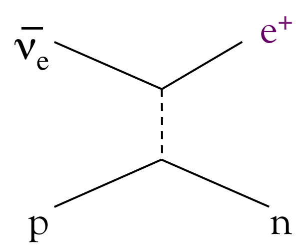


Can produce a
Very pure $\bar{\nu}_e$ beam
(Or ν_e with an EC
β+ decay)

We would like the source to be relatively high energy (few MeV).

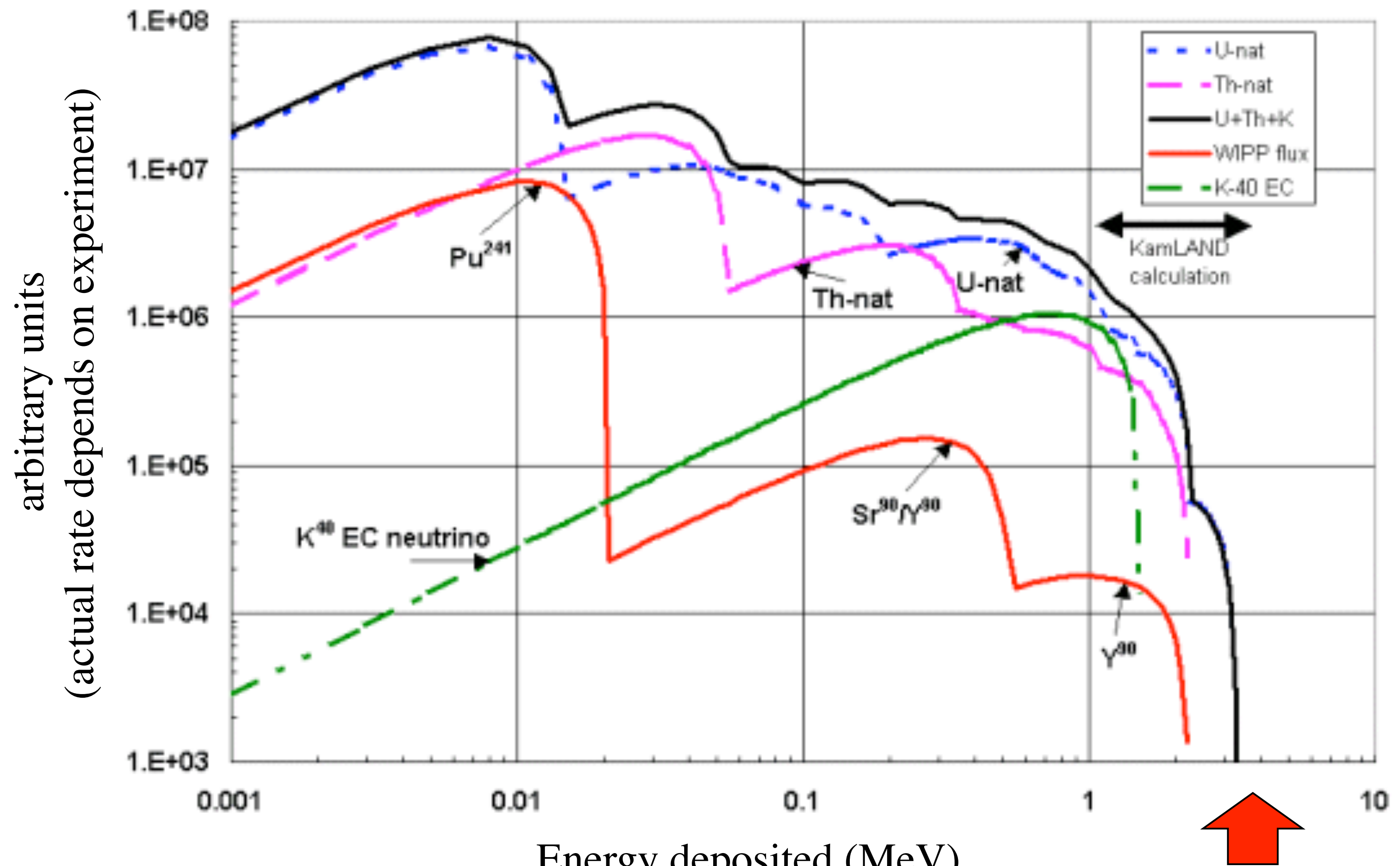
- Below ~2 MeV, you have no CC interactions
  At present we rely on $\bar{\nu}_e$-e scattering (low xsec!)
  Experiments are trying to reconstruct $\bar{\nu}_e$N (coherent scatters)
  Not yet observed!

- Above 2 MeV, you can use IBD



Inverse
beta decay
(IBD)

At very low energies you have the problem of environmental backgrounds!



about 3 MeV

The problem is that for beta-decay,
half-life and end-point are generally anticorrelated

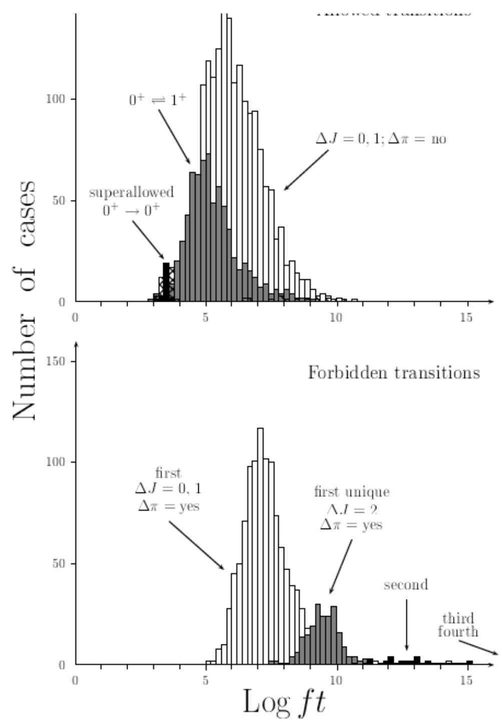
You may have heard of "comparative ½-life" (aka "ft")

$$\log ft = \log f + \log t$$

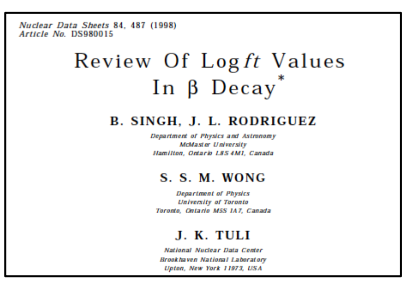
coming from calculations
depends on end-point

coming from experiment
this is the ½-life

If endpoint goes up,
log(f) gets larger…



… for log(ft) to be more or less a constant, then log(t) has to get smaller


Nuclear Data Sheets 84, 487 (1998)
Article No. DS980015

Review Of Log ft Values In β Decay*

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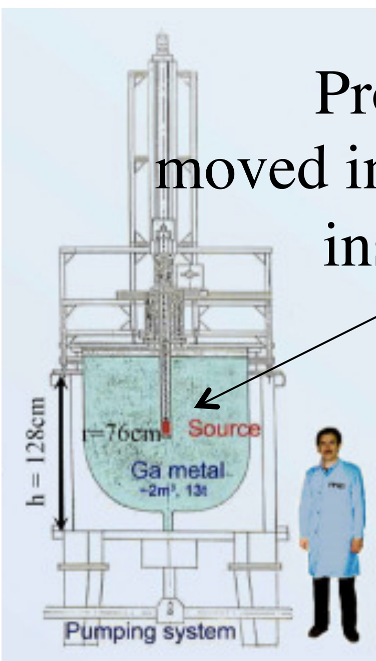
Consequence:

If we want to make a neutrino flux from sources,
and we would like a high end-point energy for the neutrino,
then the source will be relatively short-lived.

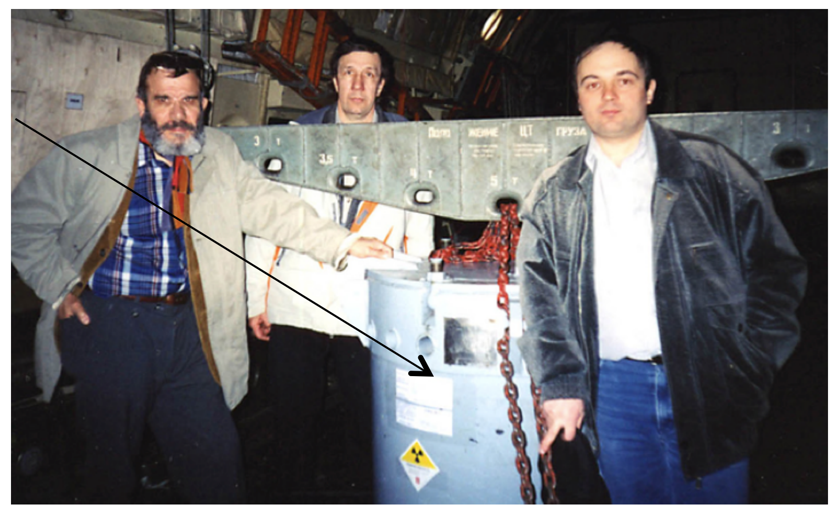
Two examples that produce ν_e (SAGE, GALLEX Expts):

^{51}Cr (27.8 day ½ life,), ^{37}Ar (35.0 day ½ life) both EC w/~700keV



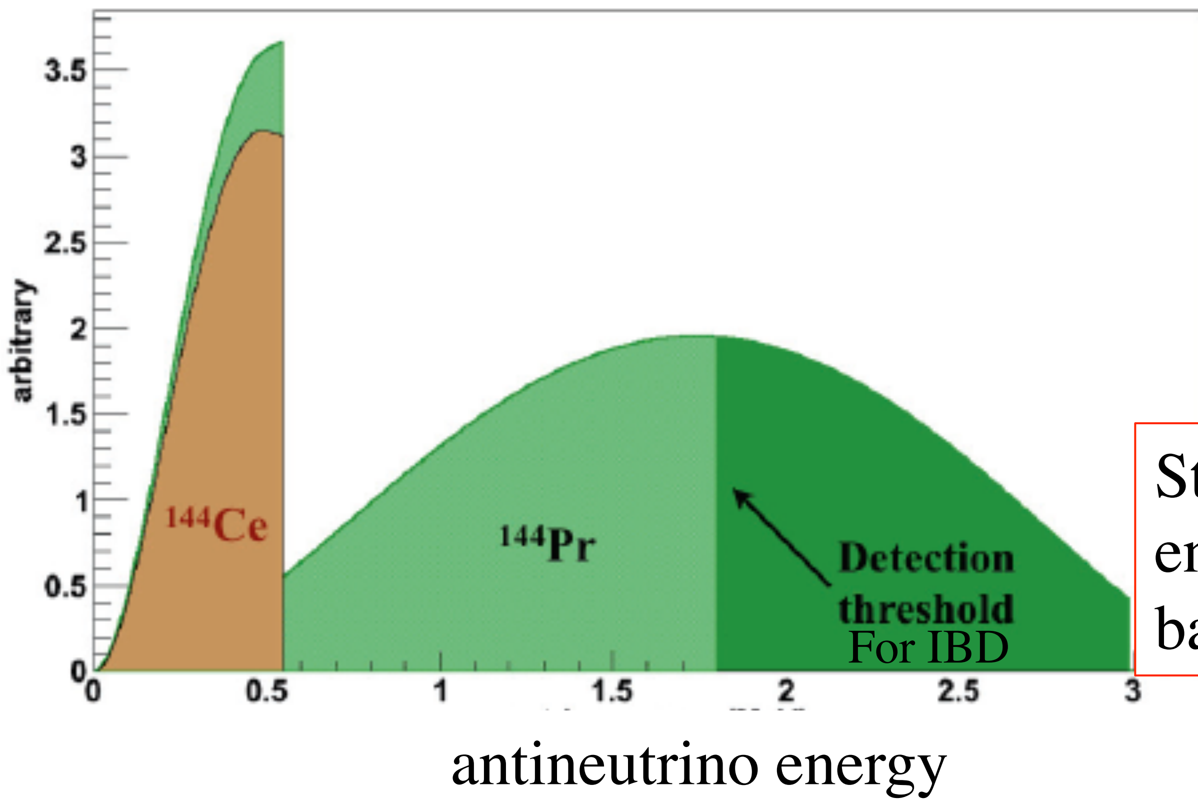
Produced at a reactor,
moved in a capsule to experiment,
inserted into detector

Source fluxes
are Isotropic!!!



Some upcoming planned sources…

^{51}Cr (ν_e) 200-400 PBq (Same source as used previously)
^{144}Ce-^{144}Pr ($\bar{\nu}_e$), ½ life= 284 days, 2-4 PBq (New!)



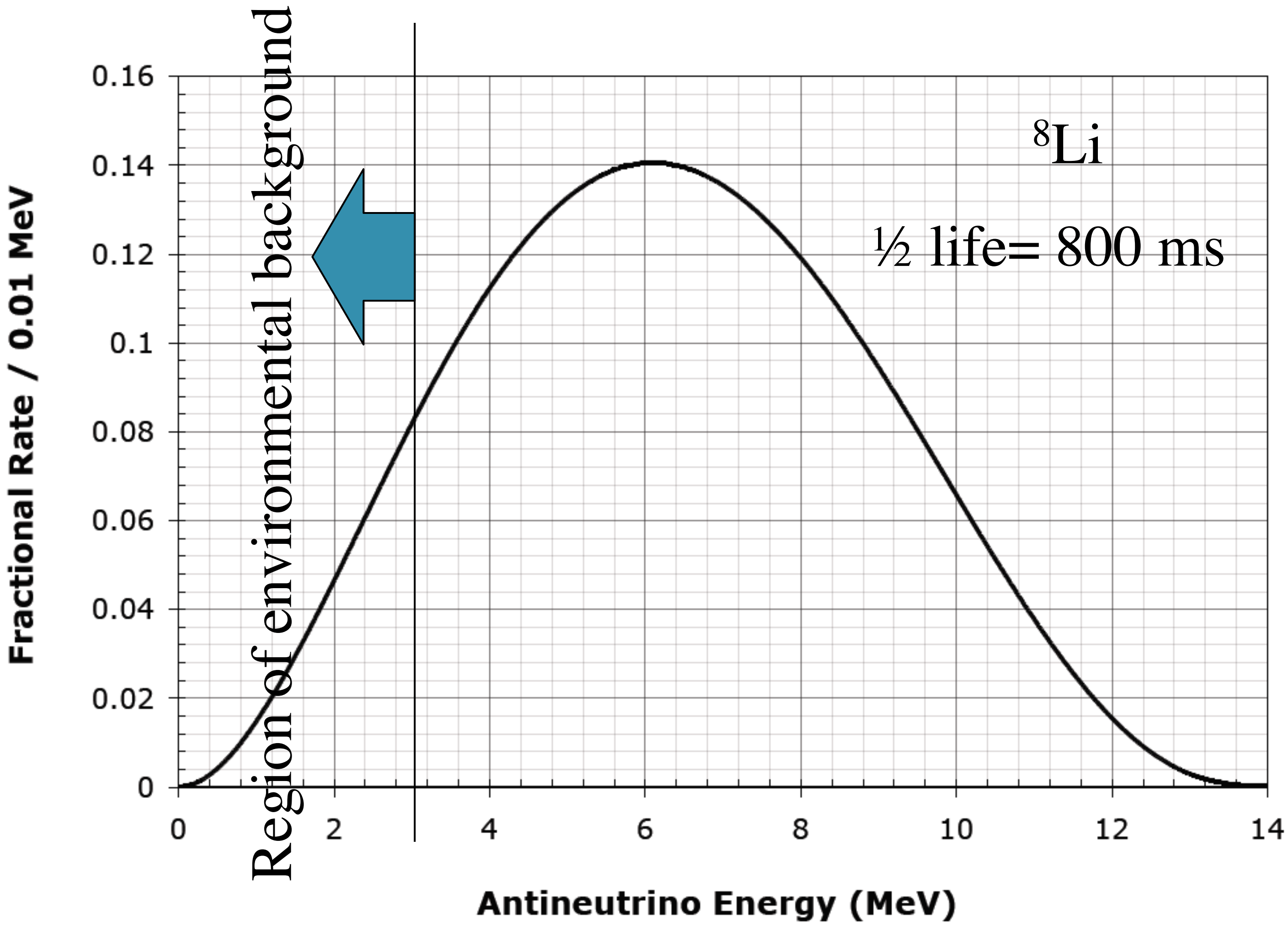
Still well below the environmental background "wall"

Just to give you a sense of scale about "PBq" (1E15 Bq)

My fiestaware plate is ~13 Bq

Driven isotope decay-at-rest

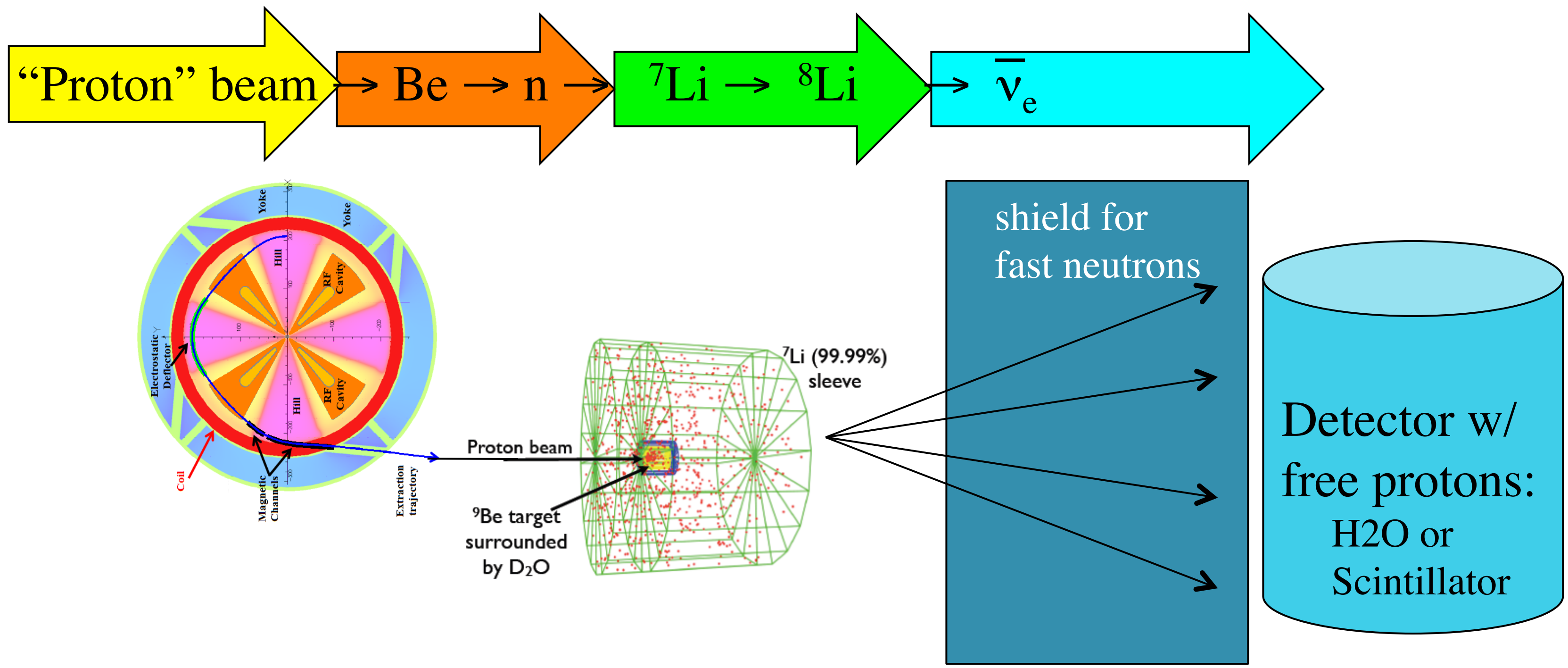
Constantly produce the isotope using an accelerator



13 MeV
Endpoint!

Very high!!!

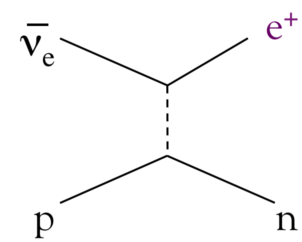
The IsoDAR experiment uses ^{8}Li Isotope DAR flux



Actually a cyclotron accelerating H_2^+

(See Daniel Winklehner’s class)

Flux is isotropic, but cannot be inside detector



Inverse beta decay (IBD)

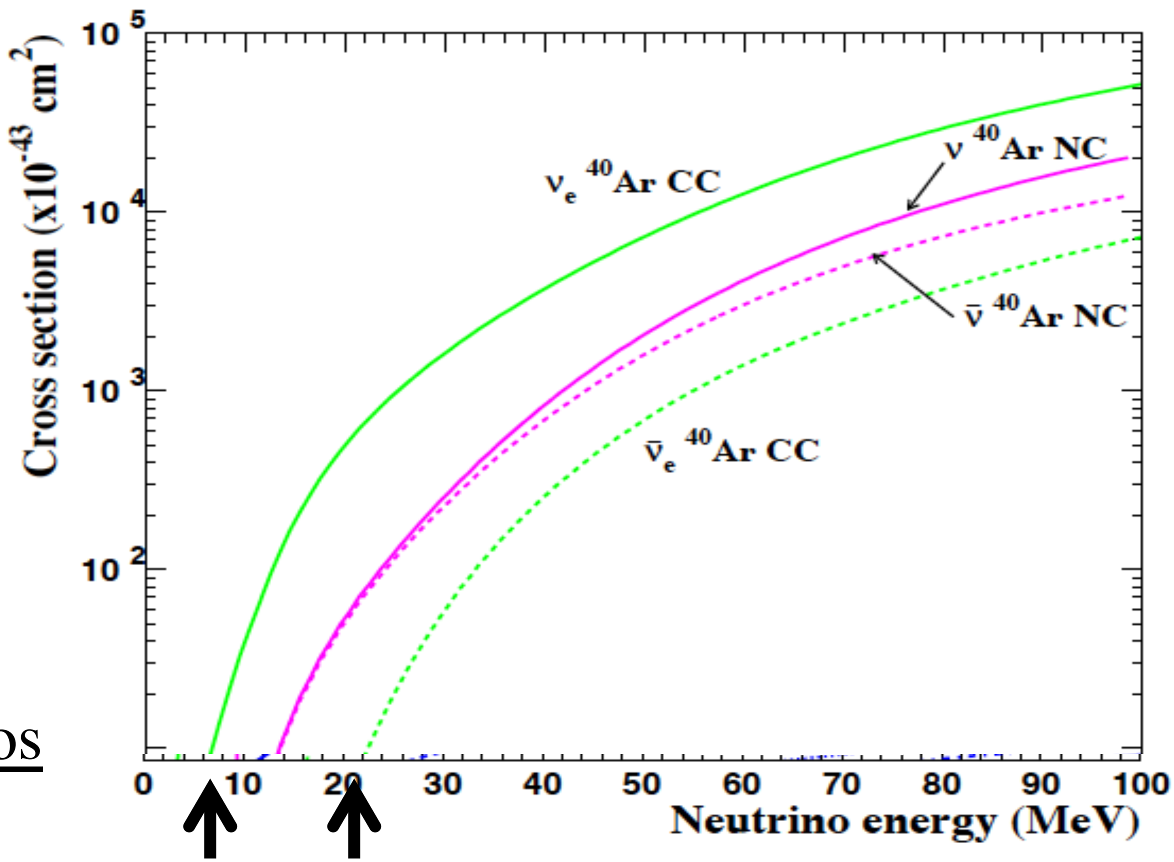
Looking for a topic that would make a good paper?

Identify a driven isotope source that produces ν_e (as vs. $\bar{\nu}_e$)

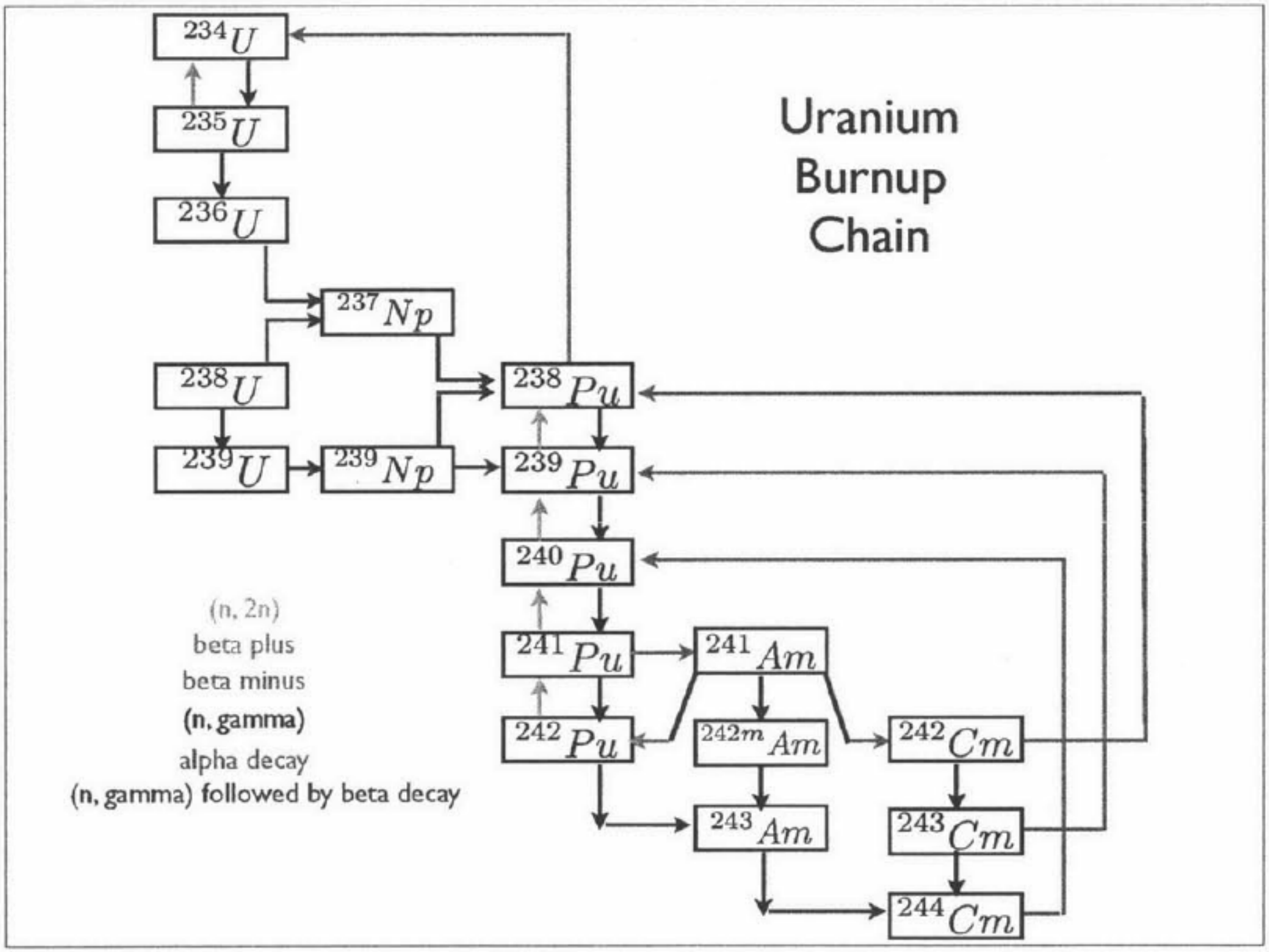
Reason: The field is investing heavily in LAr detectors that have no free-proton targets.

In LAr, the antineutrino CC threshold is ~20 MeV. It is the neutrino threshold that is low (<10 MeV).

LAr needs an isotope that produces <u>neutrinos</u>

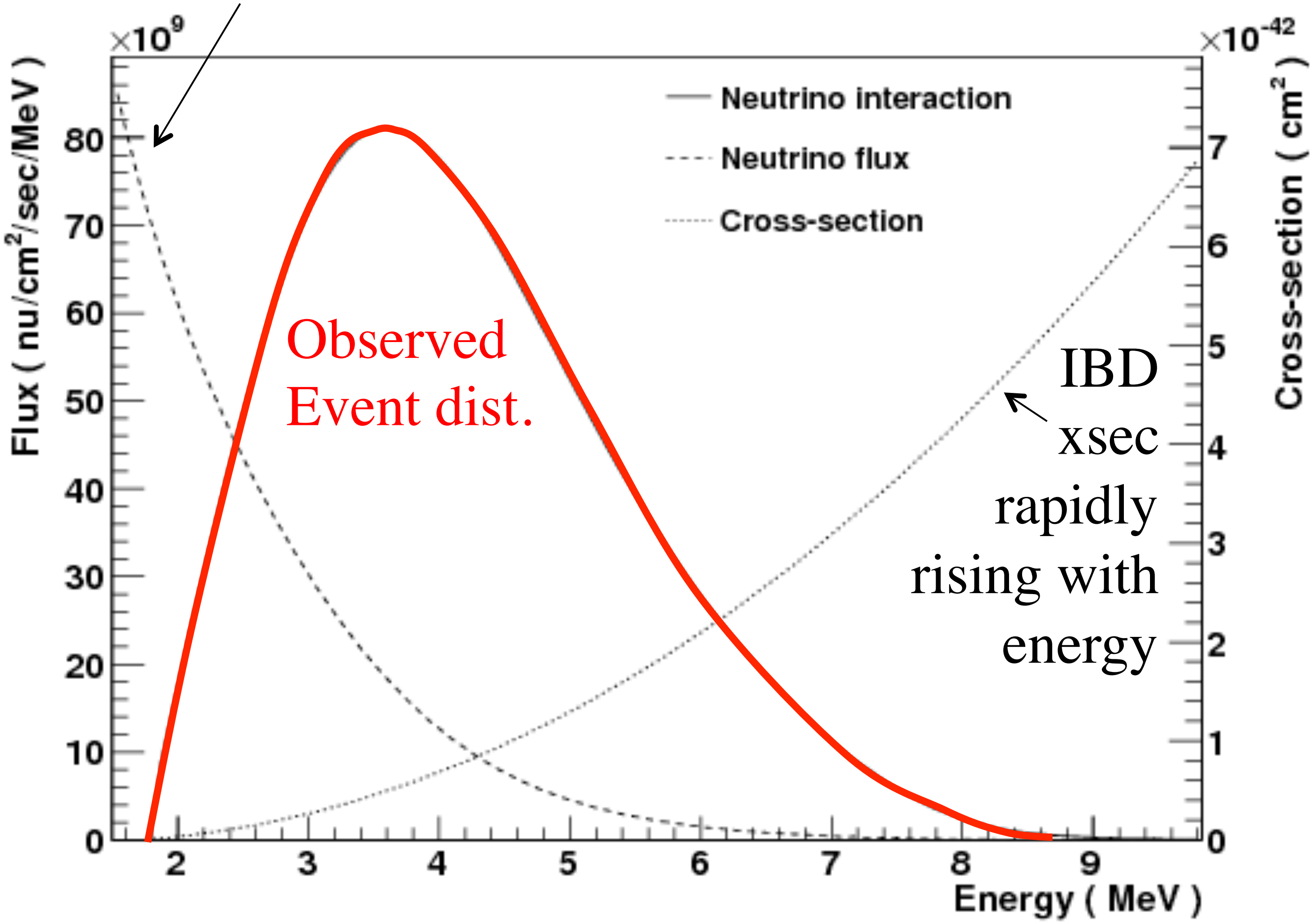


Reactors: A driven system, but not producing a <u>single</u> isotope



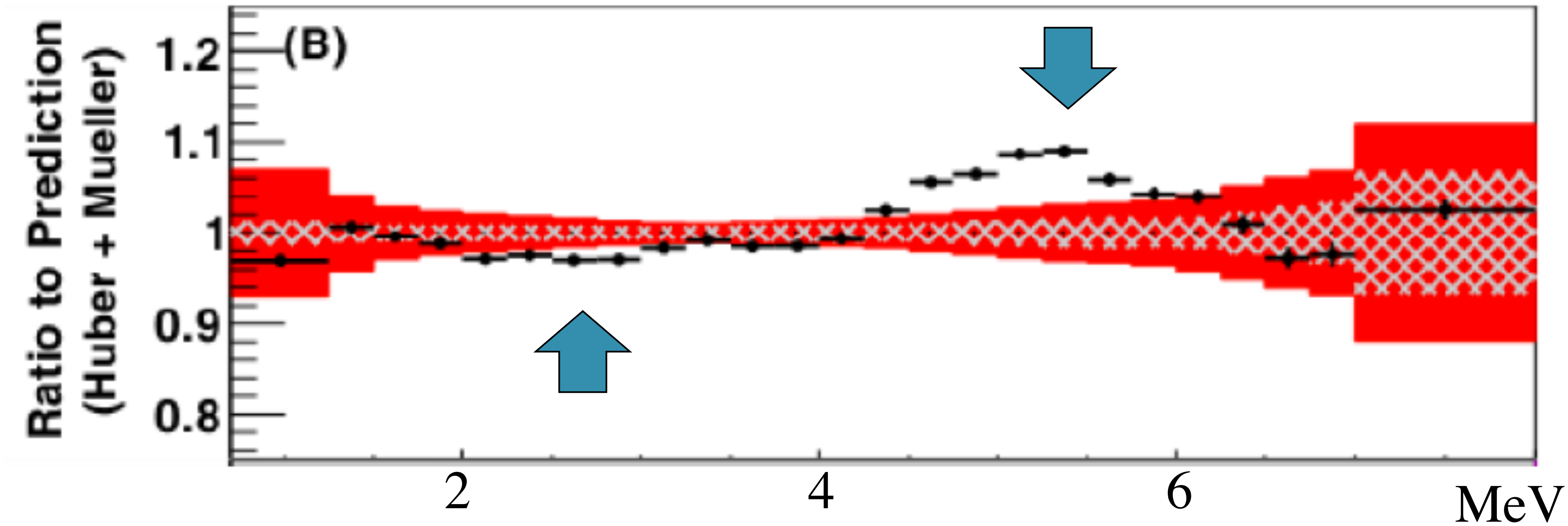
That turns out to be a problem if you need to know the flux well!

Reactor flux rapidly falling with energy



Since IBD xsec is well known, we can measure reactor flux…

Ratio of the reactor flux to prediction



Effect is seen in 3 different reactor experiments.

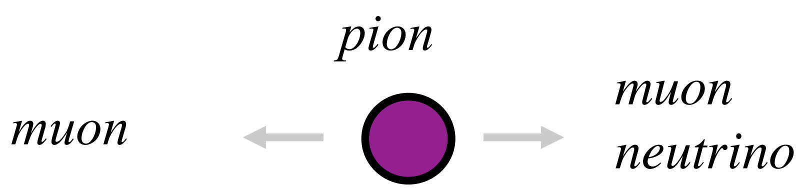
It looks like there are additional neutrino sources, affecting the first principles energy spectrum!

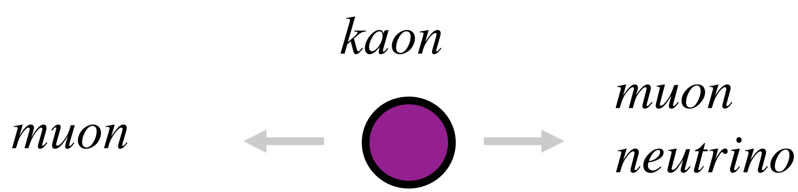
… I am going to come back to this later in the class.
For now, just know there is a problem w/ using reactors

Isotope or Reactor Sources are low energy.

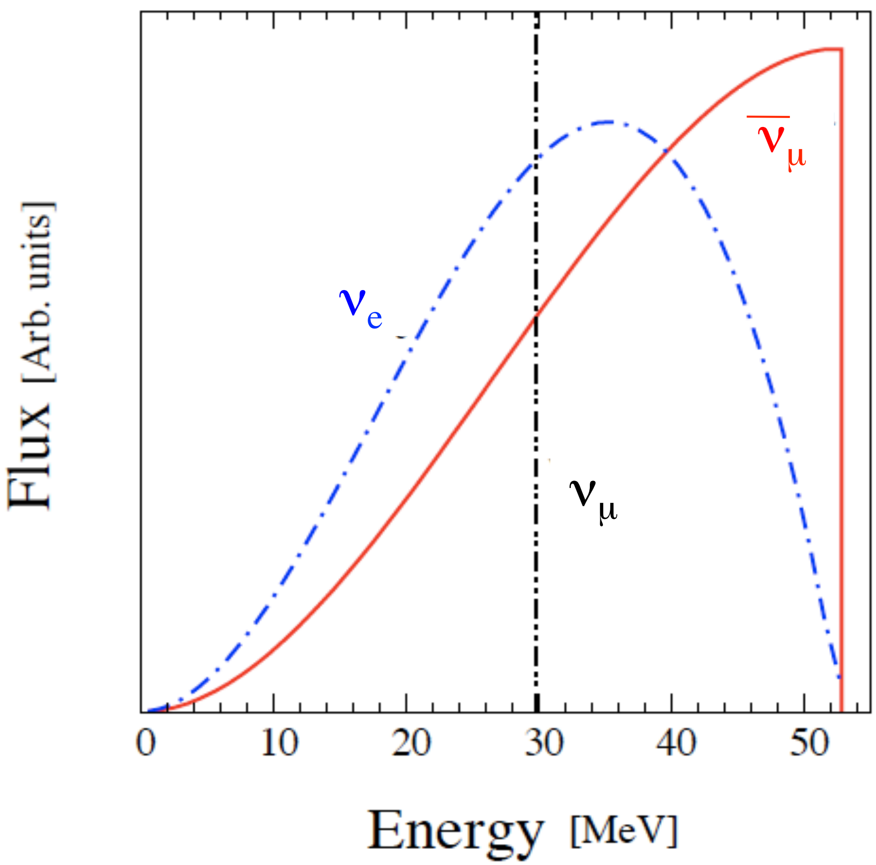
What if you would like higher energy?

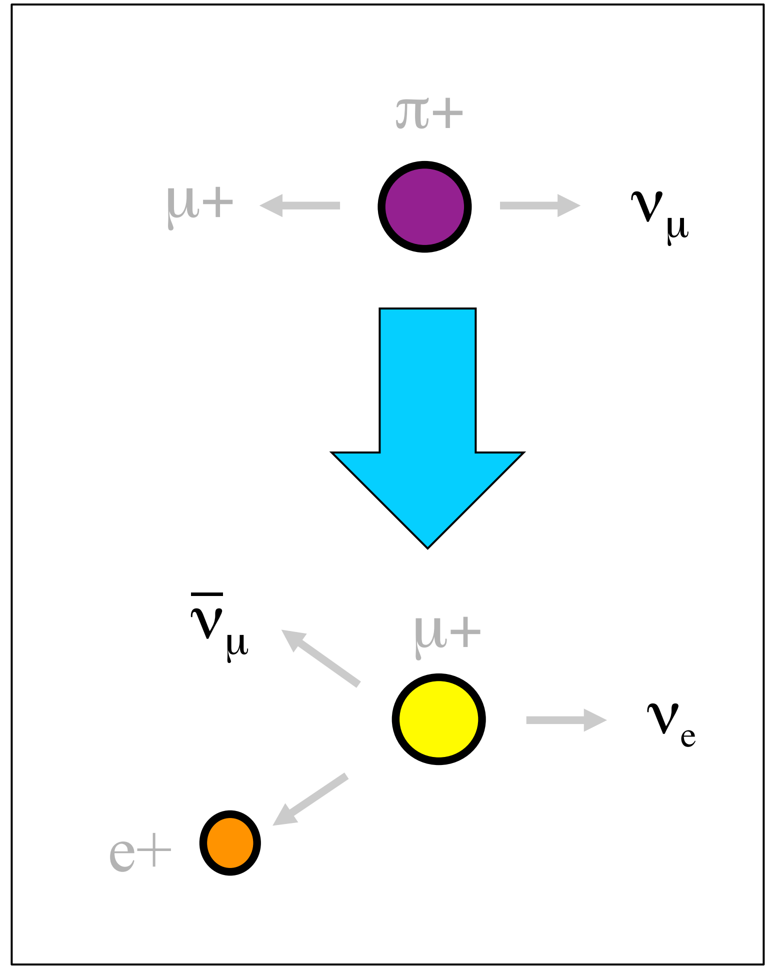
The next step up in energy, while maintaining very pure easily theoretically described beams comes from meson decays-at-rest





Pion/muon decay-at-rest,
the go together…





A great place to search for
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

If we want to use protons on a Be target to produce the pions, what's the best beam energy?

	Produced Hadron	Exclusive Reaction	M_X (GeV/c^2)	$\sqrt{s_{thresh}}$ (GeV)	E^{beam}_{thresh} GeV	KE of beam (MeV)
wanted	π^+	$pn\pi^+$	1.878	2.018	1.233	295
	π^-	$pp\pi^+\pi^-$	2.016	2.156	1.54	602
	π^0	$pp\pi^0$	1.876	2.011	1.218	280
Not wanted	K^+	$\Lambda^0 pK^+$	2.053	2.547	2.52	1582
	K^-	ppK^+K^-	2.37	2.864	3.434	2496
	K^0	$p\Sigma^+K^0$	2.13	2.628	2.743	1805

We want to be well above threshold to produce a lot of π+ but near or below threshold for π- (which we then capture)

800 MeV is a good choice…
(Used at ISIS, LAMPF, others)

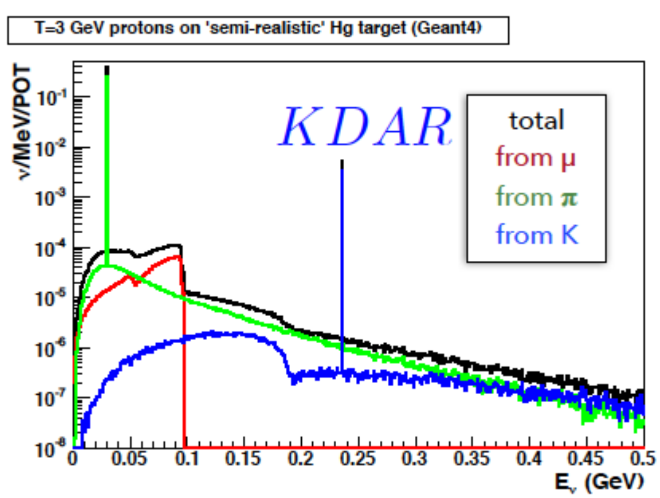
If you want to instead look at "KDAR" you need higher energy

Produced Hadron	Exclusive Reaction	M_X (GeV/c^2)	$\sqrt{s_{thresh}}$ (GeV)	E^{beam}_{thresh} GeV	KE of beam (MeV)
π^+	$\mathrm{p}\mathrm{n}\pi^+$	1.878	2.018	1.233	295
π^-	$\mathrm{pp}\pi^+\pi^-$	2.016	2.156	1.54	602
π^0	$\mathrm{pp}\pi^0$	1.876	2.011	1.218	280
K^+	$\Lambda^0 p K^+$	2.053	2.547	2.52	1582
K^-	$\mathrm{pp}K^+K^-$	2.37	2.864	3.434	2496
K^0	$\mathrm{p}\Sigma^+K^0$	2.13	2.628	2.743	1805

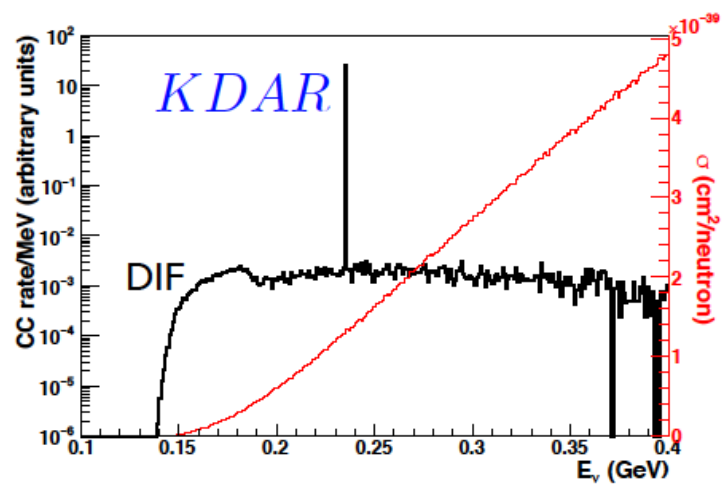
For example, JPARC's MLF has 3 GeV on target

you can expect world's first observation of KDAR neutrino events from MiniBooNE this year.

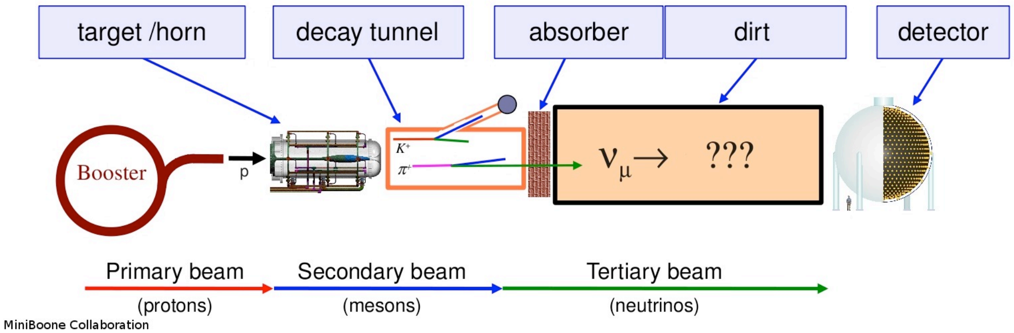
MLF Flux



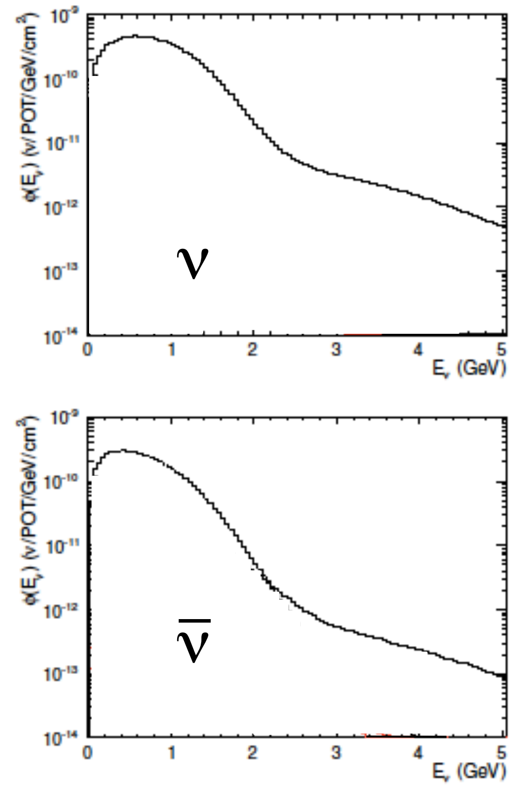
numu-CCQE Rate



The "Classic" neutrino beam is the decay-in-flight beam aka a "Conventional Beam"



MiniBooNE Flux



Weak decay in flight

Pros:

GeV-energy → high cross section

Wide-band beam

(Somewhat) tunable central energy (horn)

Similar ν and ν̄ energy dependence

Directional – not isotropic!

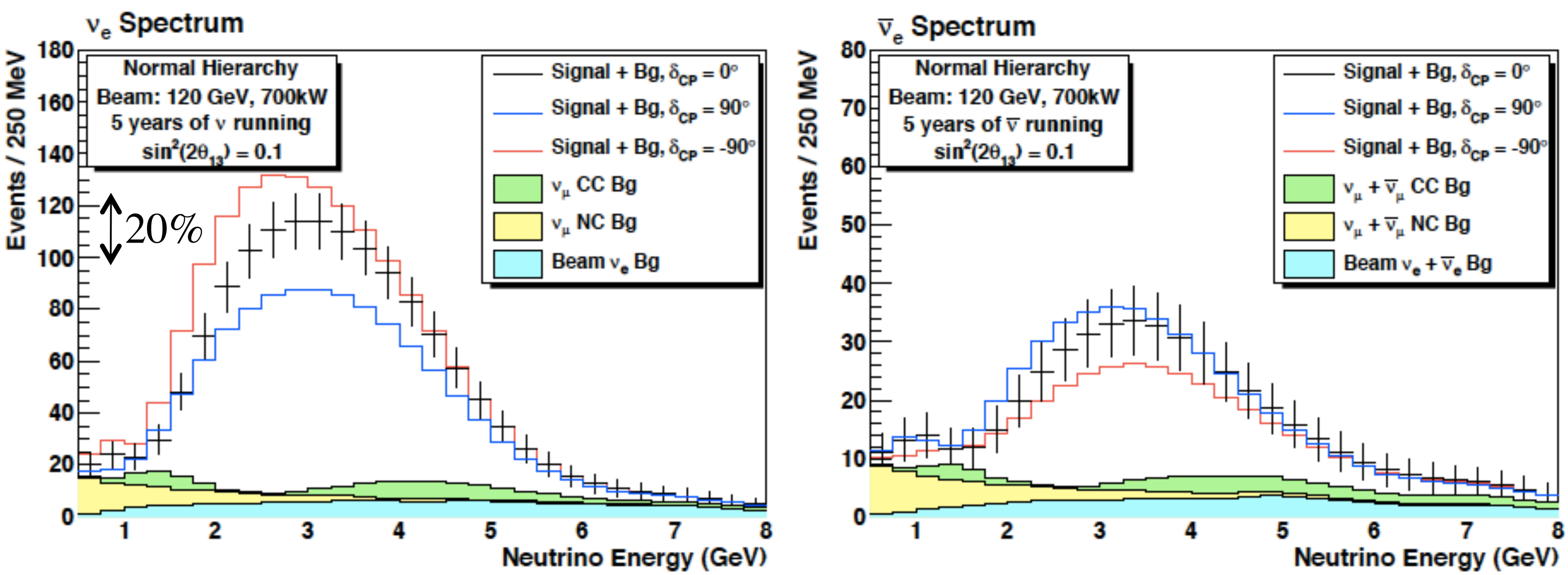
Cons:

Antineutrino rate is low (~1/5 neutrino rate)

20% normalization error if no near detector

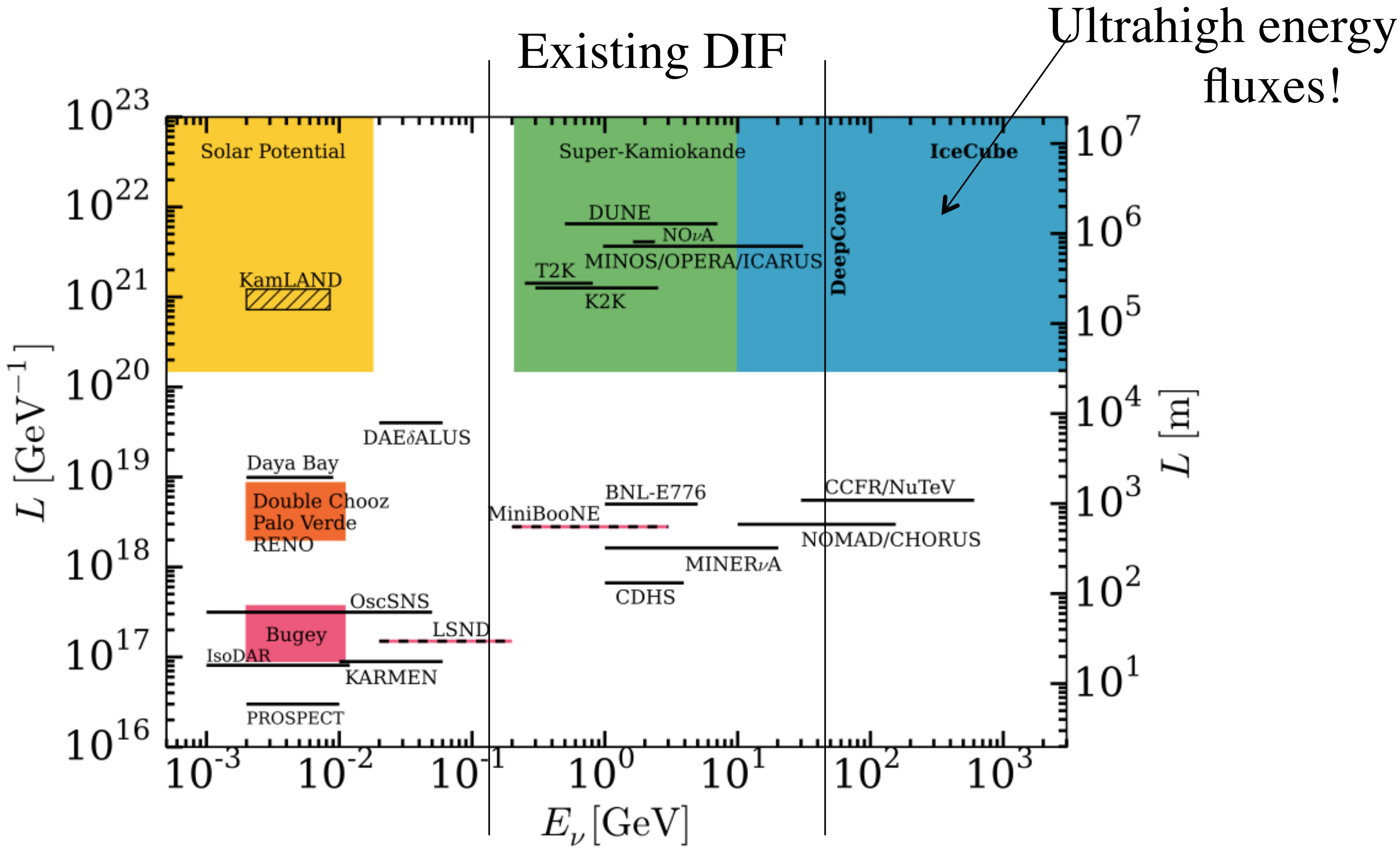
Predicting energy dependence is difficult

"Intrinsic" beam backgrounds and mis-id backgrounds are at the level of several % of expected signal, or higher, and are hard to predict.

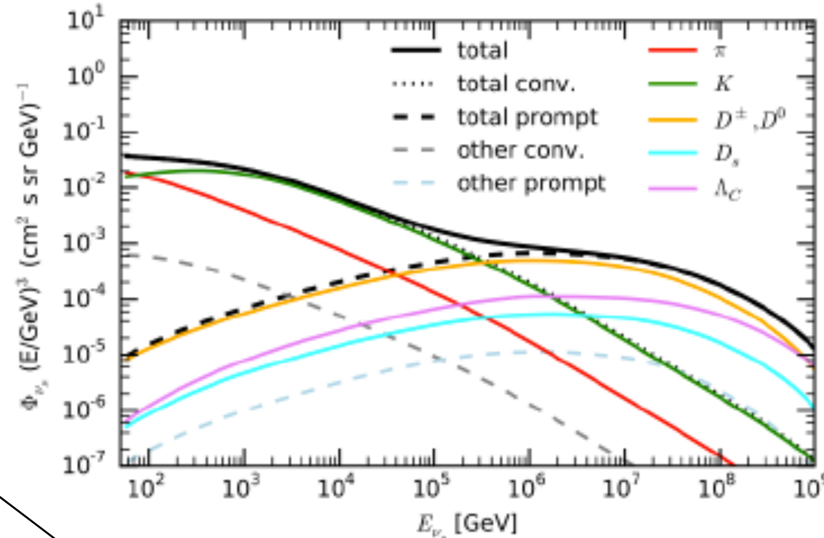


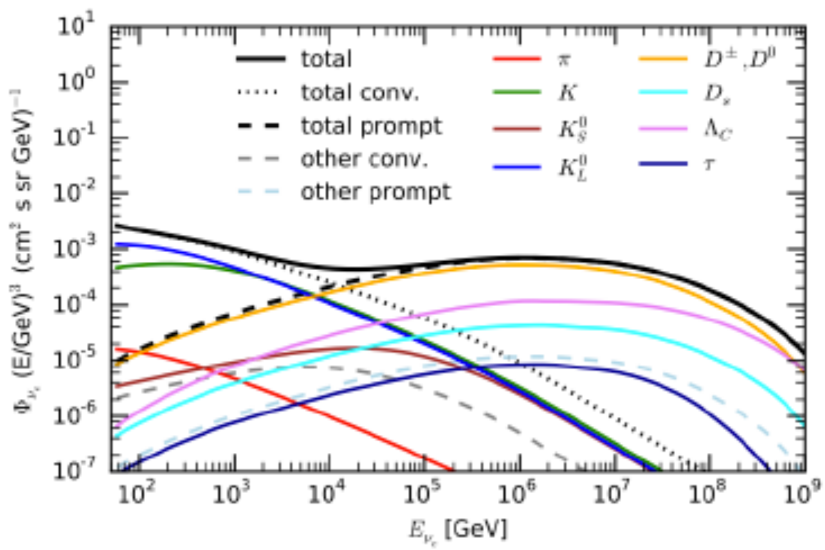
Signal and backgrounds, $\nu_\mu \rightarrow \nu_e$, 34 kton LAr detector (plan is 10 kt), LBNE beam, 10 years

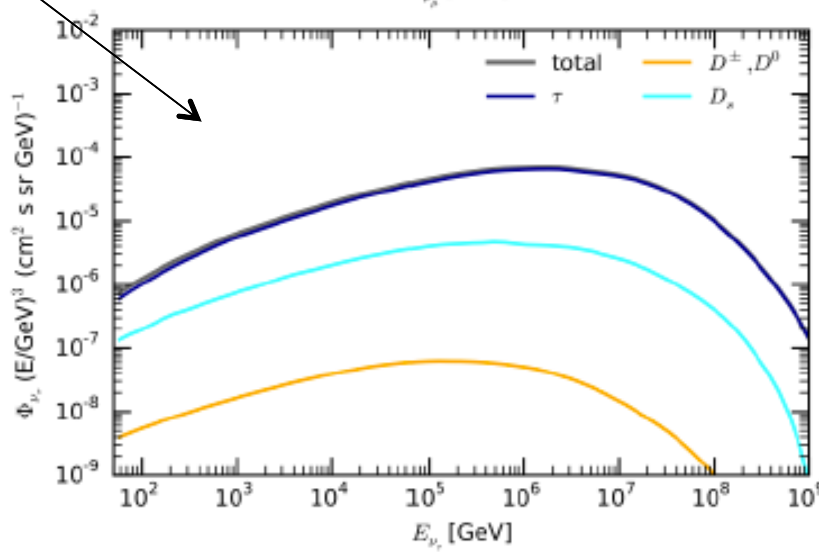
The Tevatron and SPS used to produce neutrino beams up to 500 GeV.
Now that this is shut down,
the accelerator based neutrino beams go up to about 50 GeV...



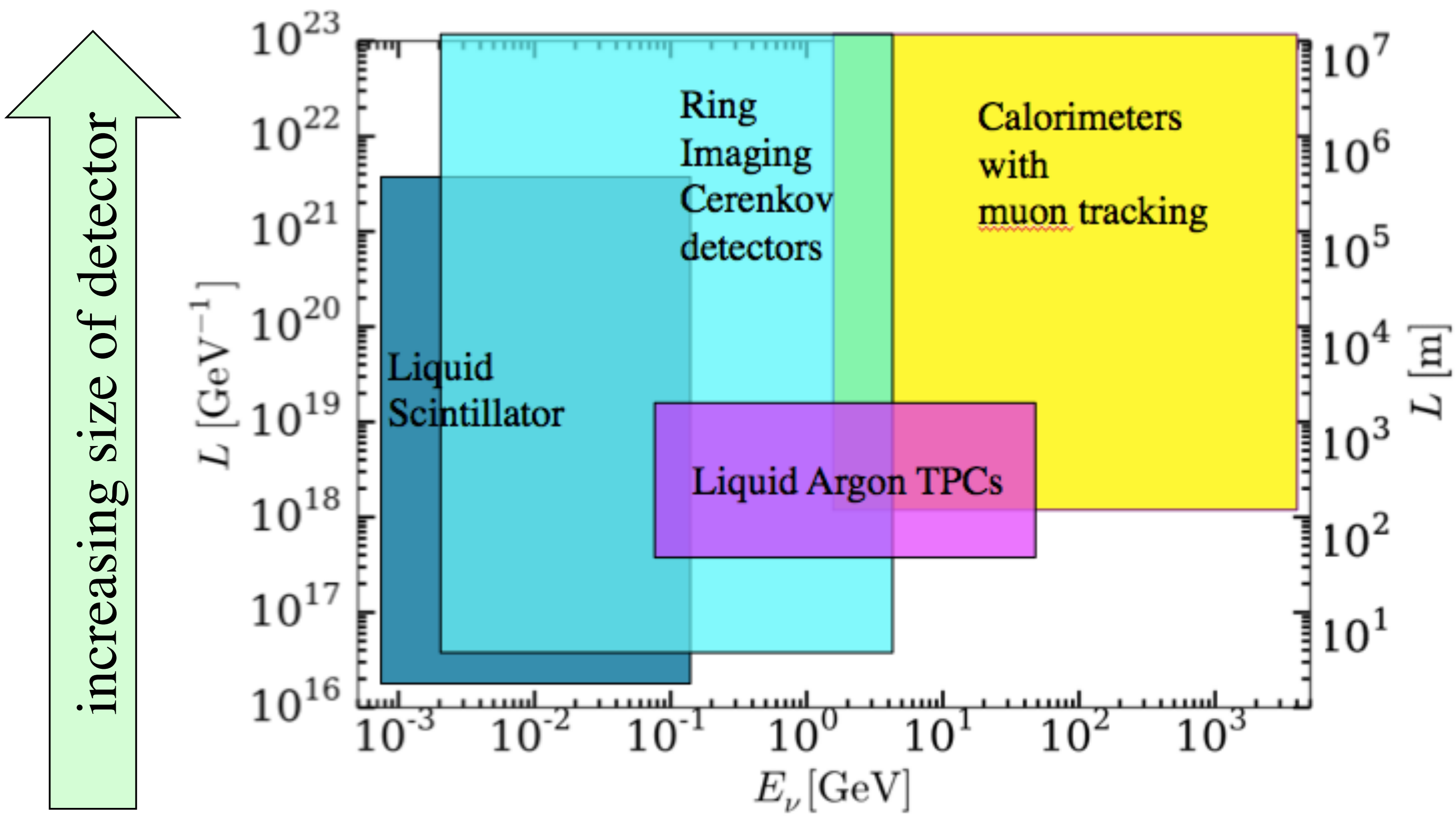
Fluxes for IceCube extend to 1E9 GeV! There is even ν_τ produced!





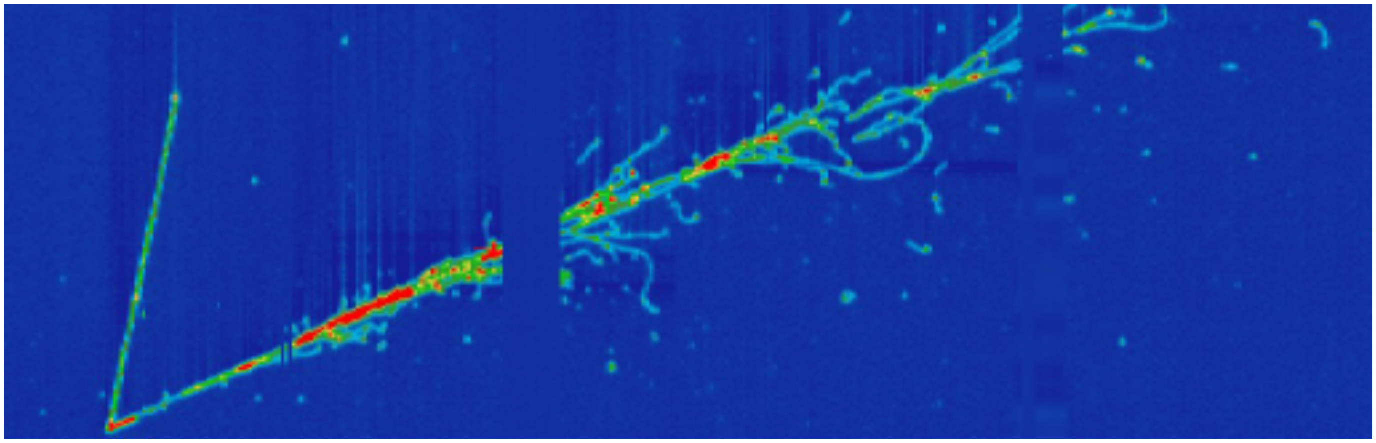


Neutrino Detectors

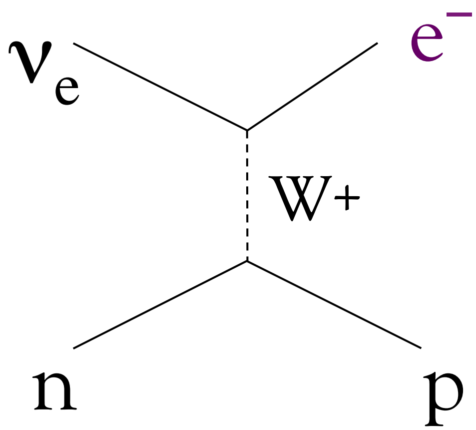


Most detectors are very common
and you already know about how they operate.

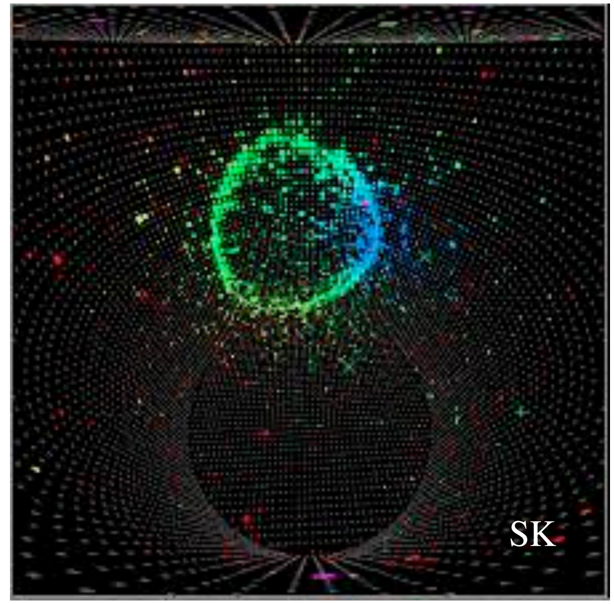
The new one is the Liquid Argon TPC,
so let me talk about that…



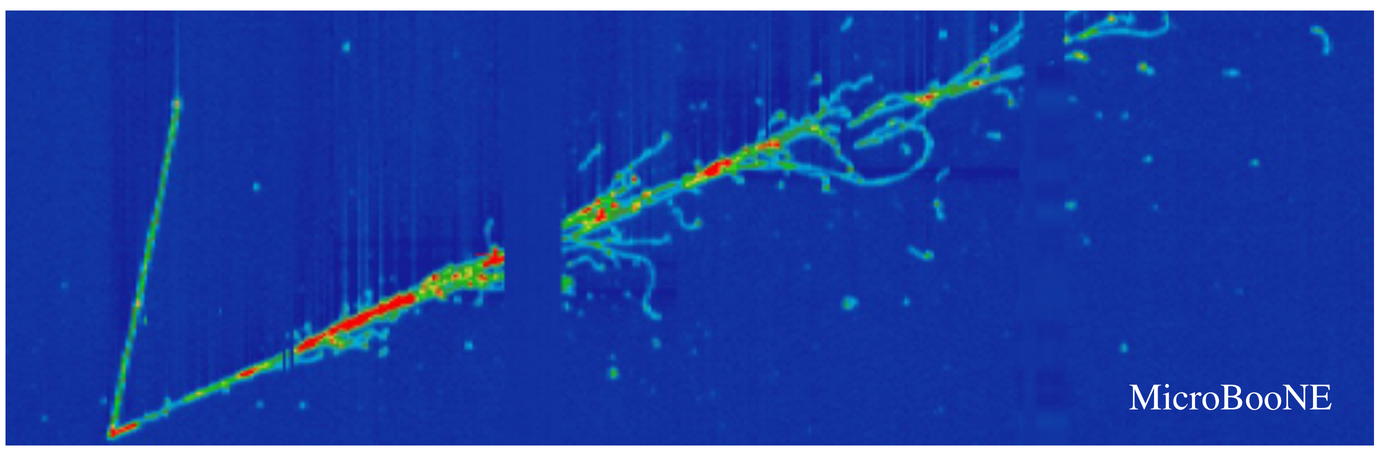
Relatively inexpensive, highly pixelized, particle-by-particle resolution



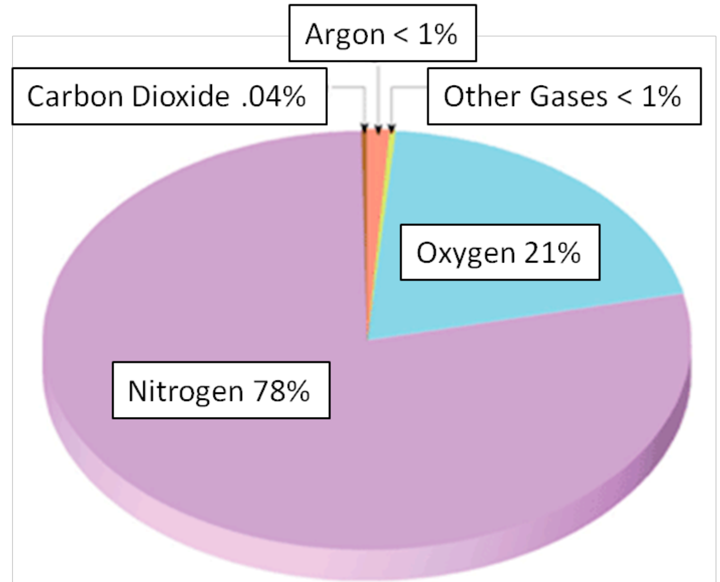
We want to go from this:



To this:



Argon – an easy noble element
to get in bulk!
air is 0.93% argon



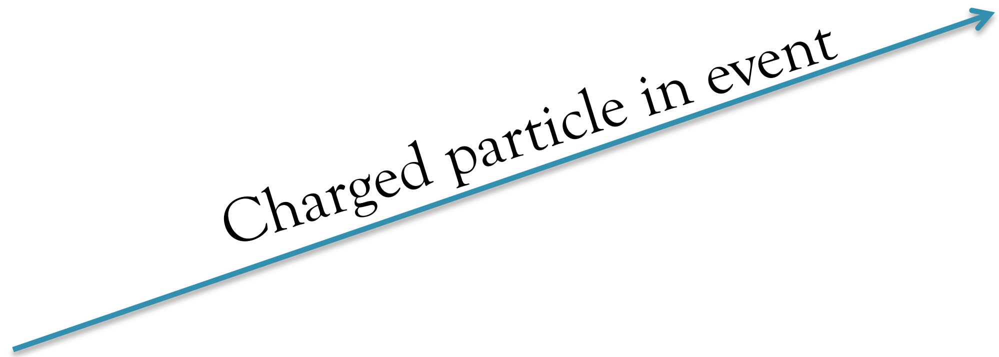
Pie Chart: Gas Composition of Atmosphere

When you produce LN_2 (77 K) from cooling Air,
LAr is the last element to condense out (87 K)

So it is relatively cheap to obtain
(since it is a byproduct of LN_2 production)

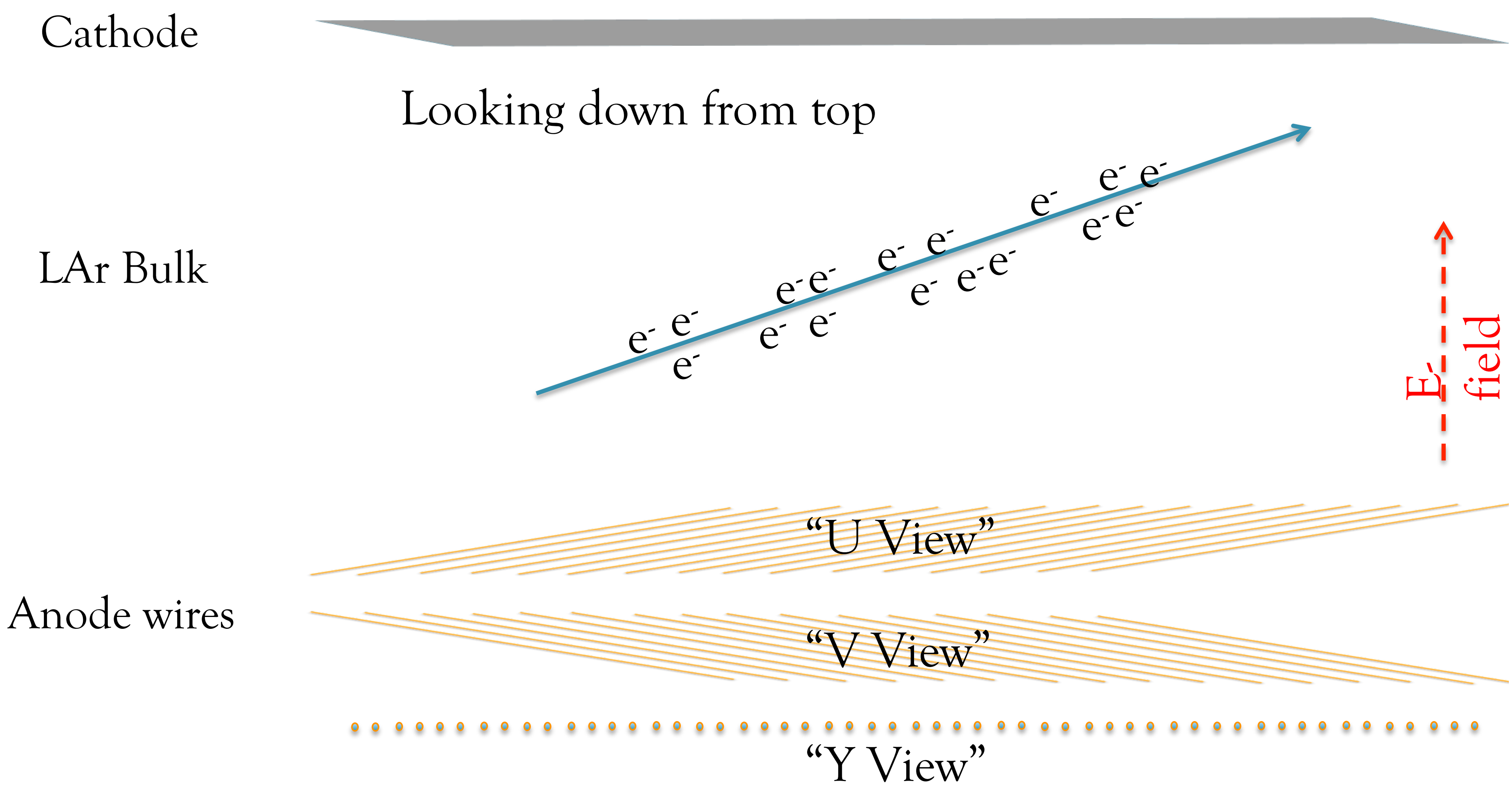
And it isn't crazy-hard to maintain as a liquid.

Looking down from top



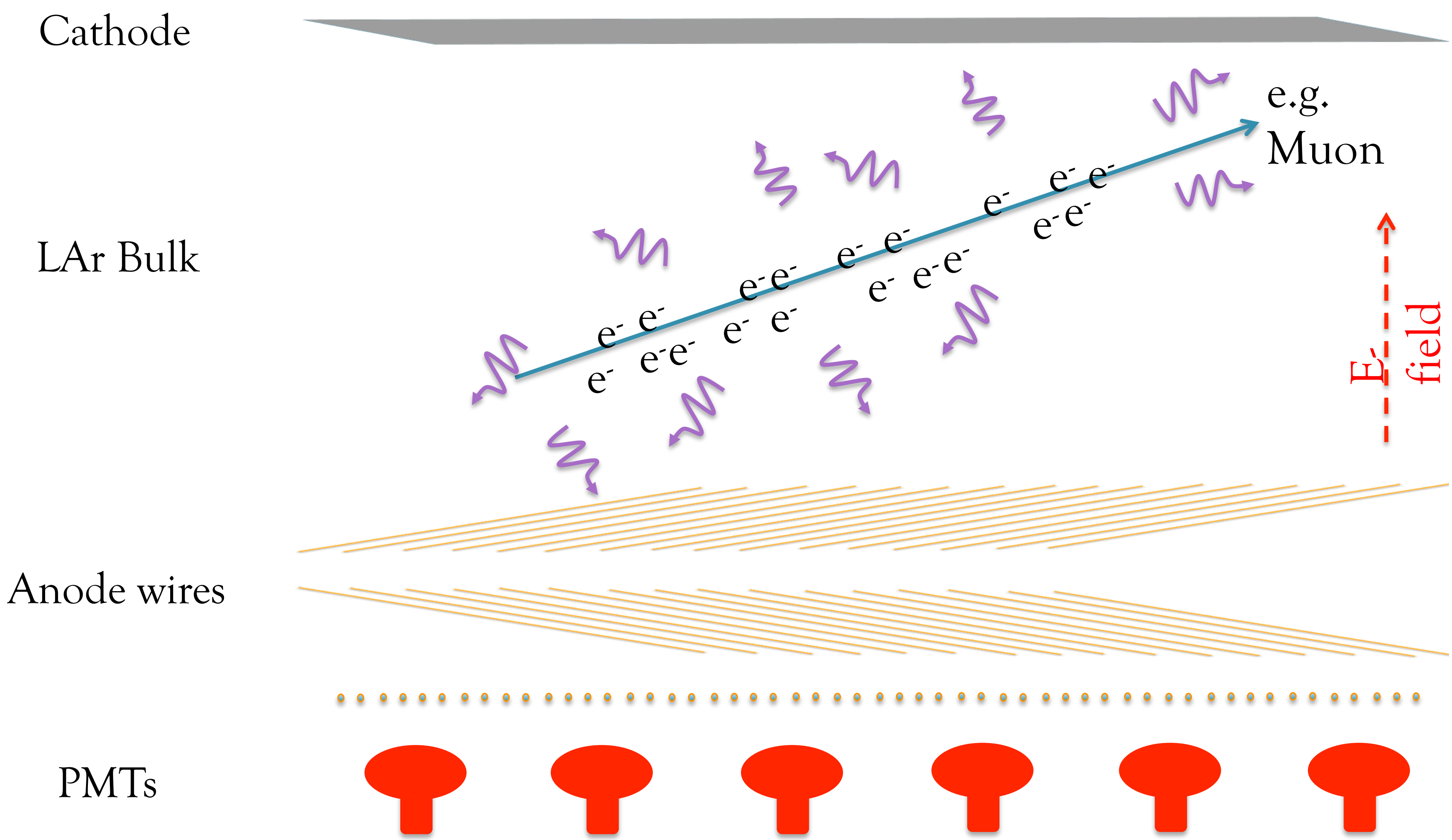
A charged particle traverses liquid argon

Add an E-field and detectors



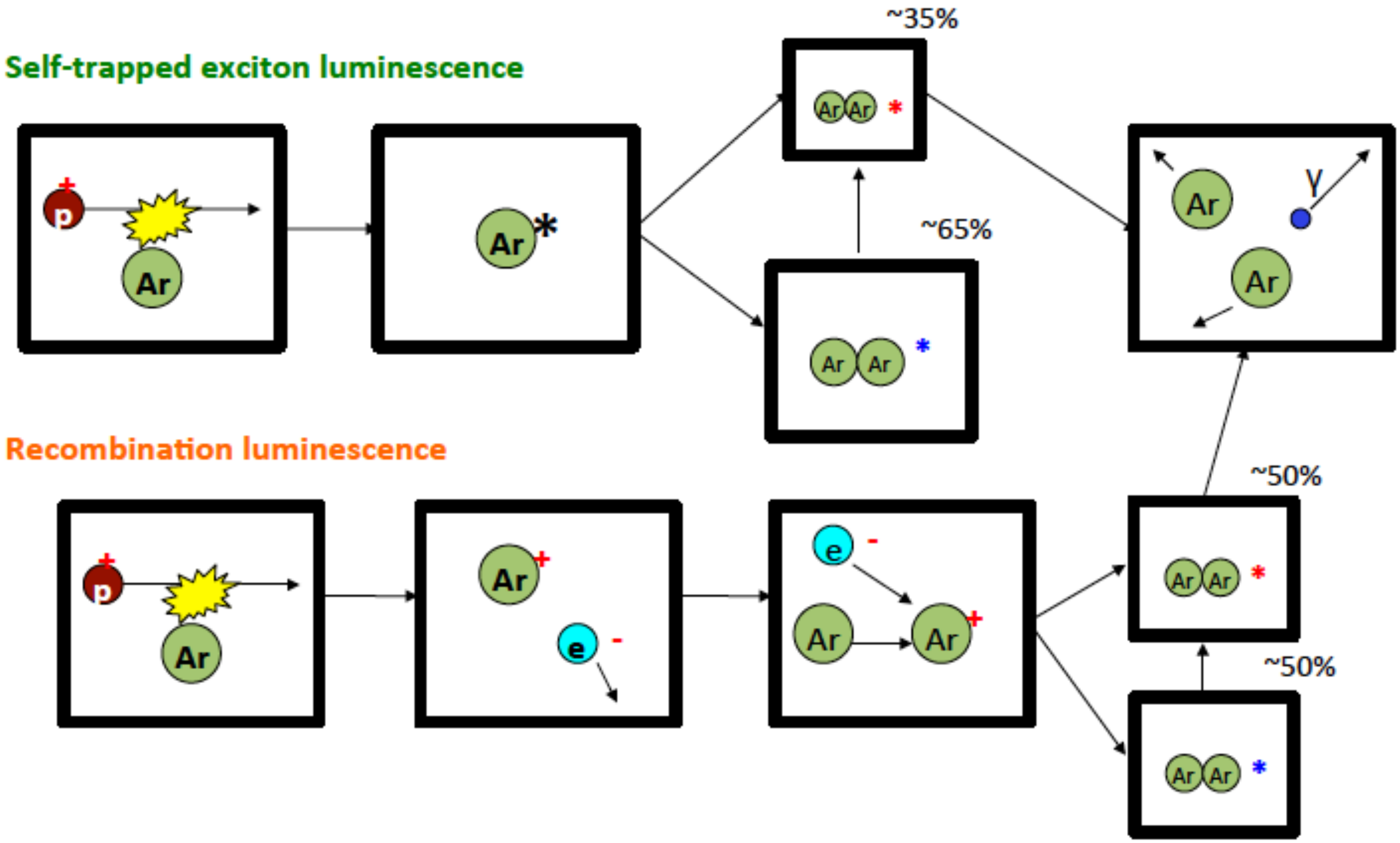
Electrons are produced – we want to observe them!
The UVY wires will give us YZ information,
The drift time will give us the X information via "time projection"

To know the drift time, I need to know the start (T_0)



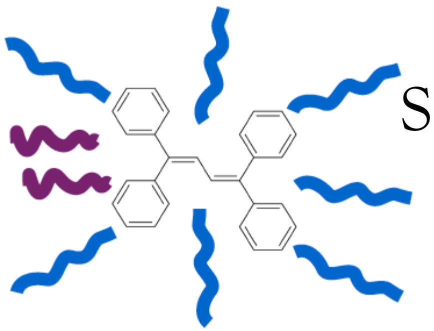
Luckily there is scintillation light!

The light comes from excimers (Ar molecules!)

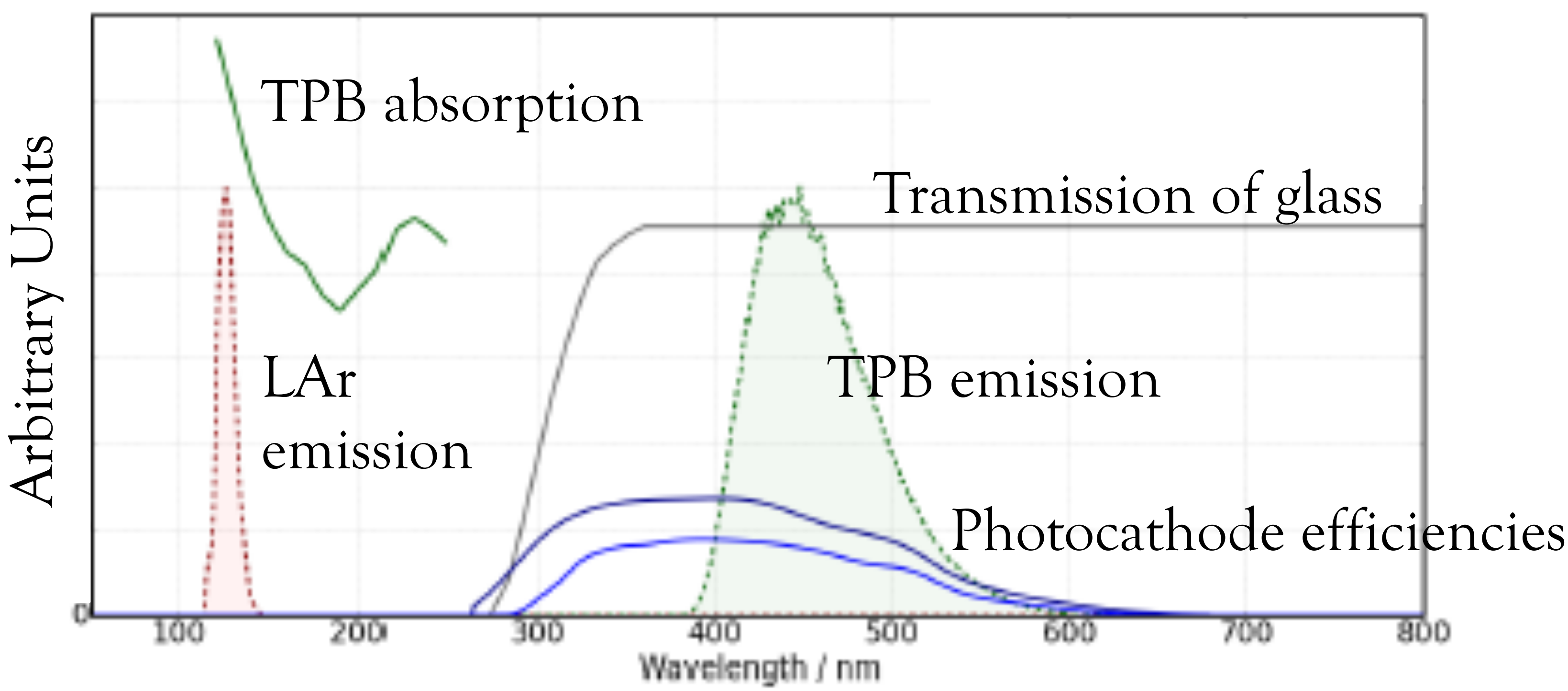


The argon atoms do not re-absorb the scintillation light

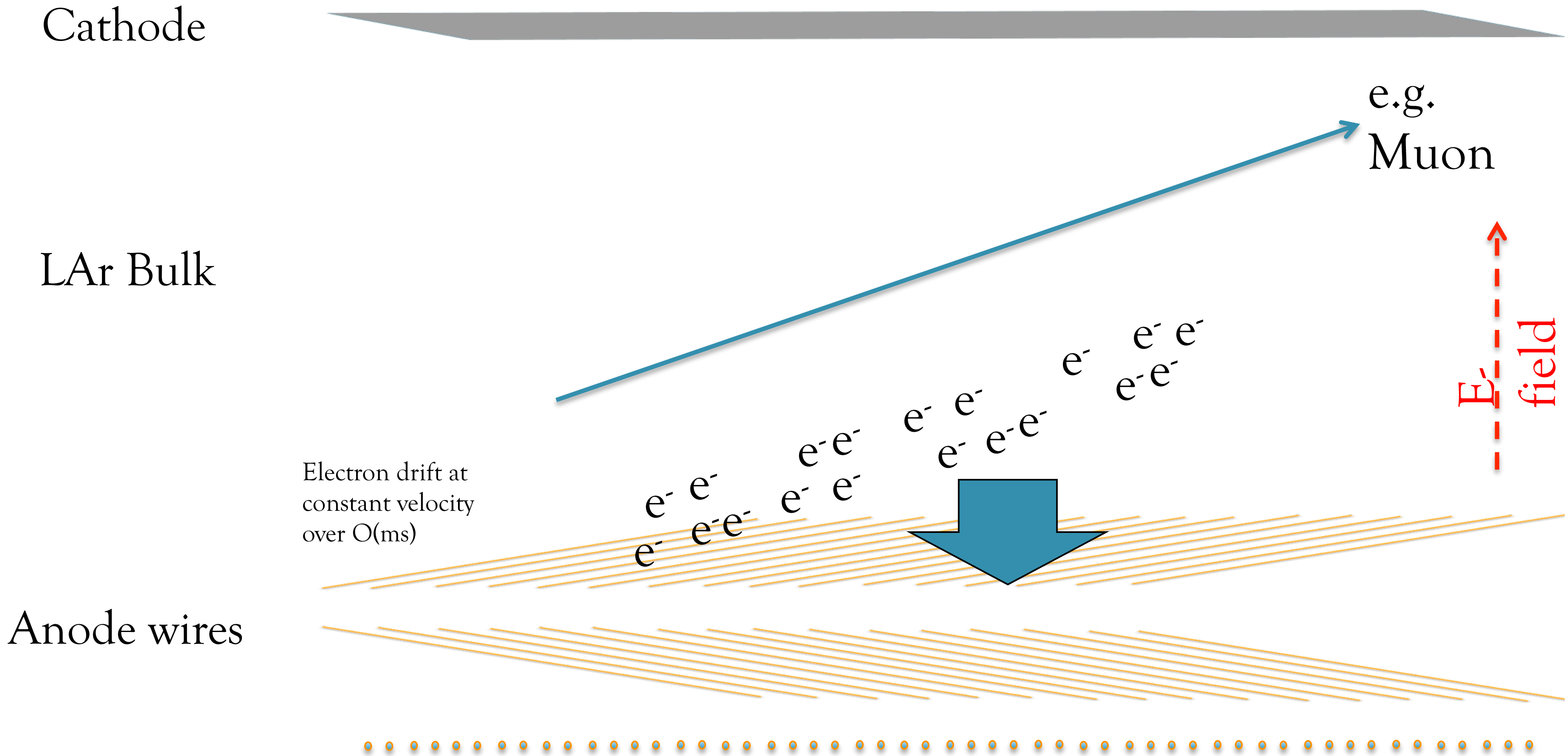
The problem is that the light is at 128 nm (VUV)



Shift the light from UV to Visible, using
Tetraphenyl Butadiene (TPB)



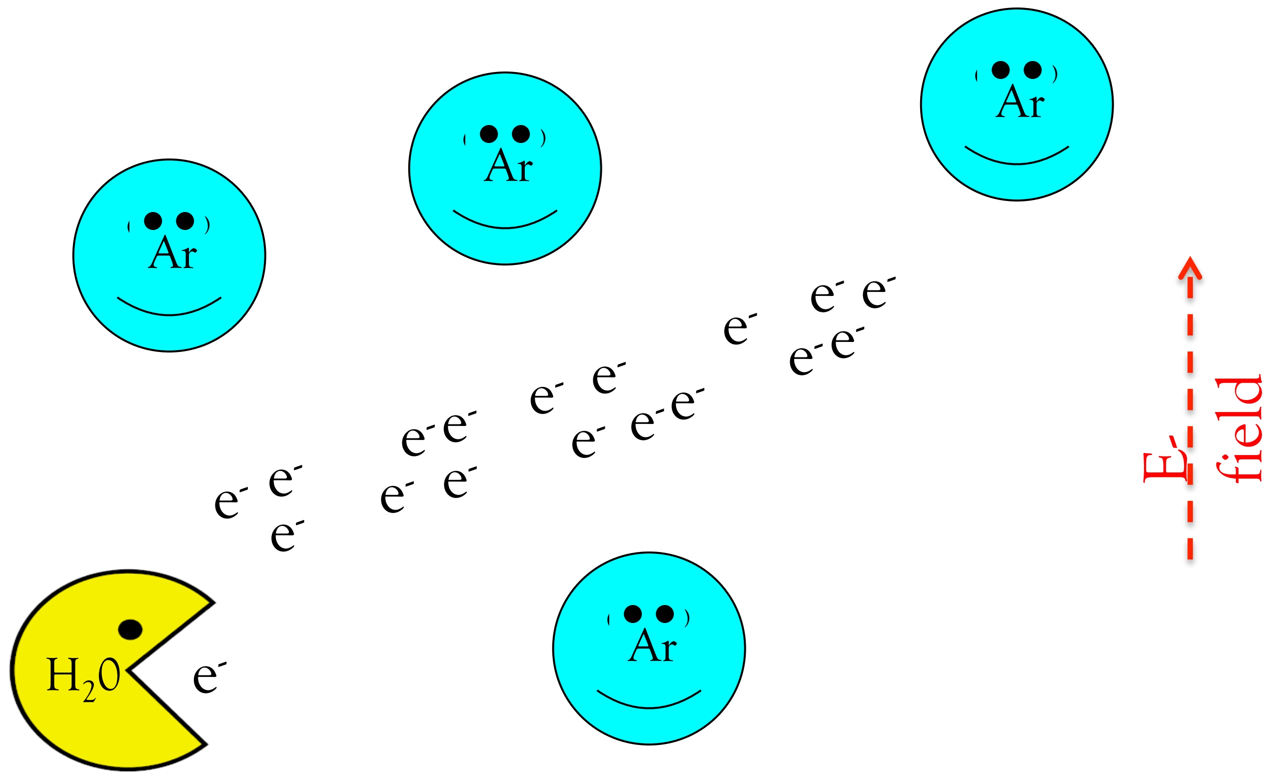
Back to our LArTPC Detector



As electrons drift,
it takes milliseconds to reach the wires!

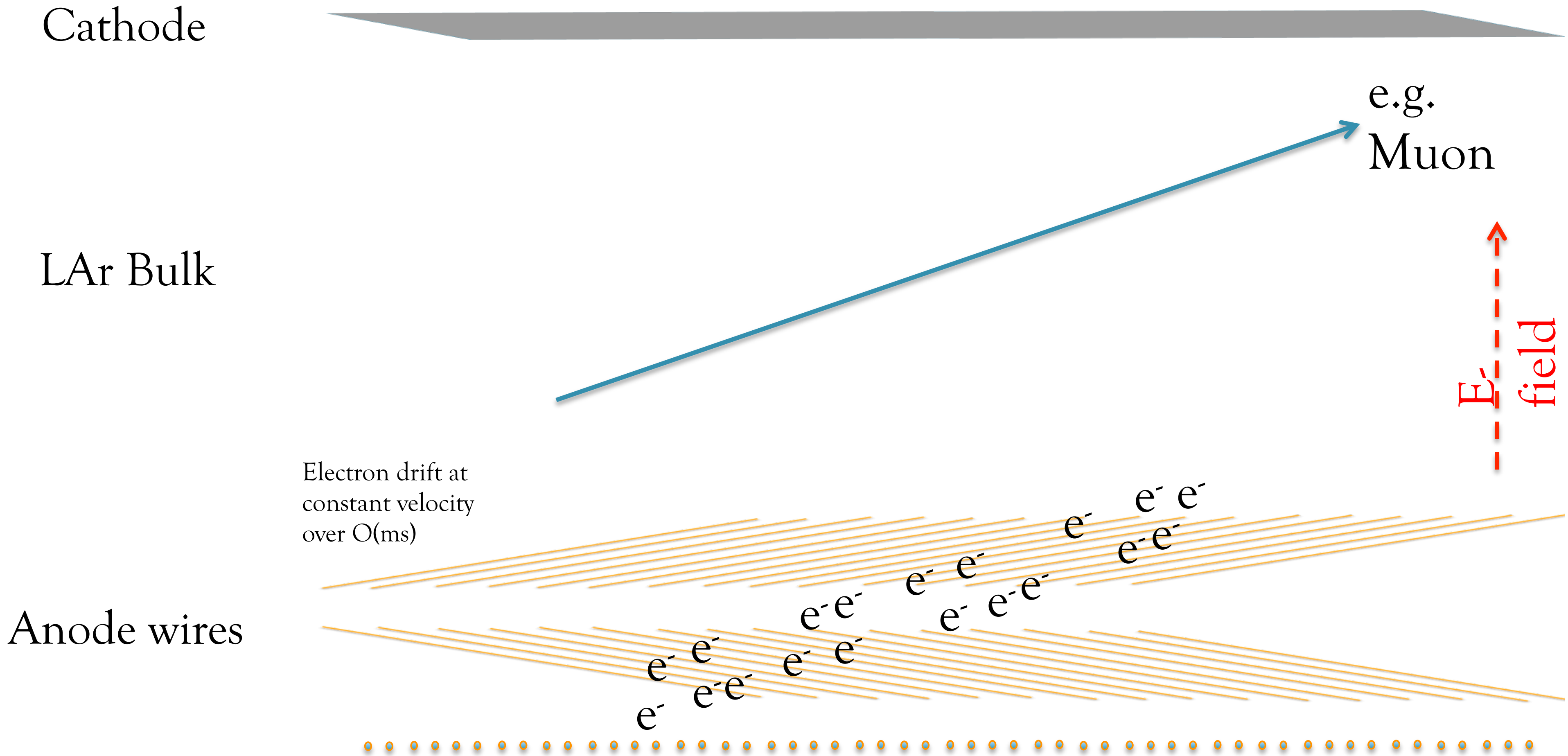
Noble elements do not want to pick up electrons

Electrons produced by ionization will drift through the LAr bulk for many meters

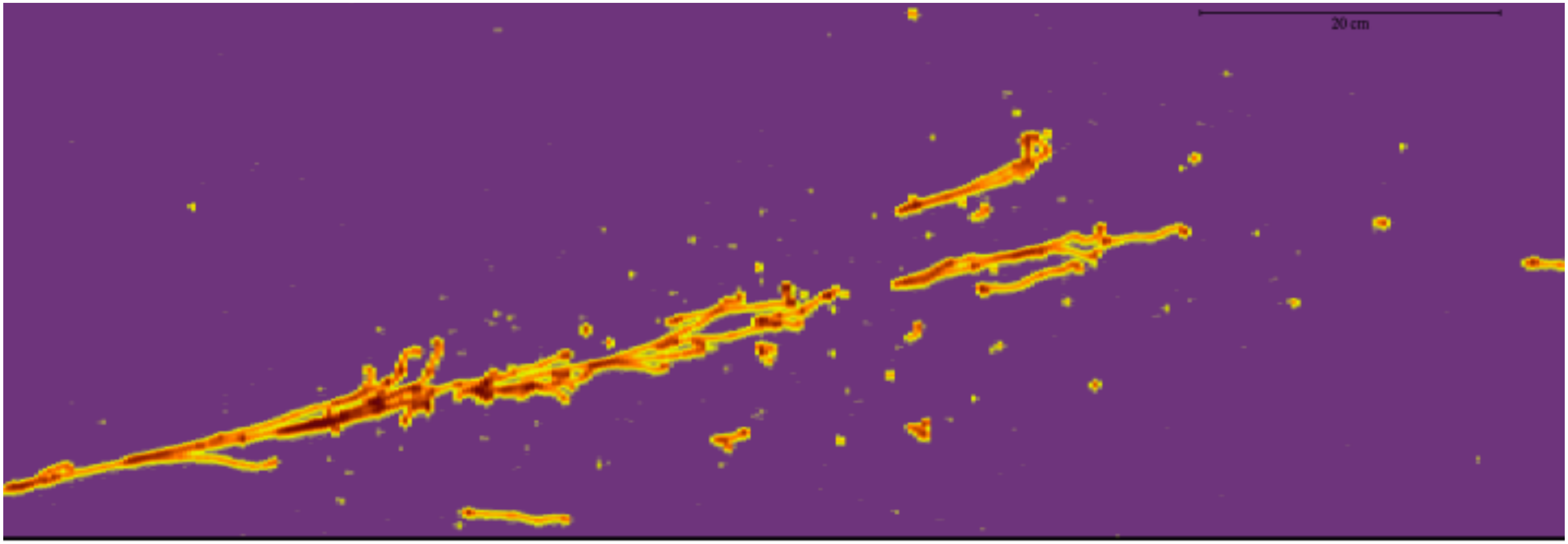


But a big problem is impurities have a high affinity for electrons → in the early 2000's we learned how to reach the needed purity level, using regenerable filters.

LArTPC Detector



There is no gain at the wires in LAr.
We needed to develop electronics that responded to unamplified signal!
(ASIC technology to amplify + digitizers)



Spatial resolution: ~mm
Energy resolution: <5%/$\sqrt{E}$ (MeV)
Works well at high energies (unlike Cerenkov)

This is a big improvement over other designs.
But…

- still state of the art – we have a lot to learn!
- still more expensive per ton than water Cerenkov,

Looking for a topic that would make a good paper?

We are building a 40 kton underground LArTPC
"DUNE" – we'll talk about this in next section of class…

When this detector is not being used to take beam-data
(beam neutrinos arrive in well-identified spills)
it can be used for other purposes…

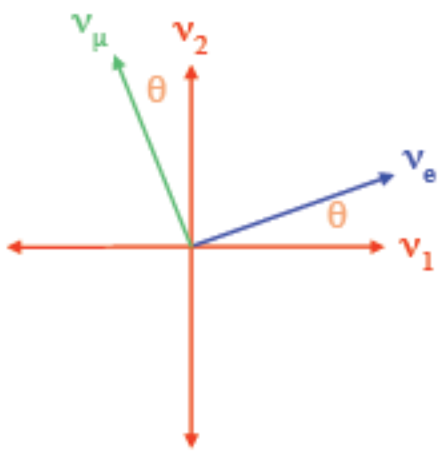
Do you have an interesting use for this detector?
Can you imagine bringing in an low-energy accelerator
for nuclear scattering studies?
Or maybe a high-rate neutron generator? check out…
http://phoenixnuclearlabs.com/product/high-yield-neutron-generator/
Or doing interesting studies related to nuclear astrophysics?

The nuclear community has not really explored the potential of this detector!

Three neutrino oscillations:
Can we fit the puzzle pieces together?

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.

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

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

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

$$t/p = L/E$$

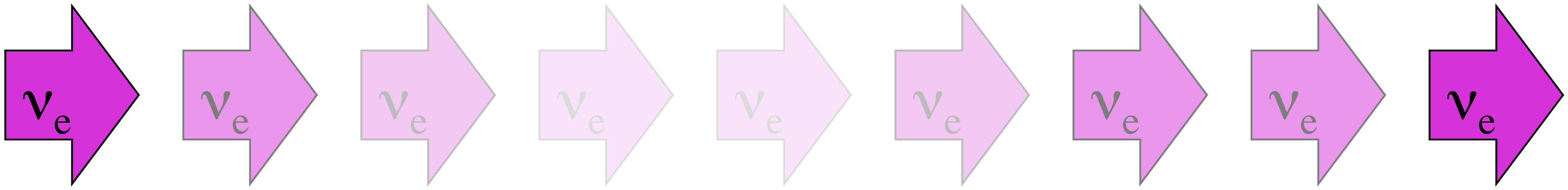
We know the mass is small so we can use a Taylor expansion and then change some units.

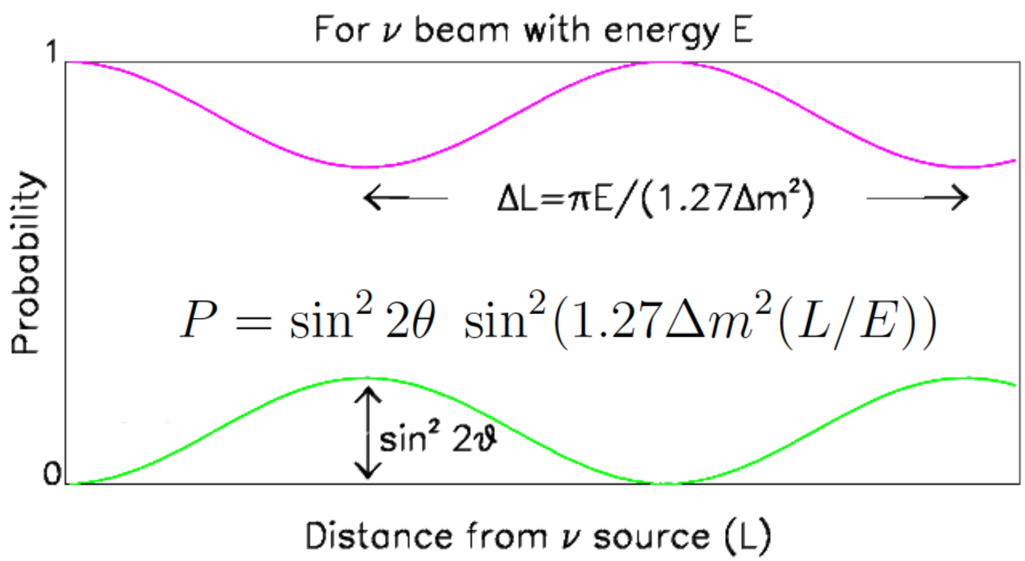
$$P_{osc} = \frac{1}{2} \sin^2 2\theta \left(1 - \cos\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)\right)$$

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

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

What happens in an experiment? 2 neutrinos





ν_e Disappearance:

Well understood energy dependence

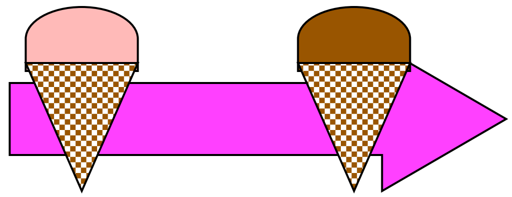
ν_μ Appearance

Well understood flavor content

Beams are designed differently for appearance versus disappearance

Appearance experiments

start with a certain flavor



Do you see a new flavor?

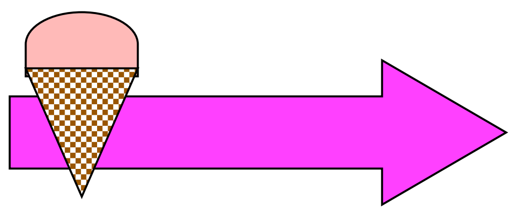
Ideally, new flavor components "sticks out" clearly in the event sample

Disappearance experiments

source

detector

start with a certain flavor



Is it still there?

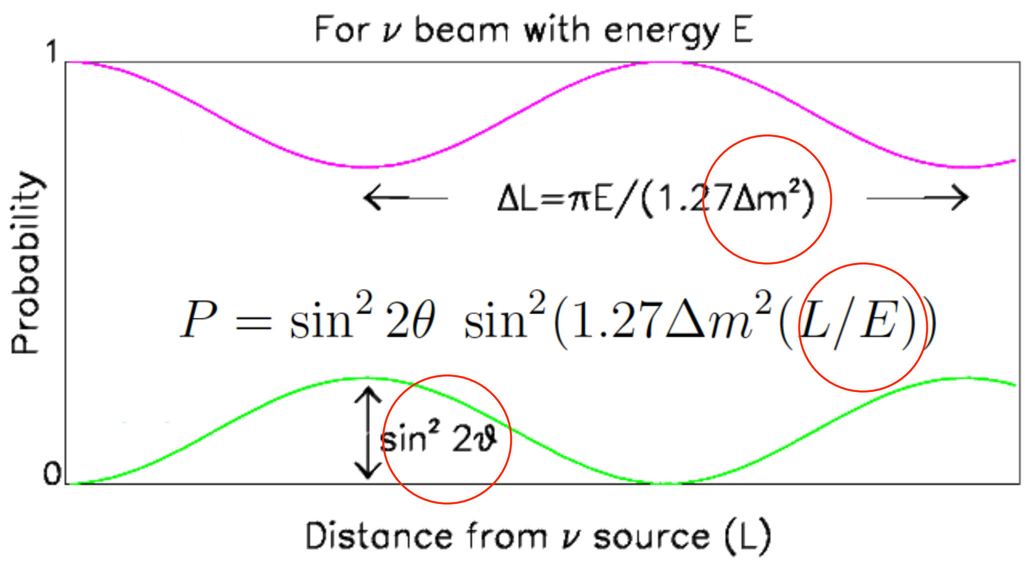
New flavor won't produce CCQE is below threshold

Two unknown parameters: Δm^2 and $sin^2 2\theta$

Parameters you can change: L and E

Flavor ($\boldsymbol{\nu_\mu}$ or $\boldsymbol{\nu_e}$) … aka the beam

Appearance or Disappearance … beam & detector



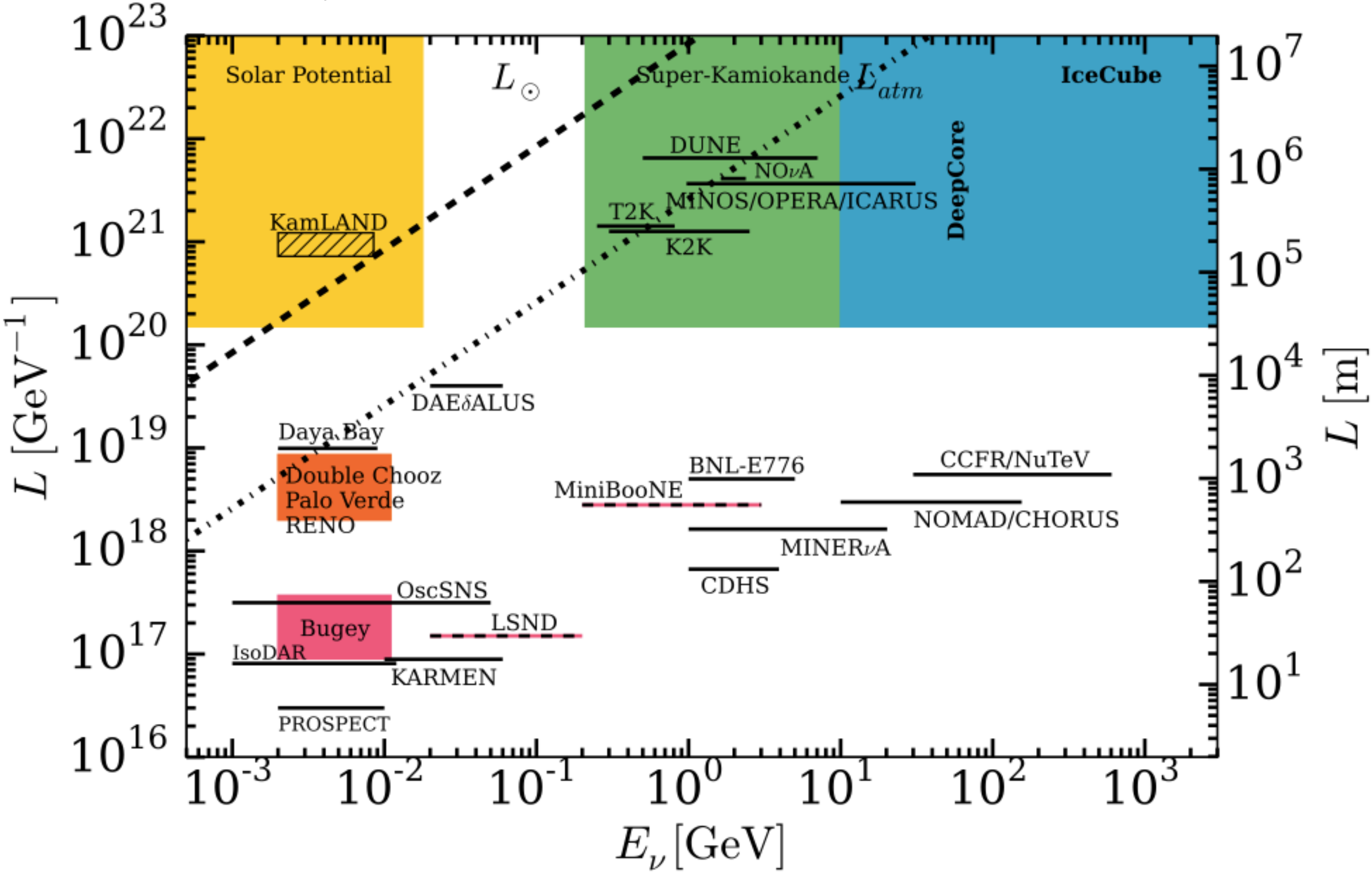
ν_μ Disappearance:

Well understood energy dependence

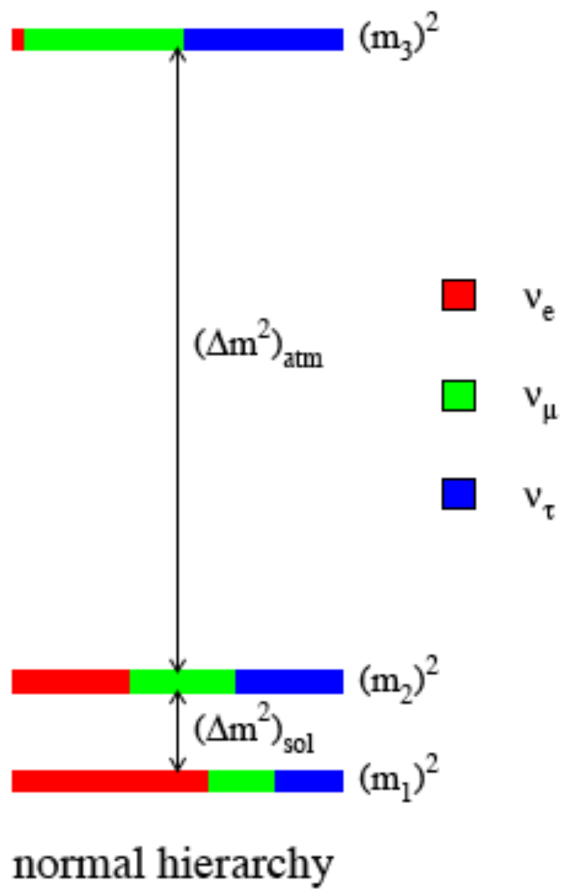
ν_e Appearance

Well understood flavor content

Experiments sensitive to same Δm^2 all lie on a line!
→ They all have the same ratio of L/E



We actually have 3 neutrinos, so lets expand the model…

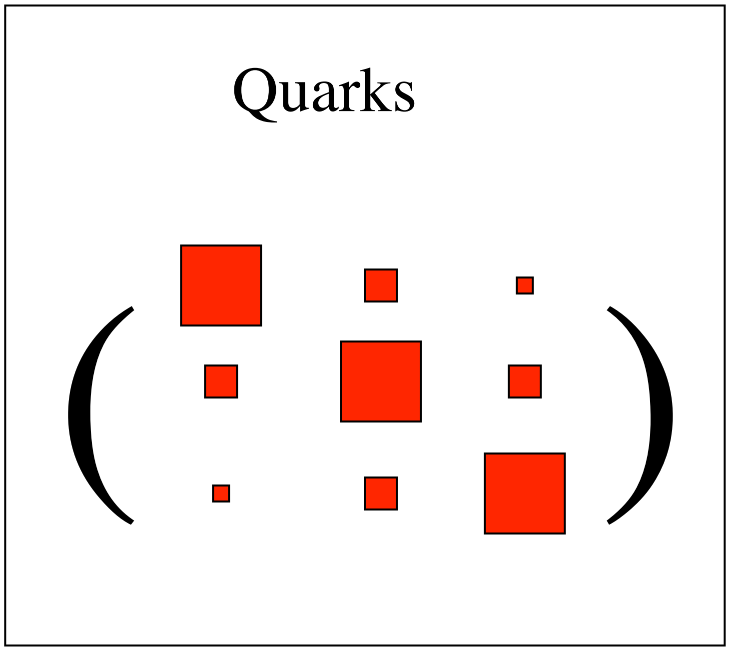


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

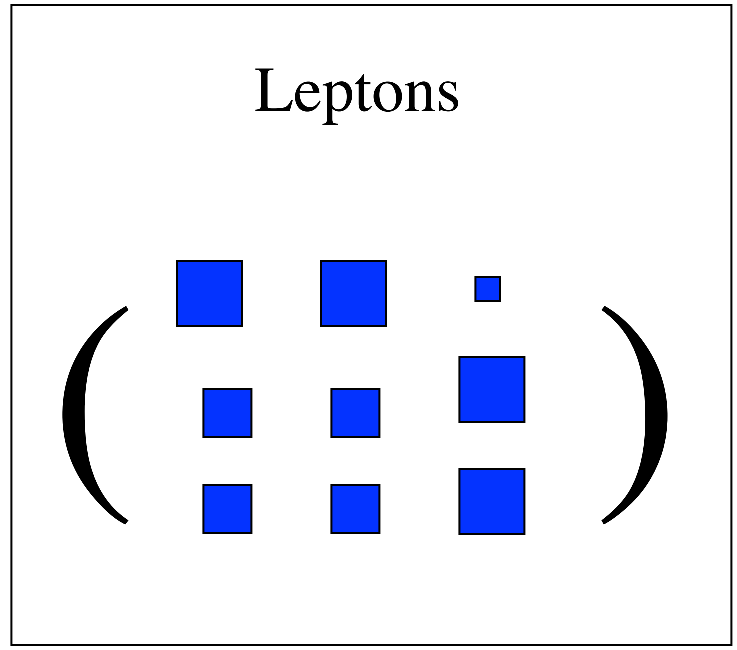
"mixing" between neutrinos
is parameterized by
three "mixing angles"
$\theta_{12}, \theta_{13}, \theta_{23}$

Five unknown parameters: 2 Δm^2's and 3 angles

What we know about mixing, since ~5 years ago



vs.



Large entries on diagonal
small off diagonal

Moderately large entries
except for one,
which is relatively small

A clue to the Beyond Standard Model Physics?

Actually, just like in the quark sector, there is a 6th unknown…

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

The CP Violation Parameter

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

Same list:

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

The CP Violation Parameter

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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

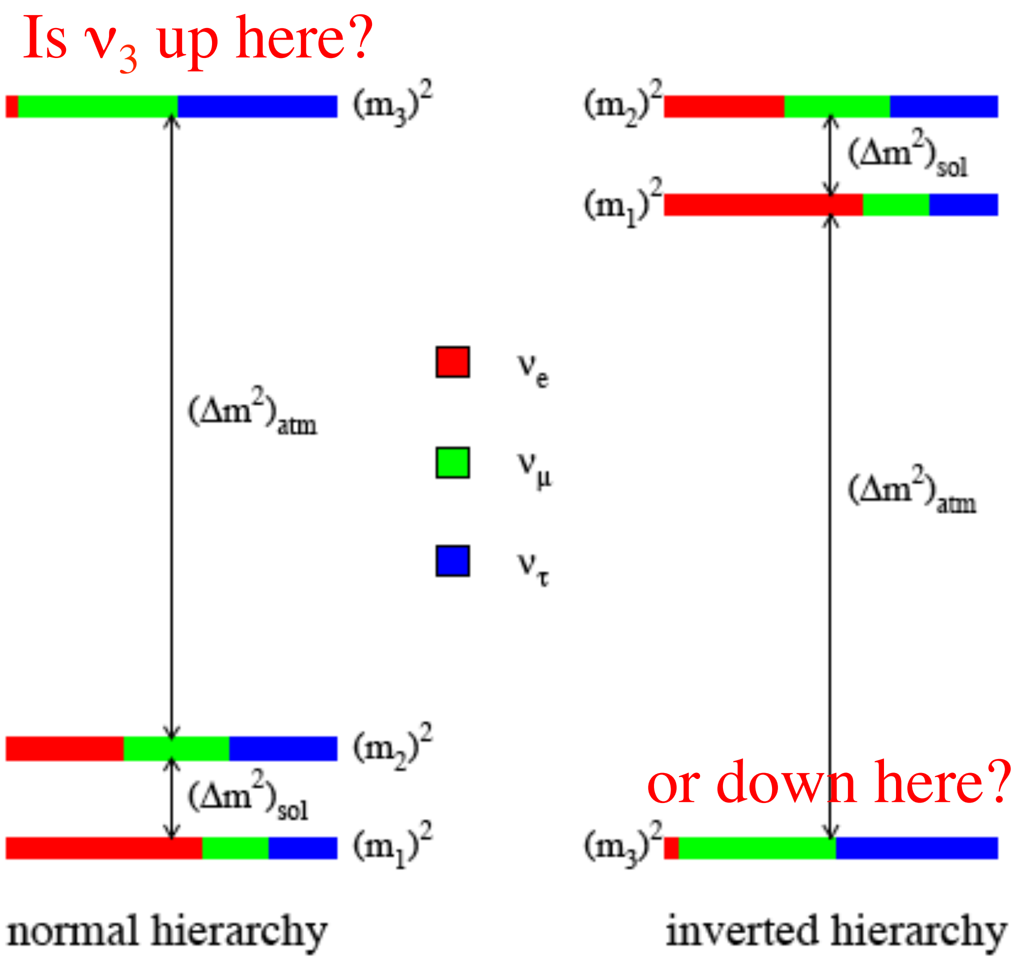
From Appearance Measurements

From Solar Neutrino Measurements

These will be special and that will help us sort this out

And we have one last problem…

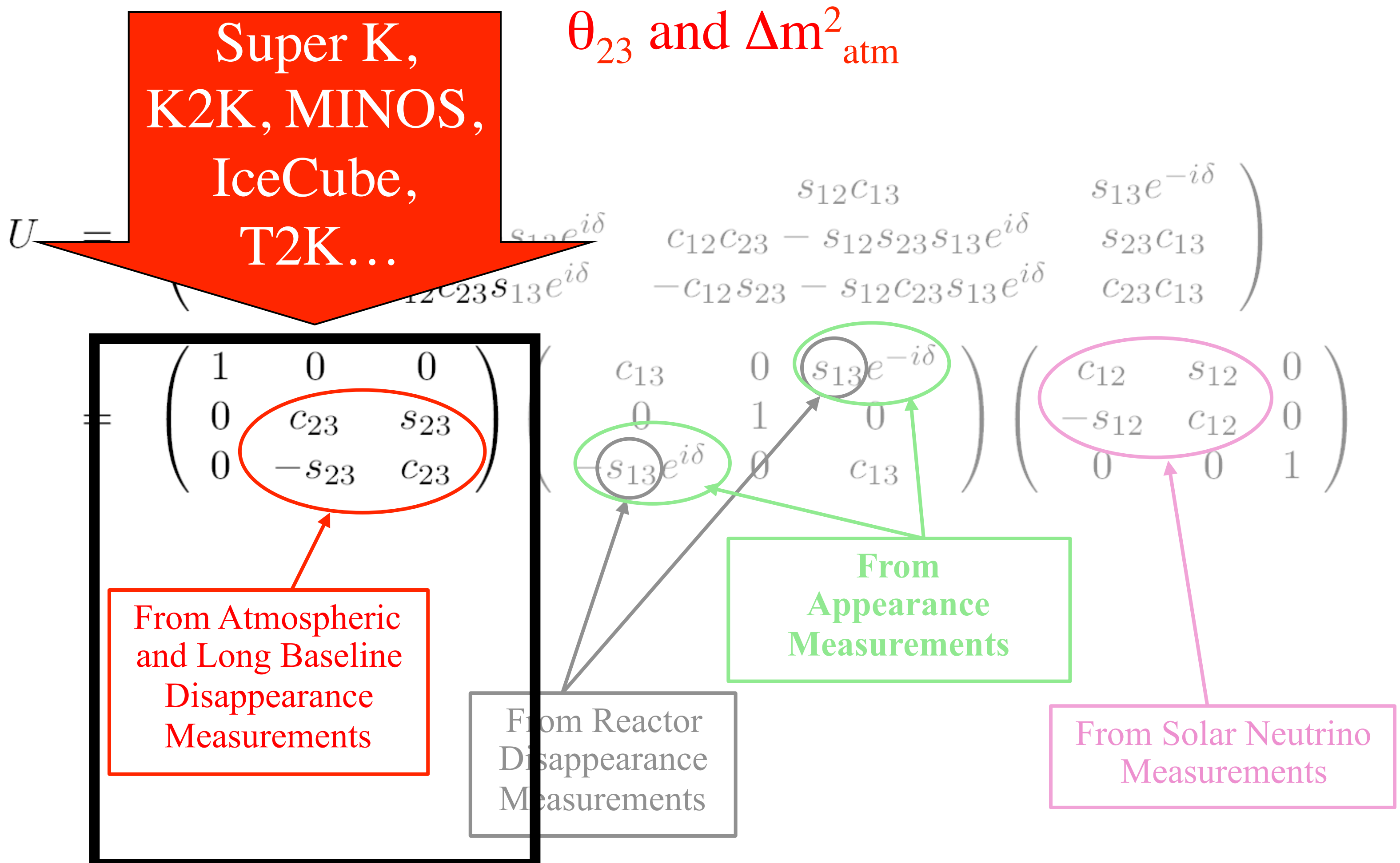
The mass hierarchy -- a 7th parameter



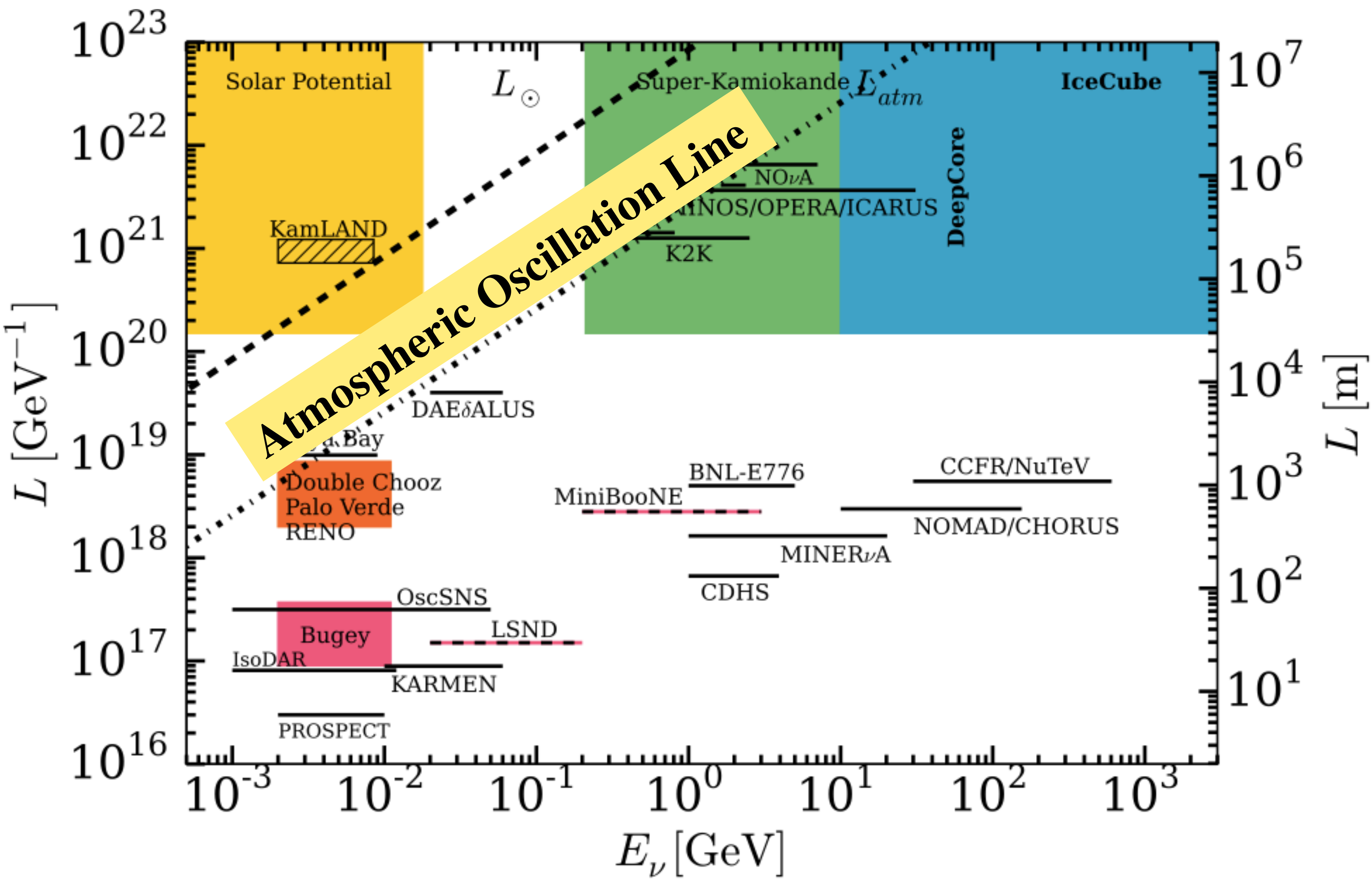
This will affect the amount of ν_e that appears at a given oscillation length.

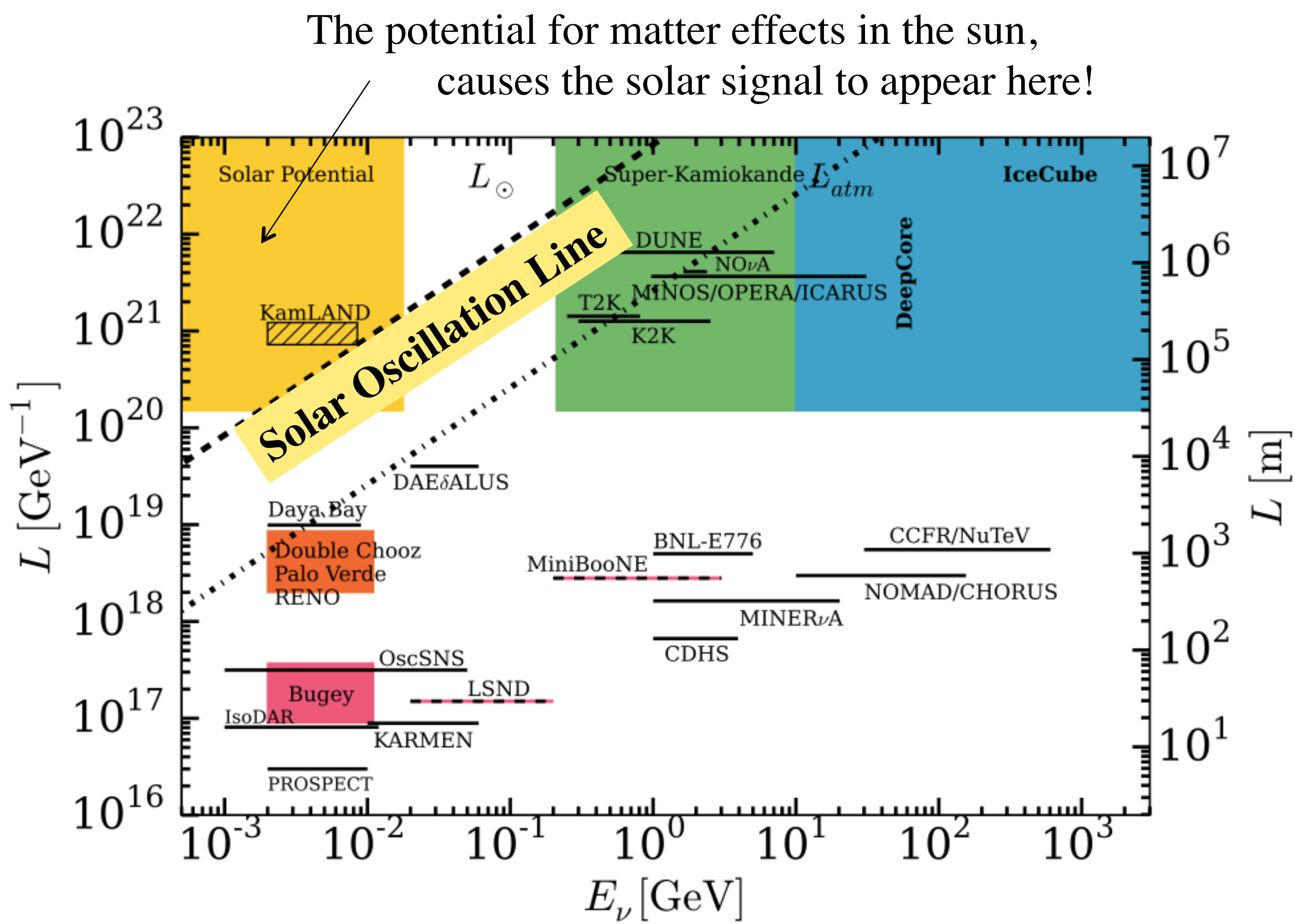
We will sort this out through “matter effects” that are L-dependent

So lets look at what is contributing information…



Returning to our L vs E world-view




The potential for matter effects in the sun,
causes the solar signal to appear here!
Solar Potential
L ⊙
Super-Kamiokande
L atm
IceCube
DeepCore
Solar Oscillation Line
DUNE
NOνA
MINOS/OPERA/ICARUS
T2K
K2K
KamLAND
DAEδALUS
Daya Bay
Double Chooz
Palo Verde
RENO
BNL-E776
CCFR/NuTeV
MiniBooNE
NOMAD/CHORUS
MINERνA
CDHS
OscSNS
LSND
Bugey
IsoDAR
KARMEN
PROSPECT
$L\ [\mathrm{GeV}^{-1}]$
$L\ [\mathrm{m}]$
$E_\nu\ [\mathrm{GeV}]$

The solar results came largely from the Nuclear Physics Community!

θ_{12}, Δm^2_{sol},
also the flavor content of 2 mass states

Super K, SNO, KamLAND

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

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Appearance Measurements

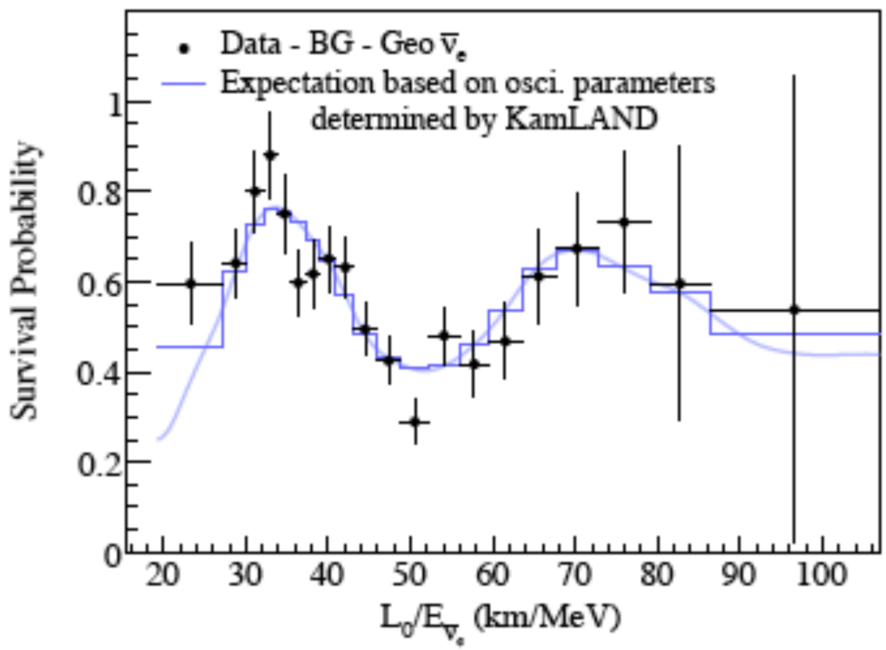
From Solar Neutrino Measurements

The Probability for Oscillations...

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

For example, in Kamland!

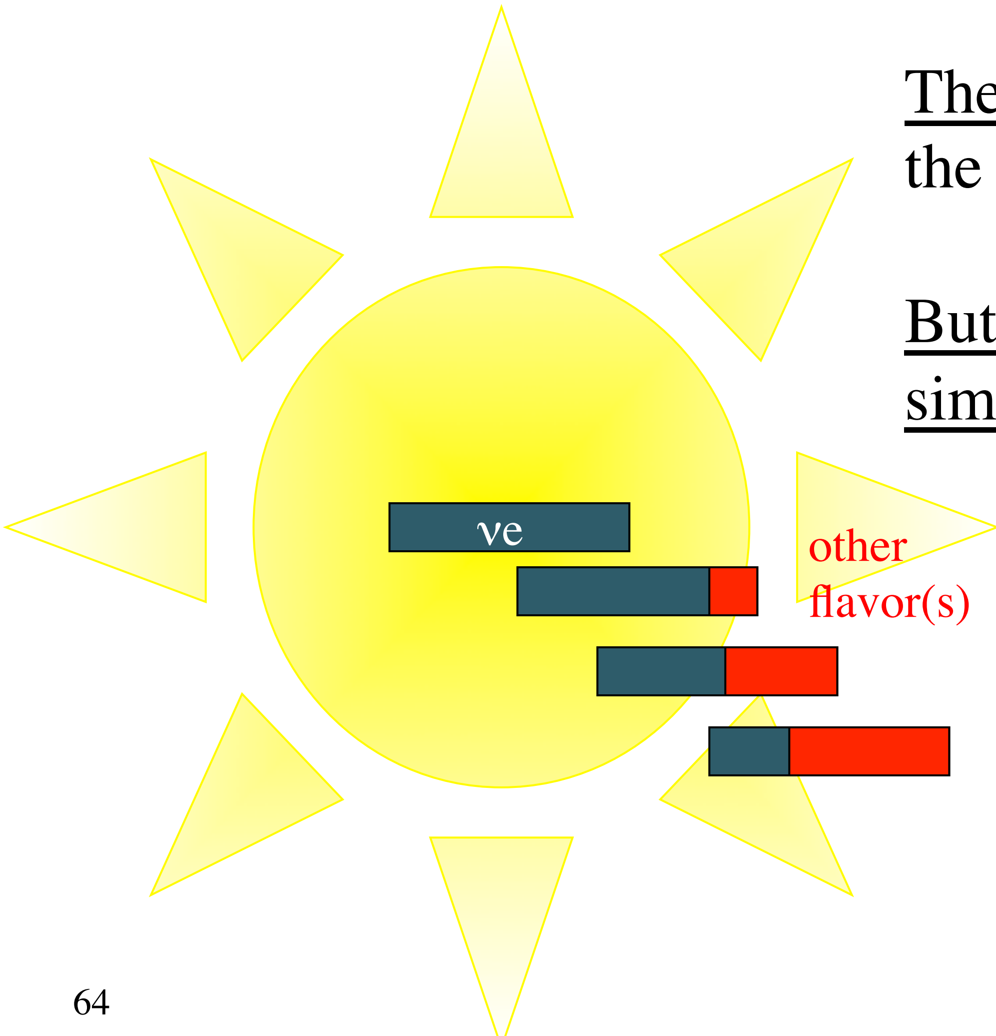
anti-electron neutrinos from a reactor disappear
with a wavelength consistent with ➡ $\Delta m^2 \sim$ 5E-5 eV^2



In the electron “soup”

The ν_e sees a CC and NC potential

The ν_μ and ν_τ see only the NC potential

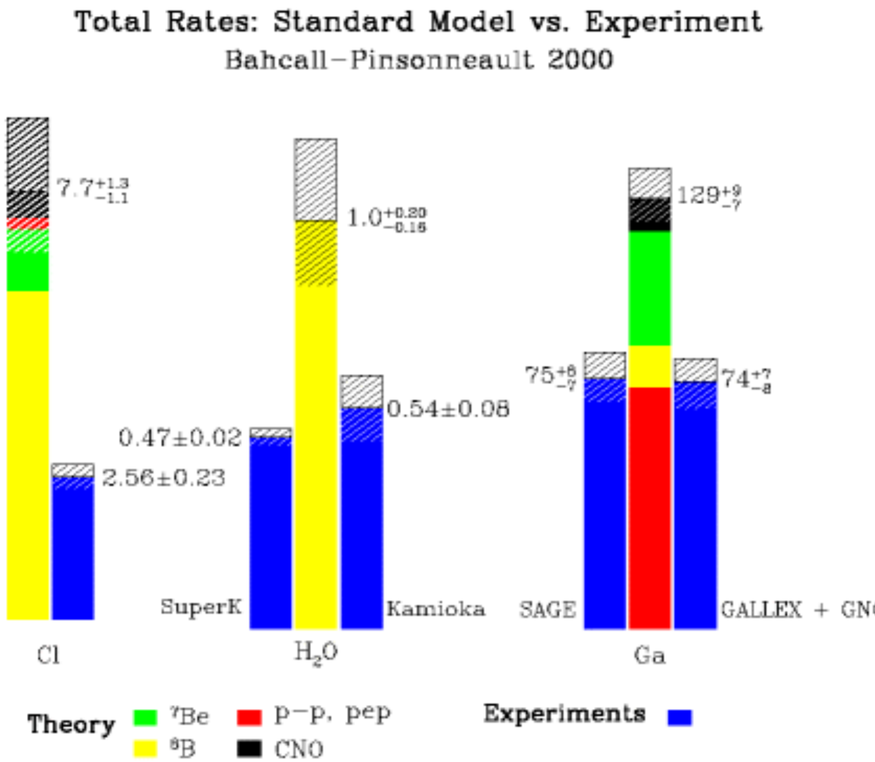


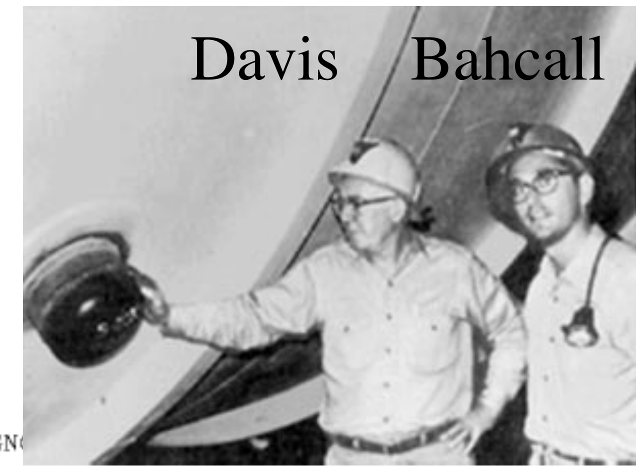
There is flavor evolution as the neutrinos traverse the sun.

But the equations do not simplify to oscillations

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

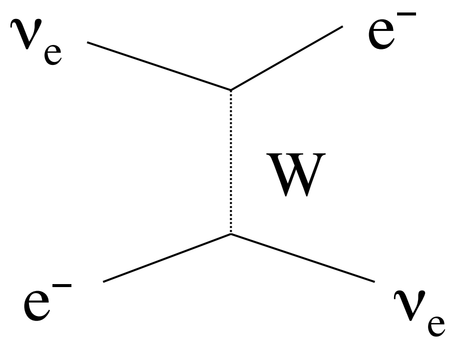
The famous “Solar Neutrino Deficit”



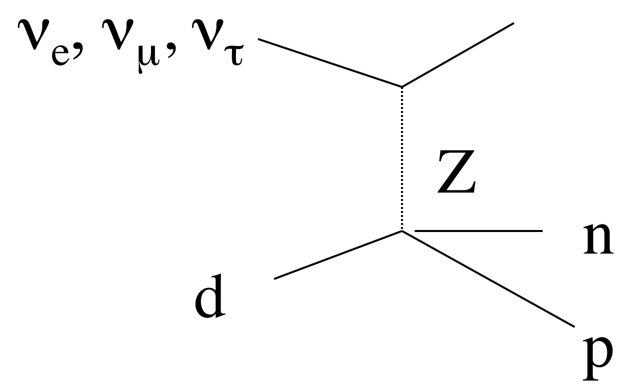


The rate of morphing with energy depends on Δm^2 and the mixing angle

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

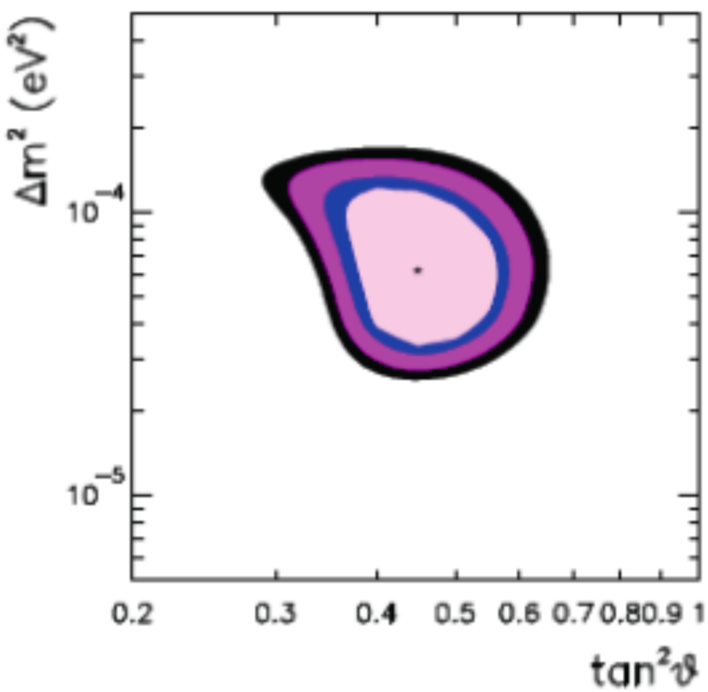
Bahcall, Basu, Serenelli

The NC interaction shows the neutrinos are still there!

This is an extra experimental knob we can use to sort things out

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 $\nu_e \rightarrow \nu_{other}$

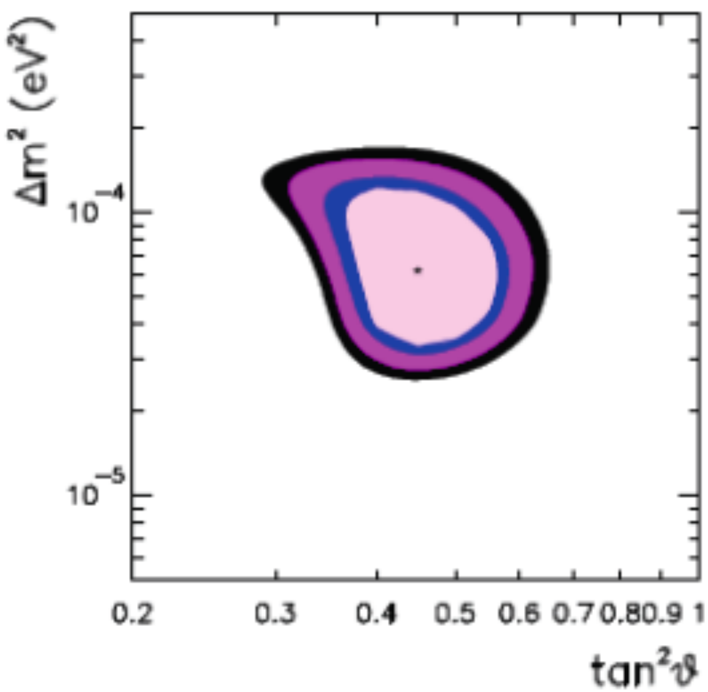
then $\bar{\nu}_e \rightarrow \bar{\nu}_{other}$
should be observable
here too!

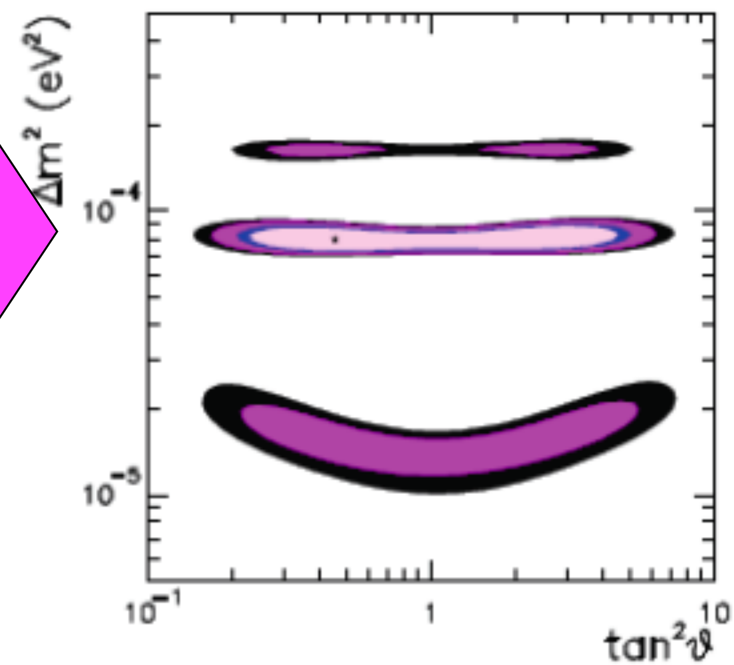
fit by Gonzalez-Garcia

It all fits together

Allowed region for
solar neutrino oscillation
measurements,

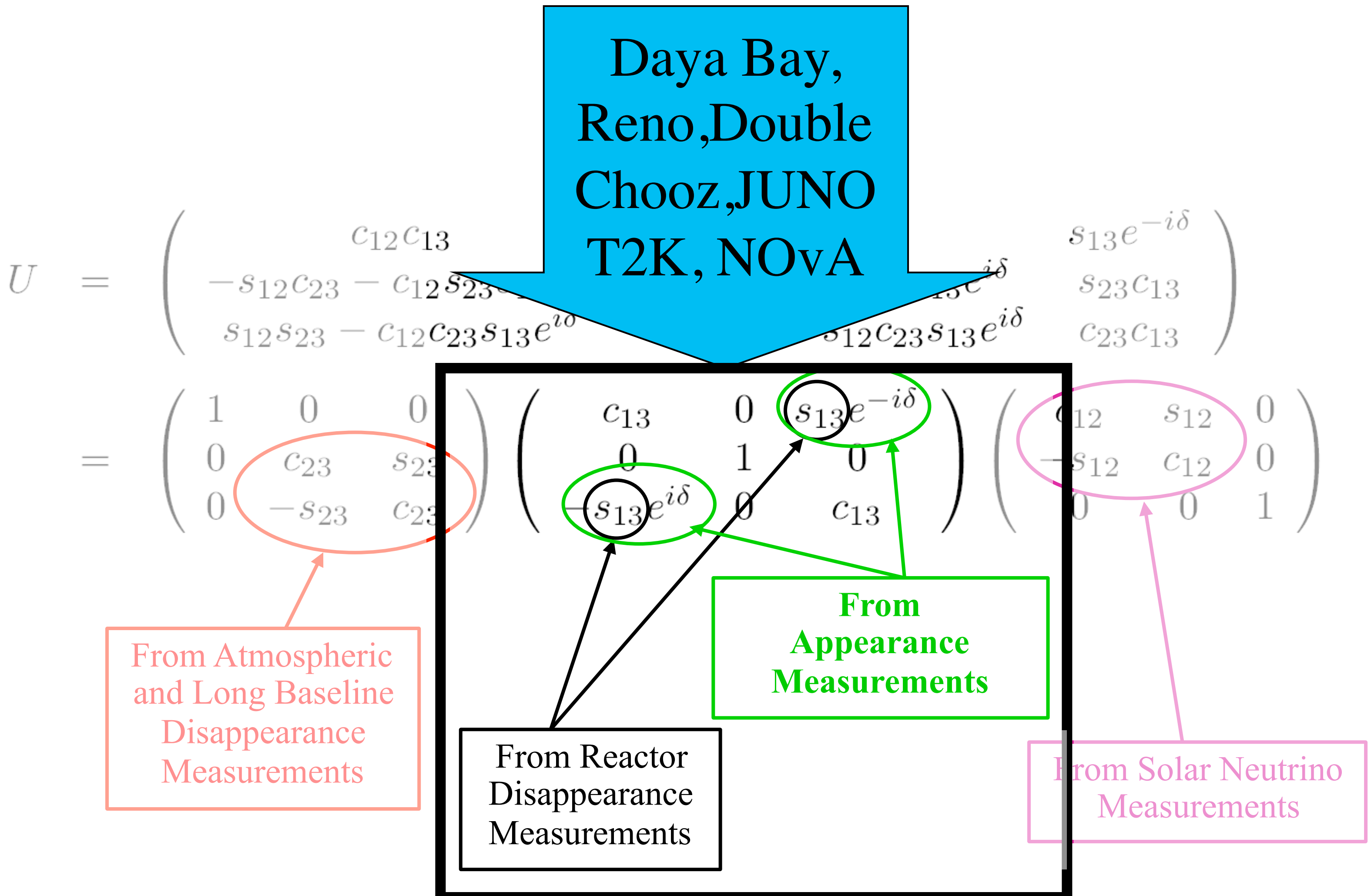
Allowed region for the
Kamland reactor
$\bar{\nu}_e \rightarrow \bar{\nu}_{other}$ Experiment!

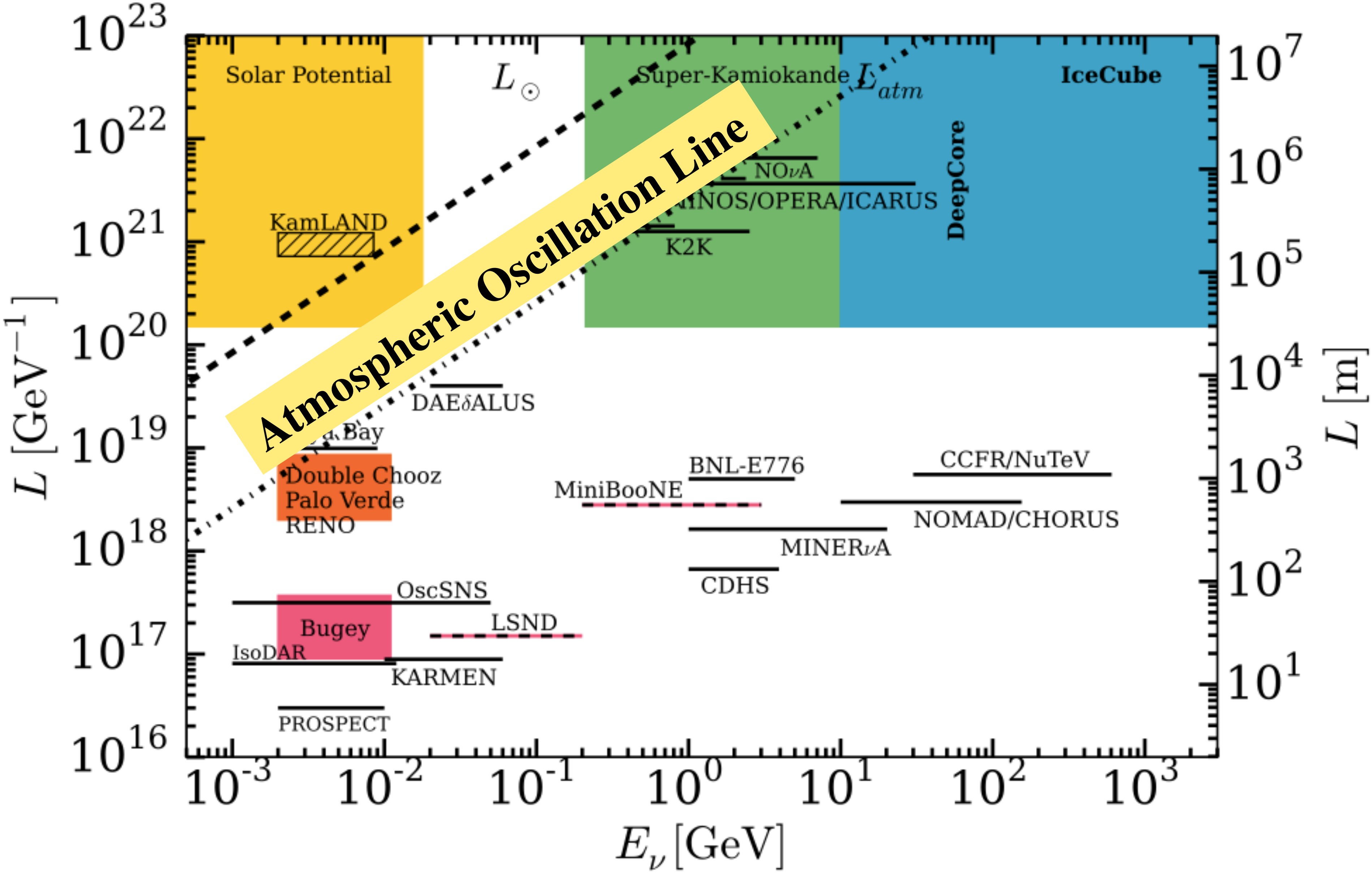




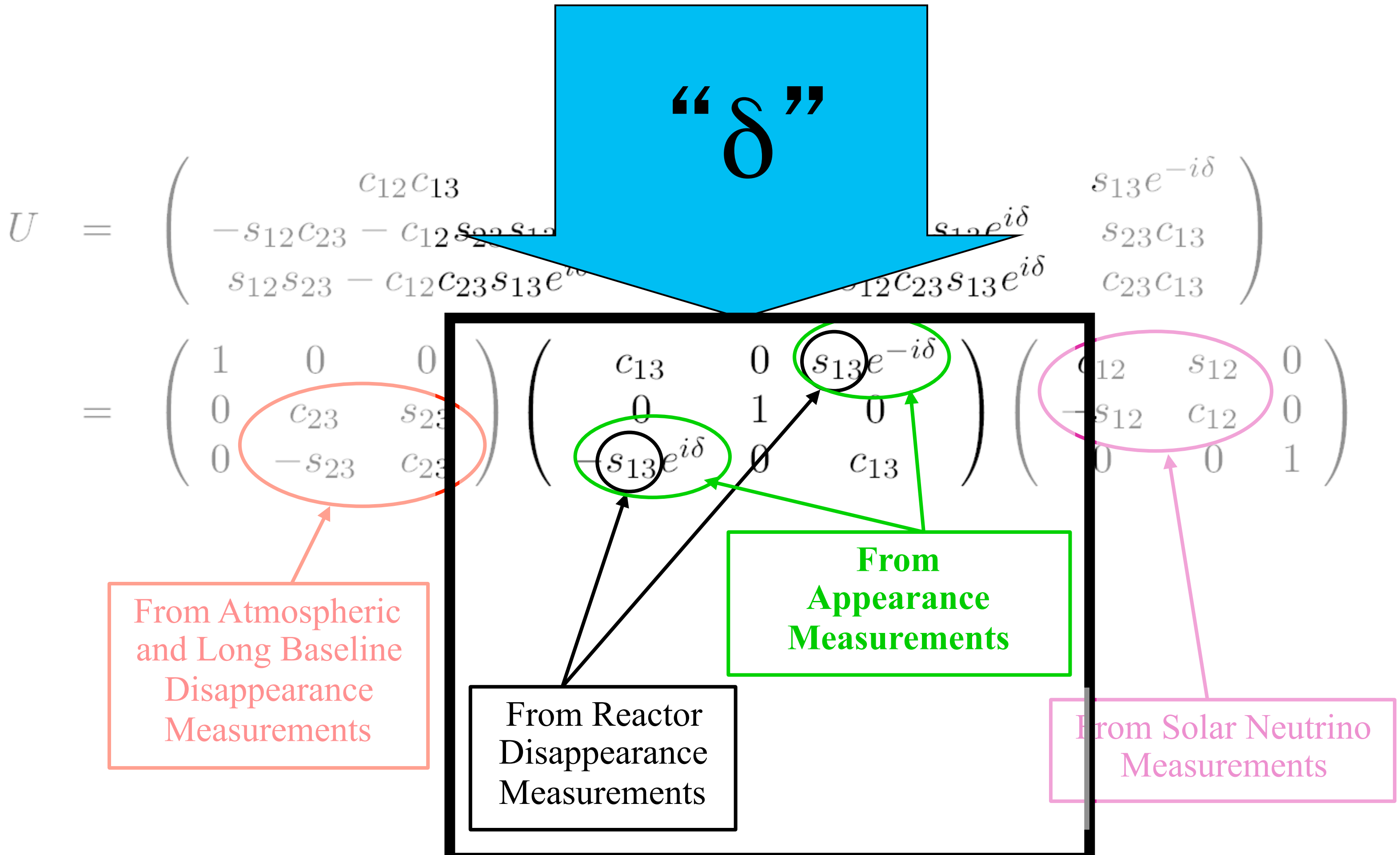
fits by Gonzalez-Garcia

θ_{13}


Daya Bay, Reno,Double Chooz,JUNO T2K, NOvA
From Atmospheric and Long Baseline Disappearance Measurements
From Reactor Disappearance Measurements
From Appearance Measurements
From Solar Neutrino Measurements

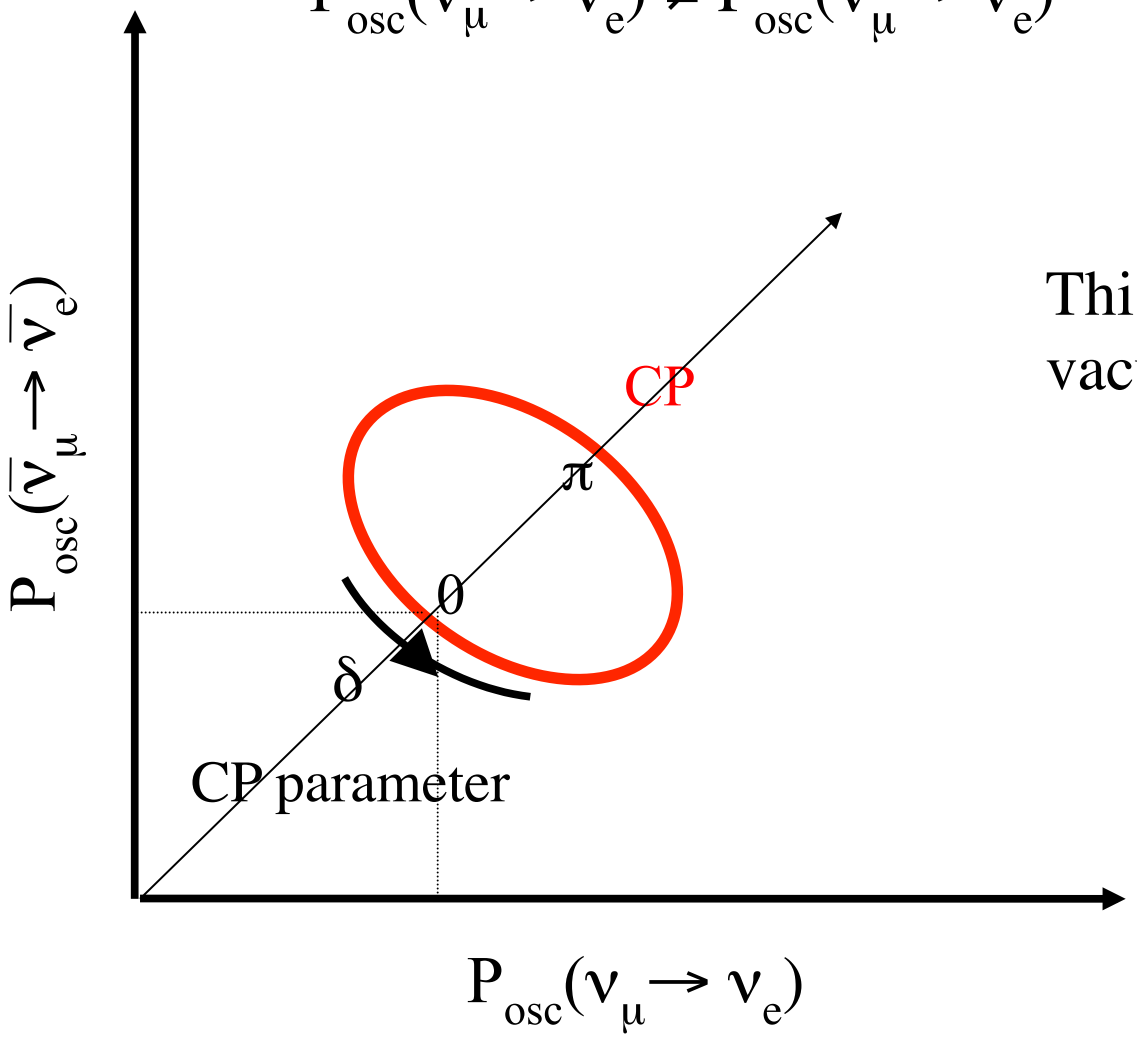

Solar Potential
$L_\odot$
Super-Kamiokande
L_{atm}
IceCube
DeepCore
Atmospheric Oscillation Line
NOνA
MINOS/OPERA/ICARUS
K2K
KamLAND
DAEδALUS
Double Chooz
Palo Verde
RENO
BNL-E776
MiniBooNE
CCFR/NuTeV
NOMAD/CHORUS
MINERνA
CDHS
OscSNS
Bugey
LSND
IsoDAR
KARMEN
PROSPECT
$L\,[\mathrm{GeV}^{-1}]$
$L\,[\mathrm{m}]$
$E_\nu\,[\mathrm{GeV}]$

Lastly the CP violating parameter.
This one is exciting because a non-zero value
fits into our larger theory of how neutrinos get mass



The classic idea for how to see CP violation:

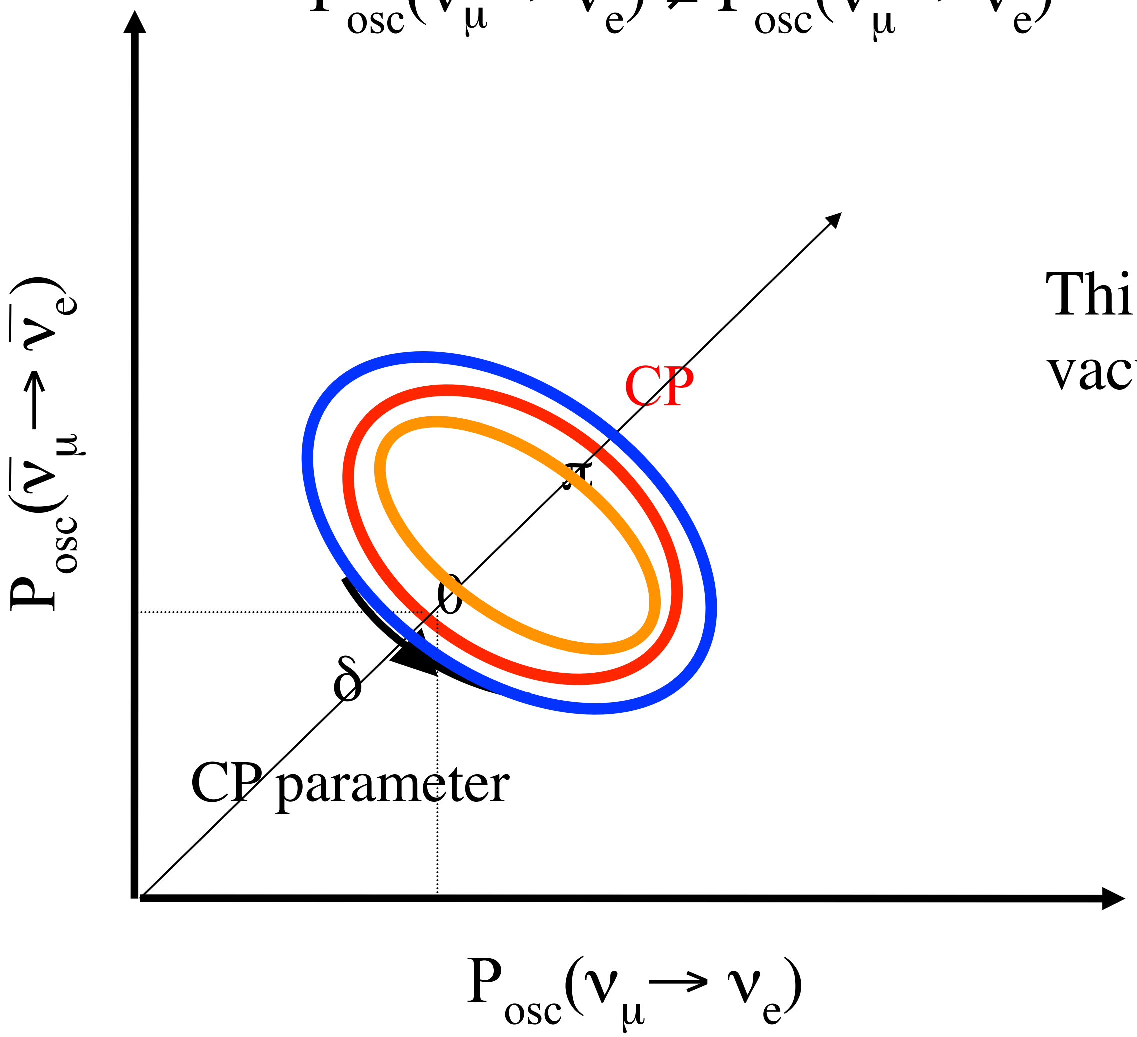
$$P_{osc}(\nu_\mu \rightarrow \nu_e) \neq P_{osc}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$



This is in a vacuum (or air).

Varying the value of θ_{13} reduces or enhances the effect, we are very lucky this is relatively large!

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

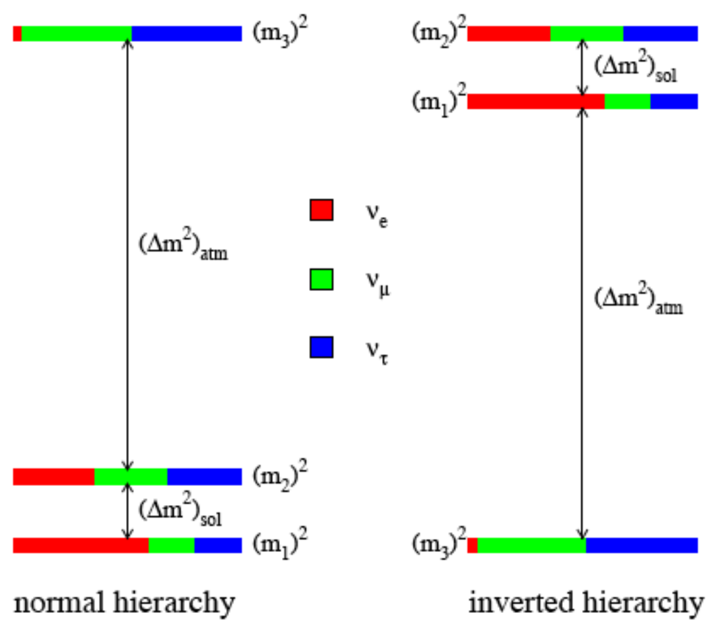


This is in a vacuum (or air).

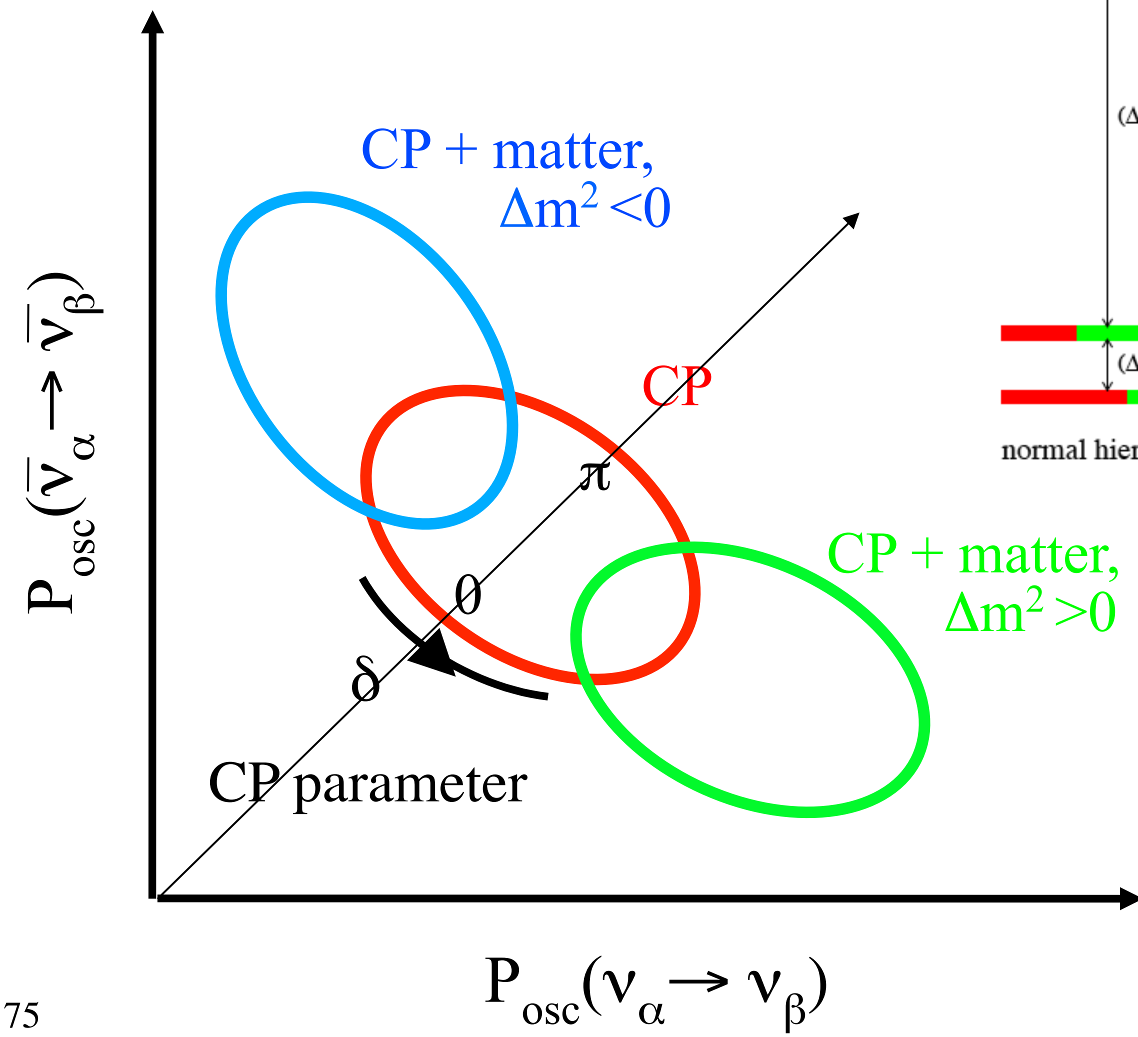
The electrons in the earth can give a “matter potential” too!
This effect grows with L and also results in…

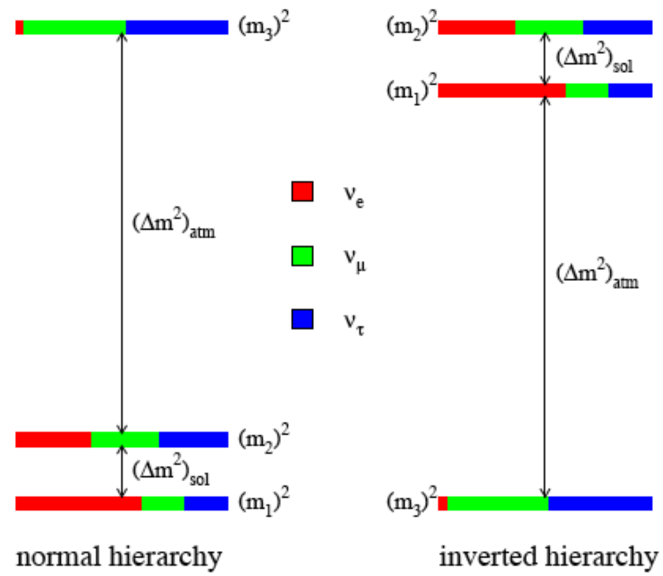
$$P_{osc}(\nu_\mu \rightarrow \nu_e) \neq P_{osc}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

This effect is sensitive to the mass hierarchy.



None of the past experiments were long enough baseline.
A present experiment, NOvA, and future experiments, will be!

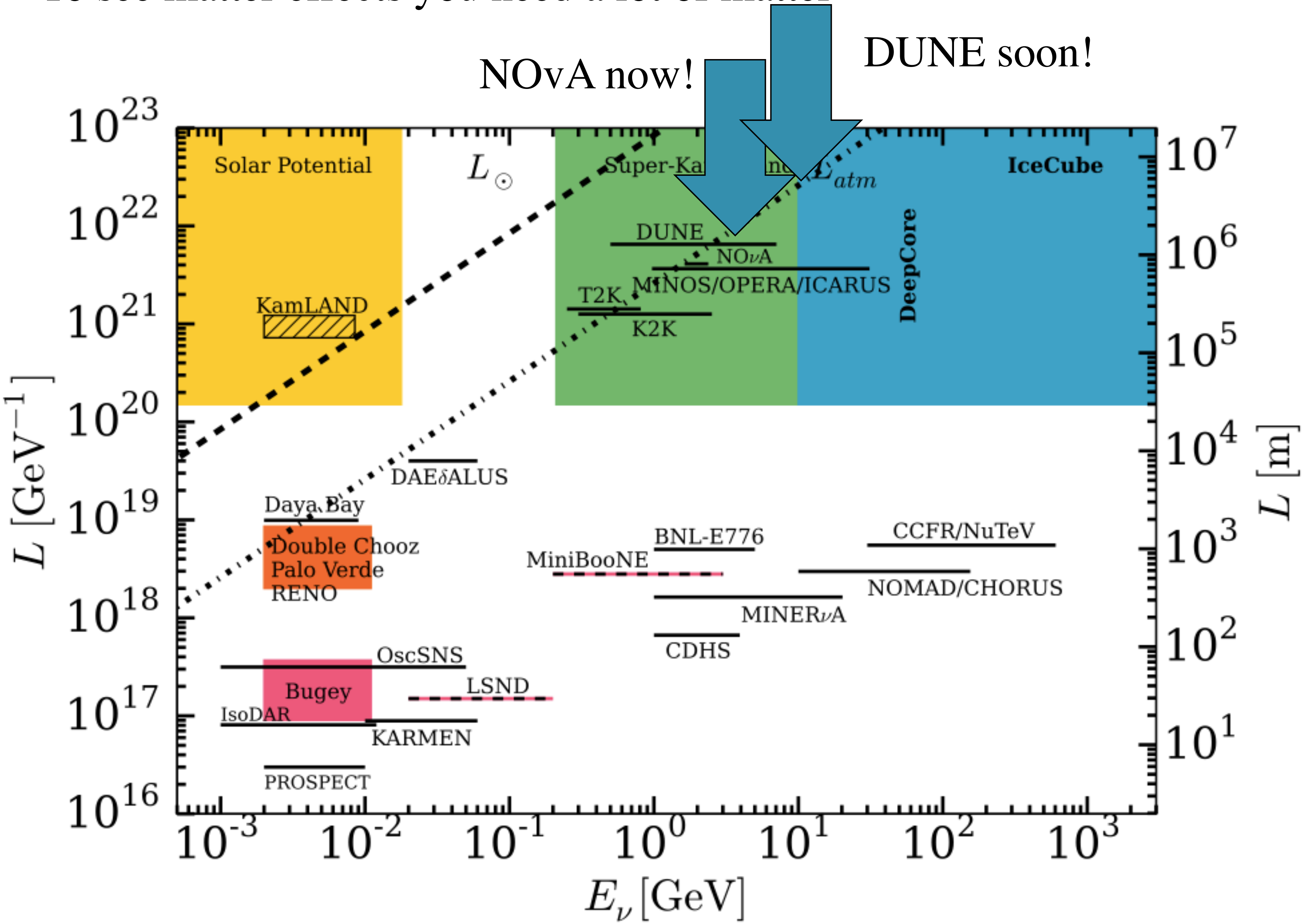

CP + matter,
Δm² <0
CP
π
0
δ
CP parameter
CP + matter,
Δm² >0
P_osc(ν̄_α → ν̄_β)
P_osc(ν_α → ν_β)


(m₃)²
(Δm²)atm
(m₂)²
(Δm²)sol
(m₁)²
normal hierarchy
νe
νμ
ντ
(m₂)²
(Δm²)sol
(m₁)²
(Δm²)atm
(m₃)²
inverted hierarchy

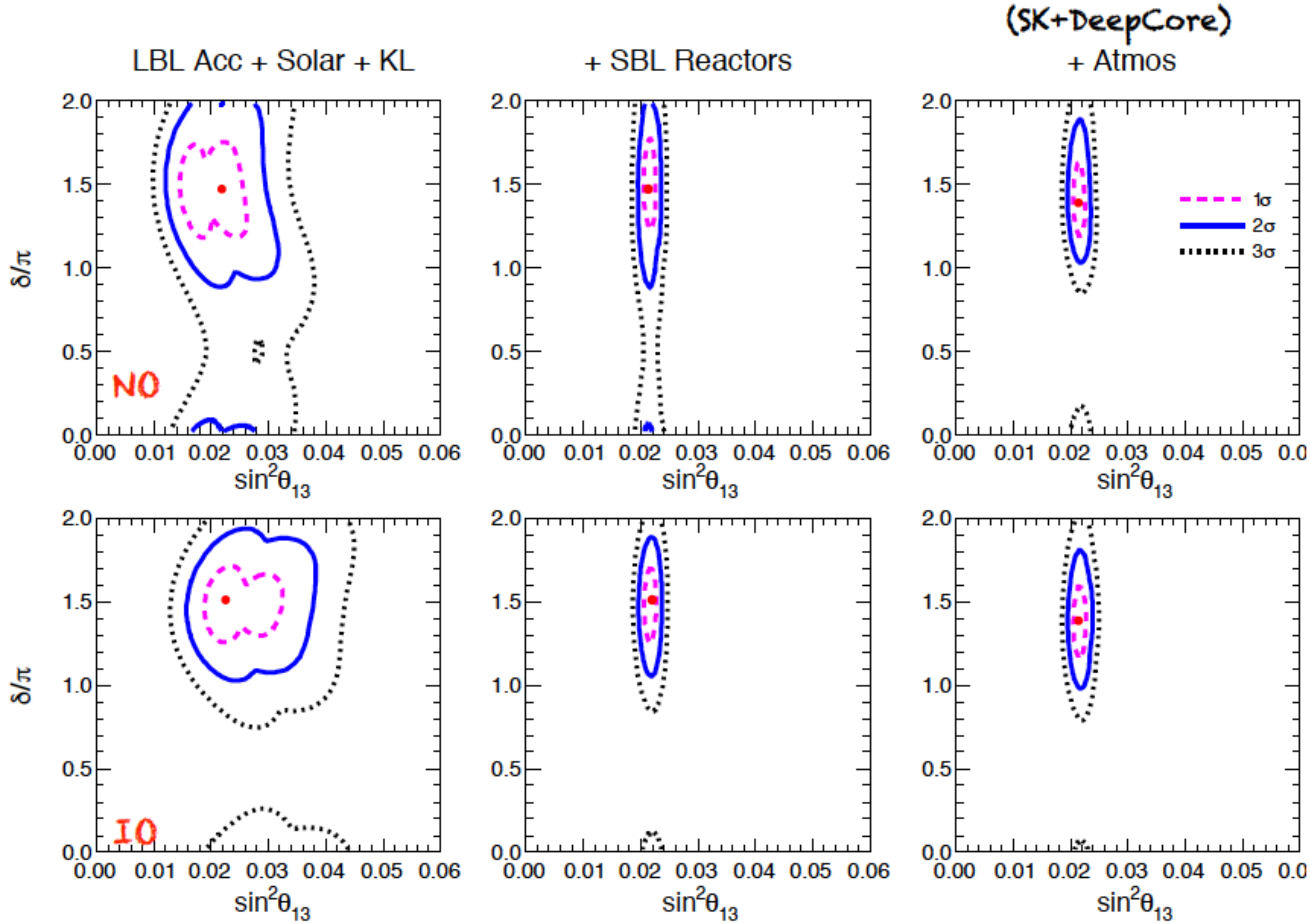
To see matter effects you need a lot of matter

NOvA now!

DUNE soon!



Where are we at in putting the pieces together?
New from Neutrino 2016



The Three Neutrino Matrix elements

Where we are at today…

$$U_{PMNS}^{2013} = \begin{pmatrix} 0.779 \; to \; 0.848 & 0.510 \; to \; 0.604 & 0.122 \; to \; 0.190 \\ 0.183 \; to \; 0.568 & 0.385 \; to \; 0.728 & 0.613 \; to \; 0.794 \\ 0.200 \; to \; 0.576 & 0.408 \; to \; 0.742 & 0.589 \; to \; 0.775 \end{pmatrix}$$

We are far from being able to test for non-unitarity, but that is exactly the kind of new physics we seek!

The Three Neutrino Matrix elements

Where we are at today…

$$U_{PMNS}^{2013} = \begin{pmatrix} 0.779\ to\ 0.848 & 0.510\ to\ 0.604 & 0.122\ to\ 0.190 \\ 0.183\ to\ 0.568 & 0.385\ to\ 0.728 & 0.613\ to\ 0.794 \\ 0.200\ to\ 0.576 & 0.408\ to\ 0.742 & 0.589\ to\ 0.775 \end{pmatrix}$$

More or less where the quark sector was in 1995!

$$U_{CKM}^{1995} = \begin{pmatrix} 0.9745\ to\ 0.9757 & 0.219\ to\ 0.224 & 0.002\ to\ 0.005 \\ 0.218\ to\ 0.224 & 0.9736\ to\ 0.9750 & 0.036\ to\ 0.046 \\ 0.004\ to\ 0.014 & 0.034\ to\ 0.046 & 0.9989\ to\ 0.9993 \end{pmatrix}$$

Looking for a topic that would make a good paper?

The same CP violation parameter should drive:

$P(\nu_\mu \rightarrow \nu_e) \quad \neq \quad P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$P(\nu_\mu \rightarrow \nu_\tau) \quad \neq \quad P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau)$

$P(\nu_\tau \rightarrow \nu_e) \quad \neq \quad P(\bar{\nu}_\tau \rightarrow \bar{\nu}_e)$

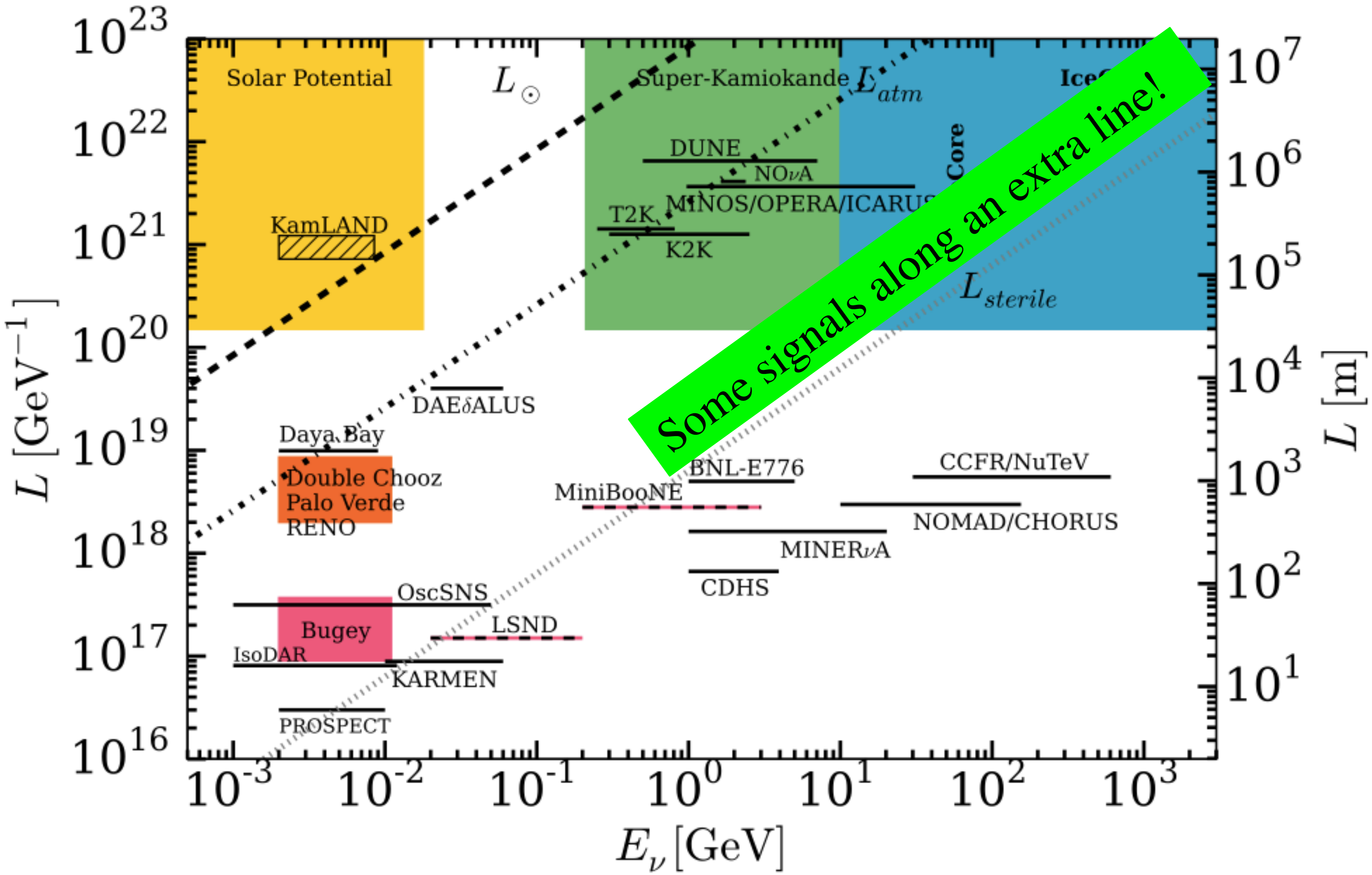
→ Right now we only know how to extract δ from $\nu_\mu \rightarrow \nu_e$

Do you have ideas on how to measure CPV the others?

That would be very interesting!

A place to look: A lot of ν_τ's are produced in the LHC beam dump

Four (or more!) neutrino oscillations?
Puzzle pieces that already don’t fit…



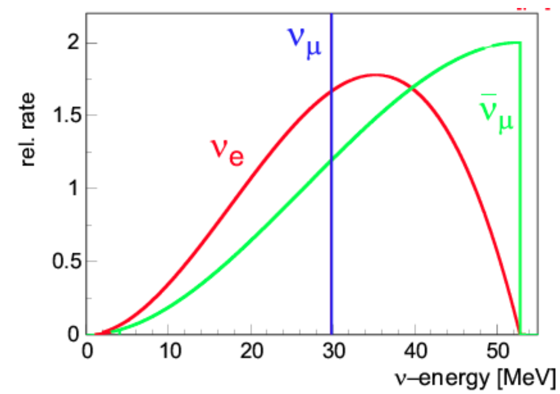
Solar Potential
$L_\odot$
Super-Kamiokande
L_{atm}
IceC
Core
DUNE
NOνA
MINOS/OPERA/ICARUS
T2K
K2K
KamLAND
$L_{sterile}$
Some signals along an extra line!
DAEδALUS
Daya Bay
Double Chooz
Palo Verde
RENO
BNL-E776
CCFR/NuTeV
MiniBooNE
NOMAD/CHORUS
MINERνA
CDHS
OscSNS
LSND
Bugey
IsoDAR
KARMEN
PROSPECT
$L\ [\mathrm{GeV}^{-1}]$
$L\ [\mathrm{m}]$
$E_\nu\ [\mathrm{GeV}]$

LSND Anomaly

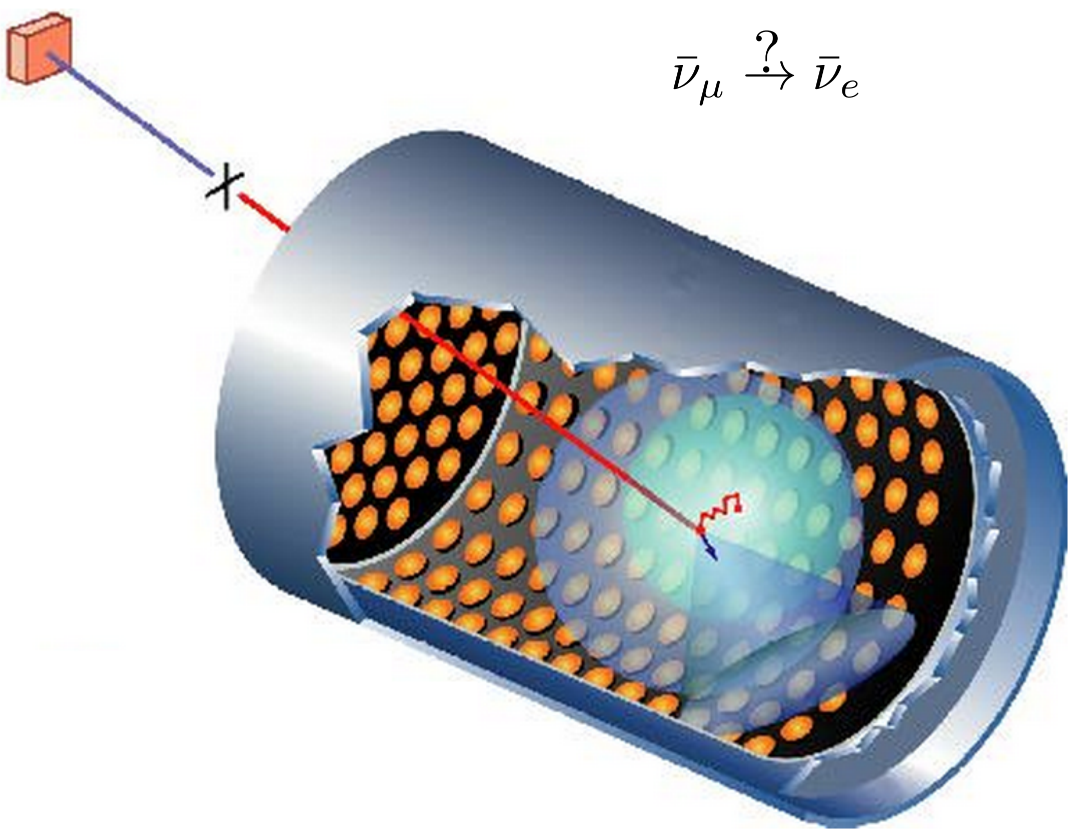
Liquid scintillator detector using stopped pion beam

$$\pi^+ \to \mu^+ + \nu_\mu \ ,$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$



$$\bar{\nu}_\mu \stackrel{?}{\to} \bar{\nu}_e$$



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

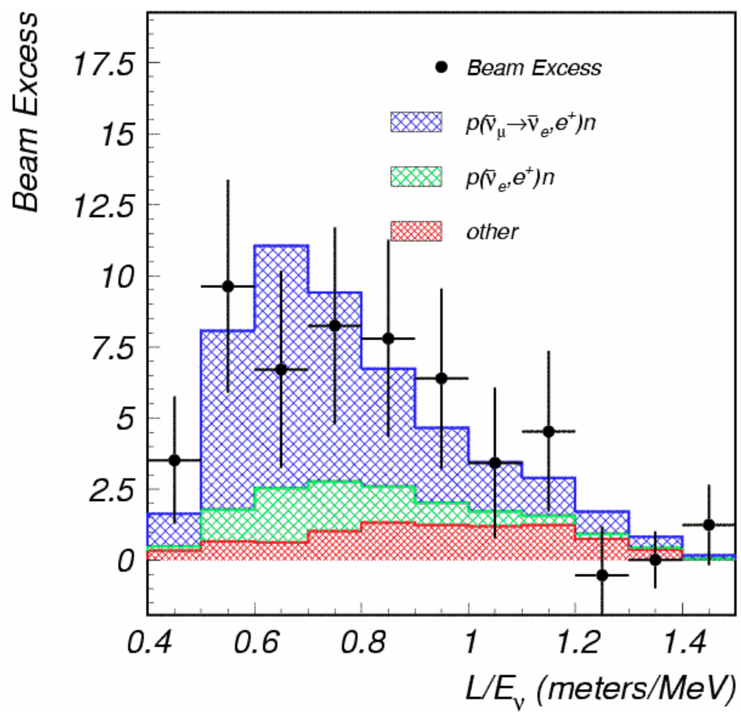
LSND Anomaly

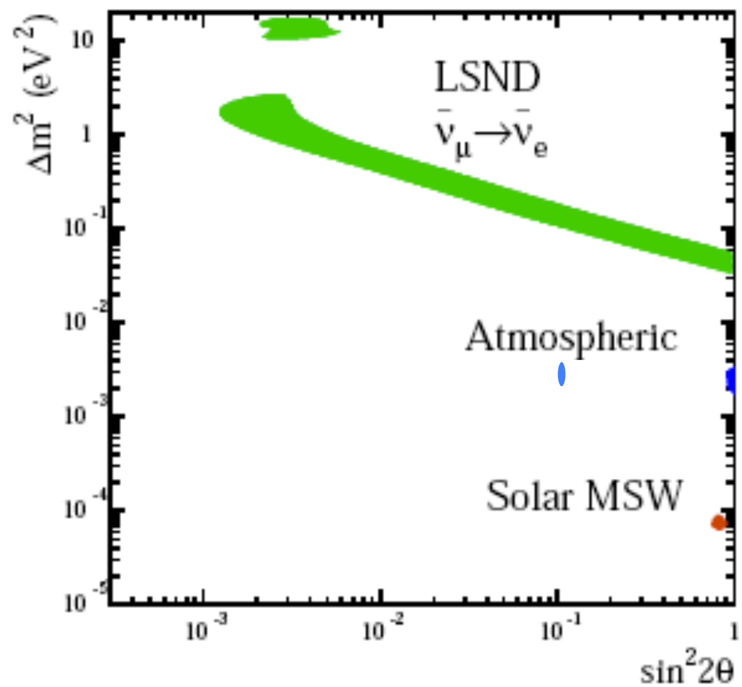
Observed excess of $\bar{\nu}_e$' s, which corresponds to oscillations on the order of

$\Delta m^2 \sim 1\ eV^2$ at (3.8 σ)

– Not consistent with "solar" and "atmospheric" mass splittings!

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

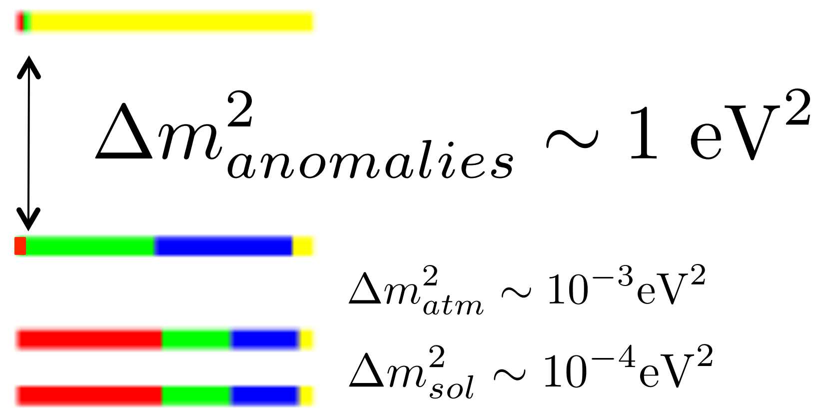




Wait, didn't you say sterile?

How can a sterile neutrino produce an appearance signal?

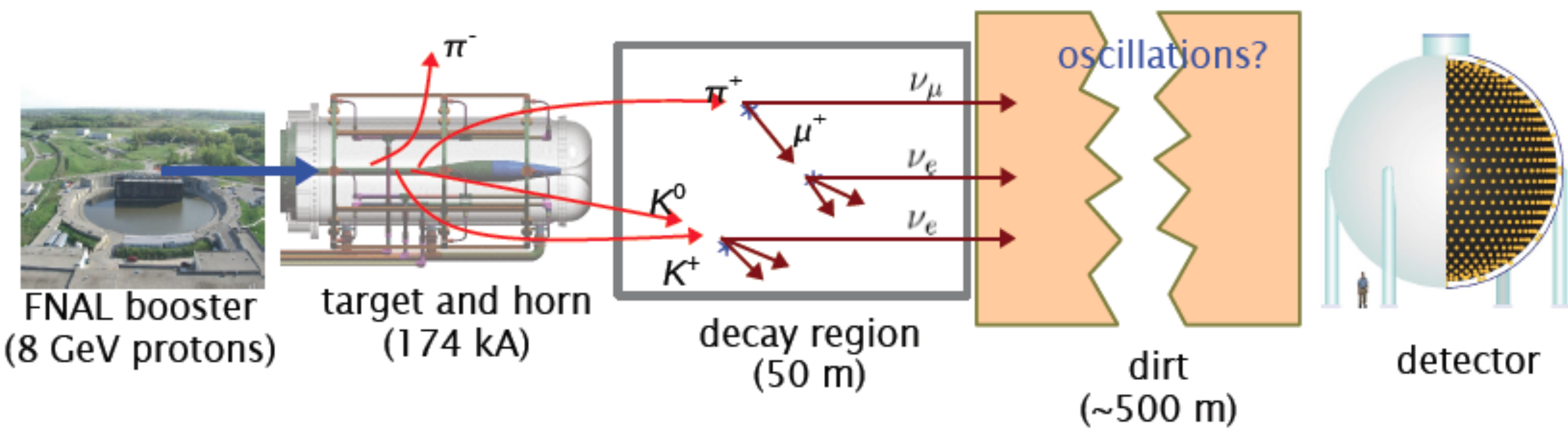
Remember, no mass state is 100% sterile



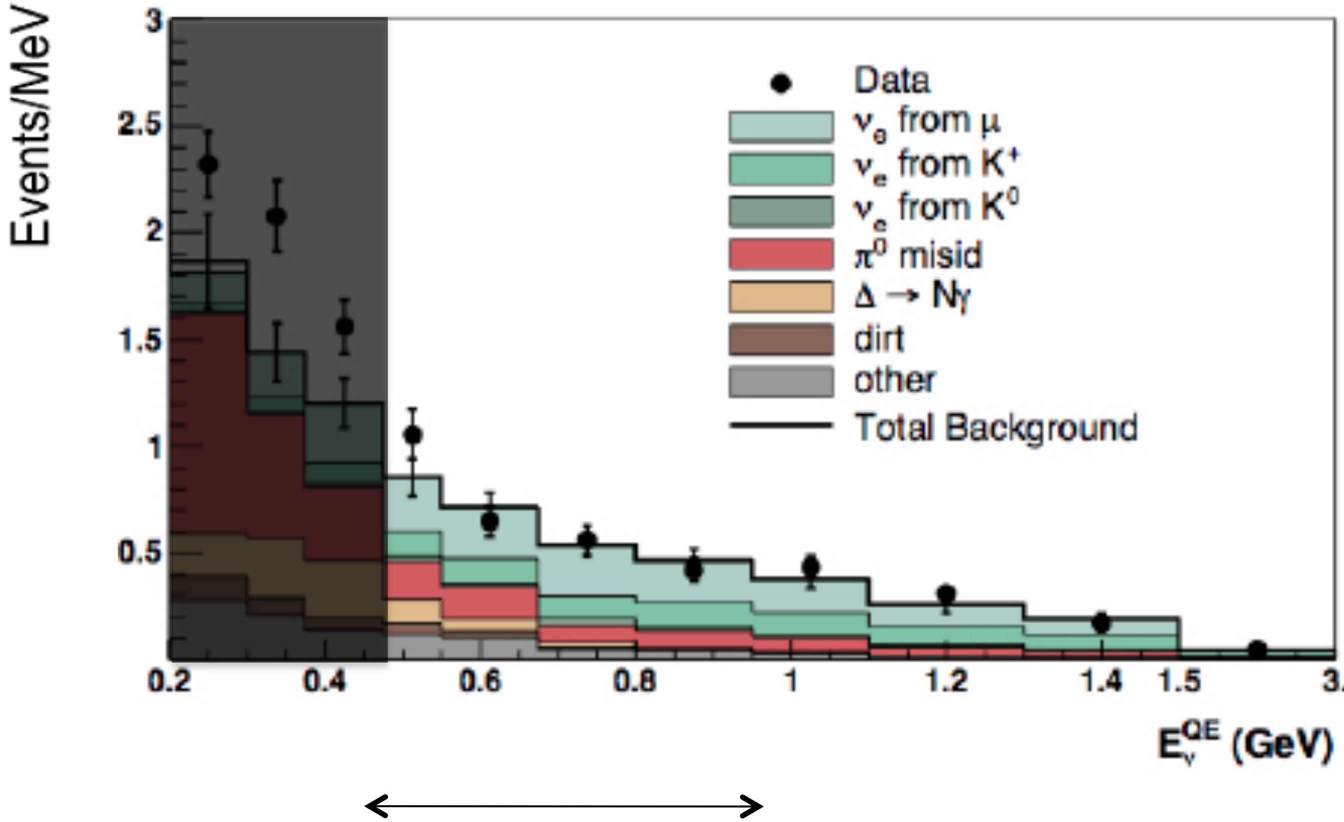
There can be a transition from muon (green) to electron (red) with a large Δm^2

MiniBooNE

- Designed to explore LSND anomaly (maintains same L/E Ratio)
  - Different detector design and systematics
  - Can run in neutrino or antineutrino mode by choosing positive or negative mesons with a focusing horn
  - Start in neutrino mode … get more events faster!

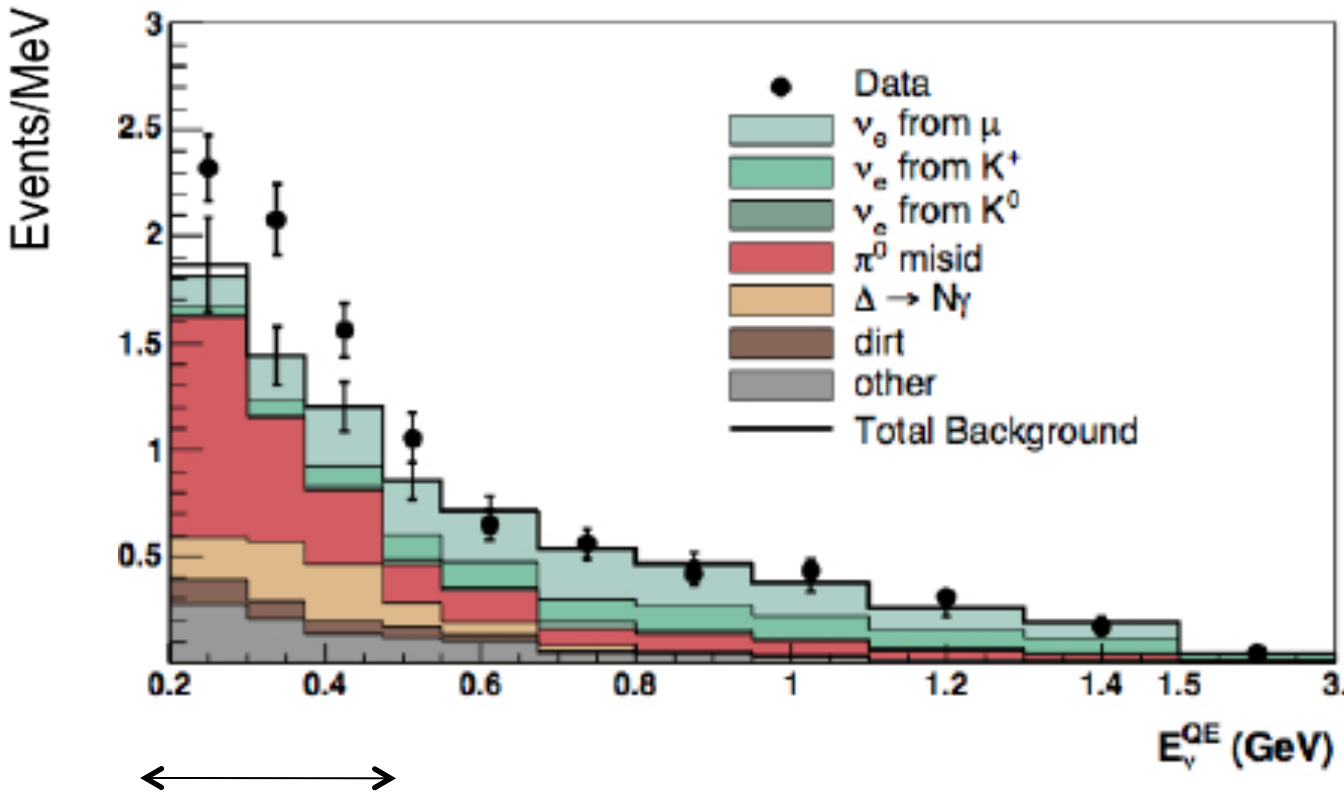


MiniBooNE $\nu_\mu \rightarrow \nu_e$



Signal region predicted
based on LSND signal

MiniBooNE $\nu_\mu \to \nu_e$

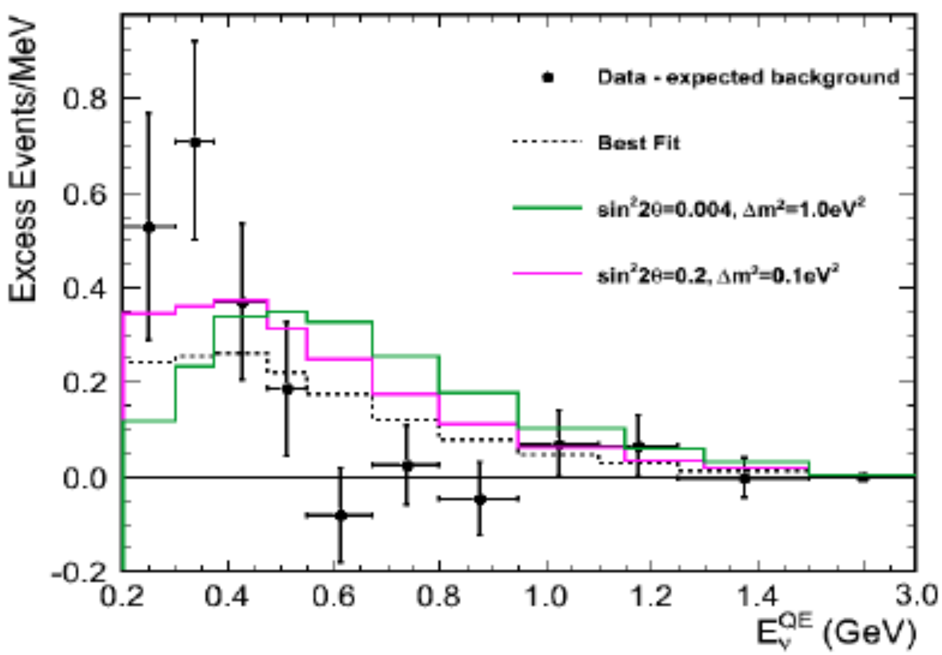


Signal, but not where it is
"supposed to be" !!!

“MiniBooNE low energy excess”

- Still unexplained
- Not a statistical fluctuation (6σ)
- Unlikely intrinsic ν_e (this background is low)
- Mis-identification backgrounds are well-constrained.

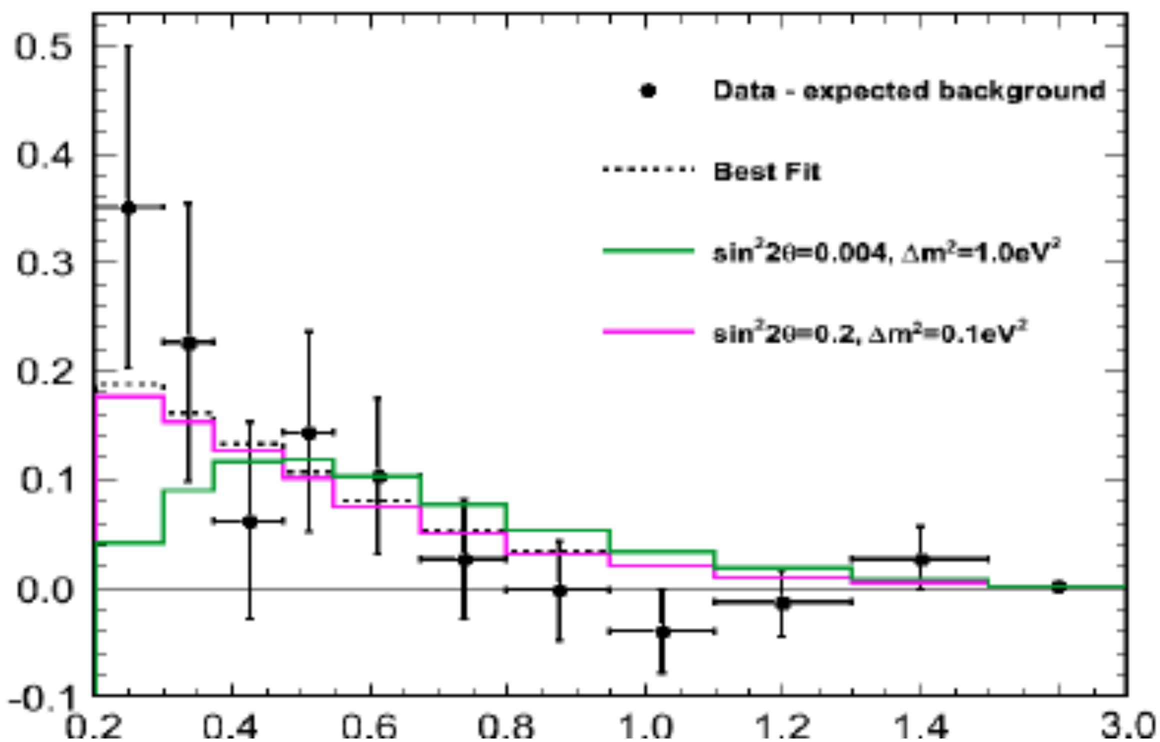
Data−Predicted background



Doesn’t fit a “3+1” predictions from LSND

But remember: The LSND signal was seen in antineutrinos!

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

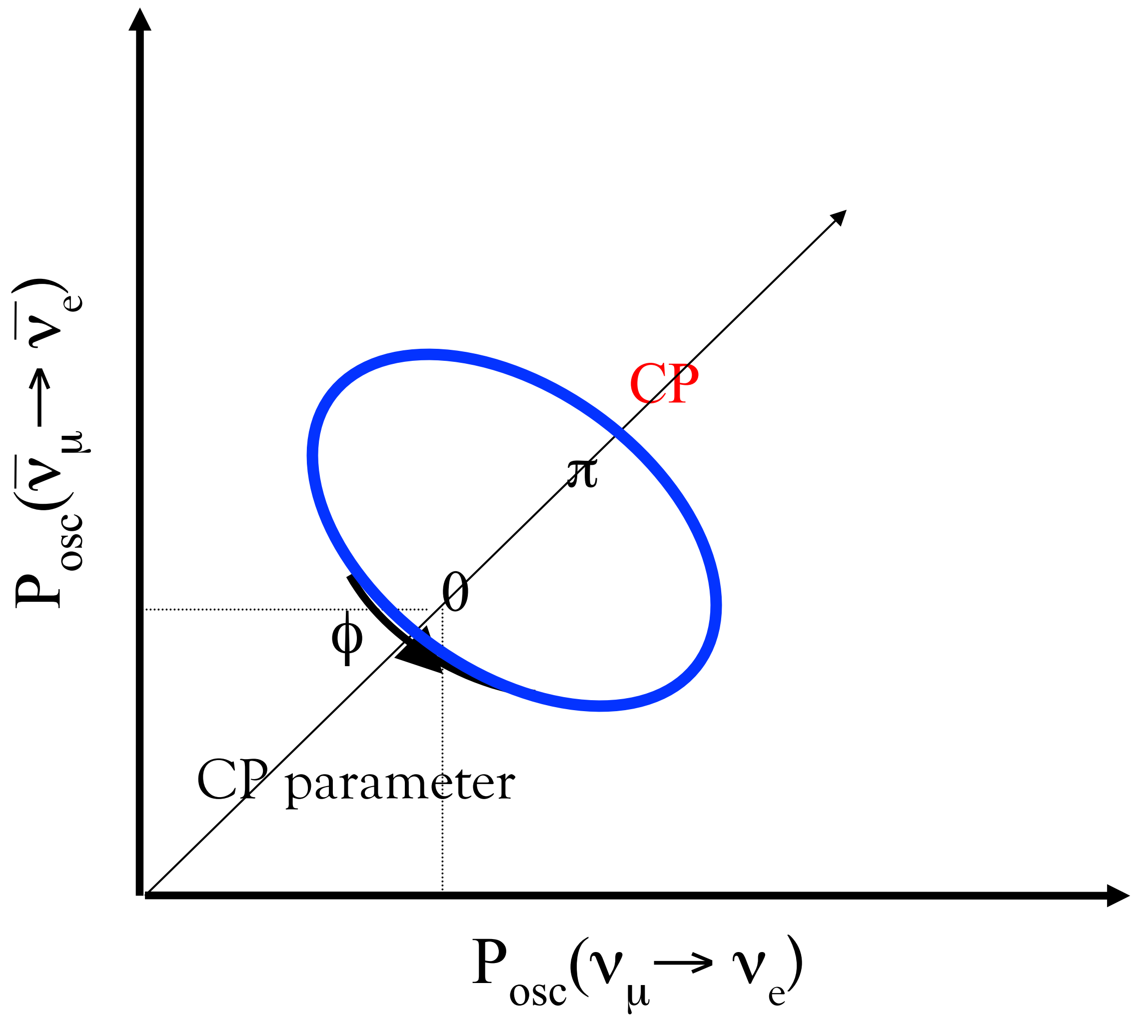


There is a signal, and it does fit the LSND prediction…

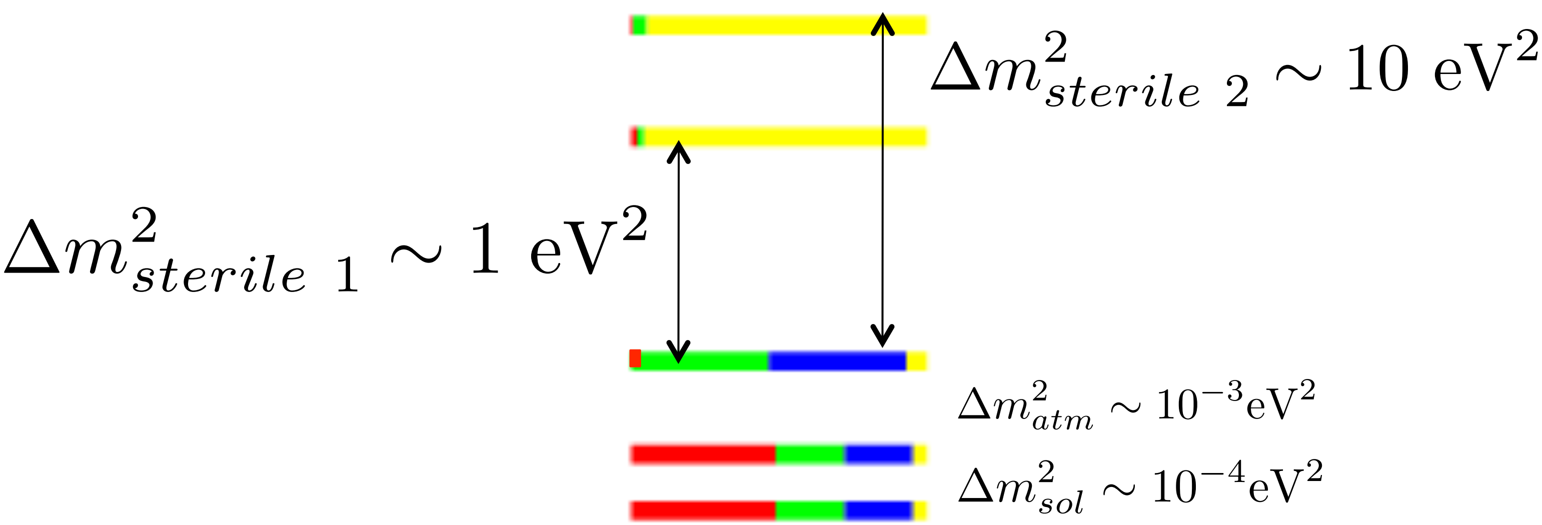
Apparently we need...

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

We can get that effect by introducing more CP violation



CP violation is an interference effect, and will only appear if we have at least two sterile neutrinos, fairly close in mass.

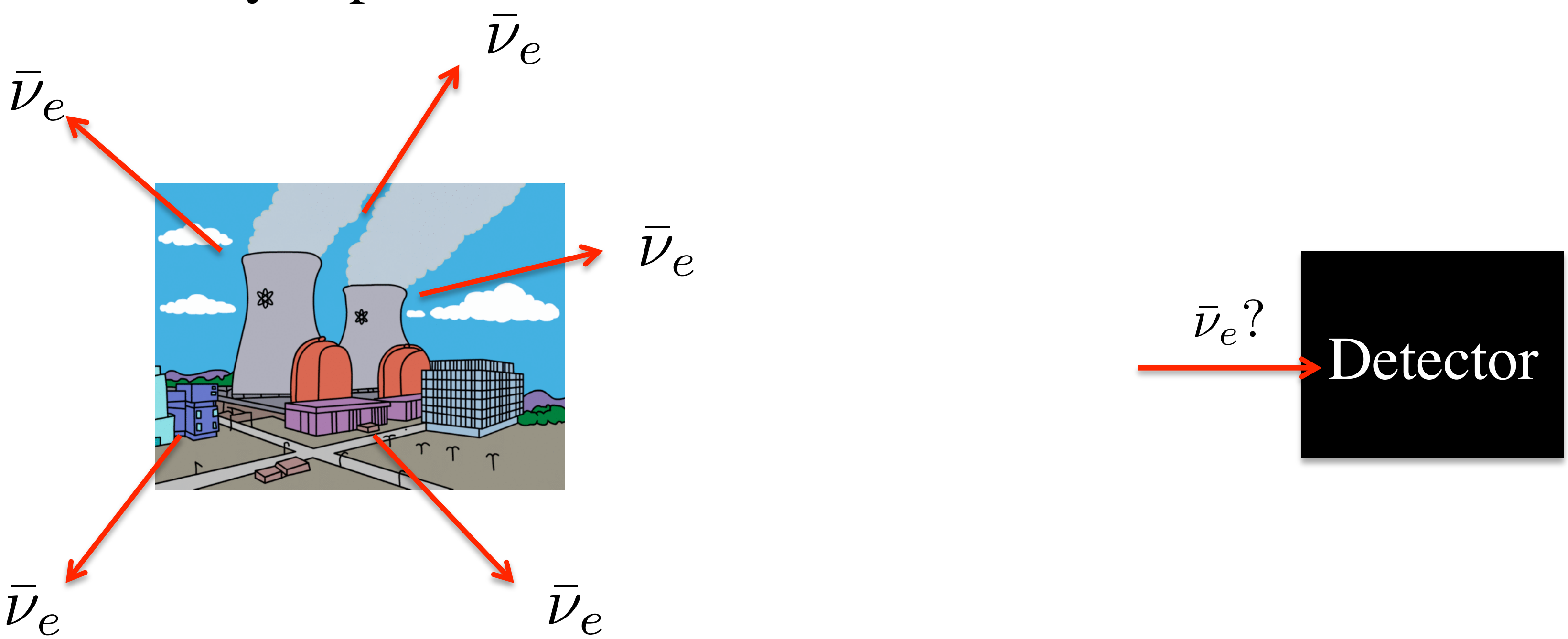


“3+2 Model”

What about the transitions to the sterile "flavor" (disappearance)?

Reactor Anomaly

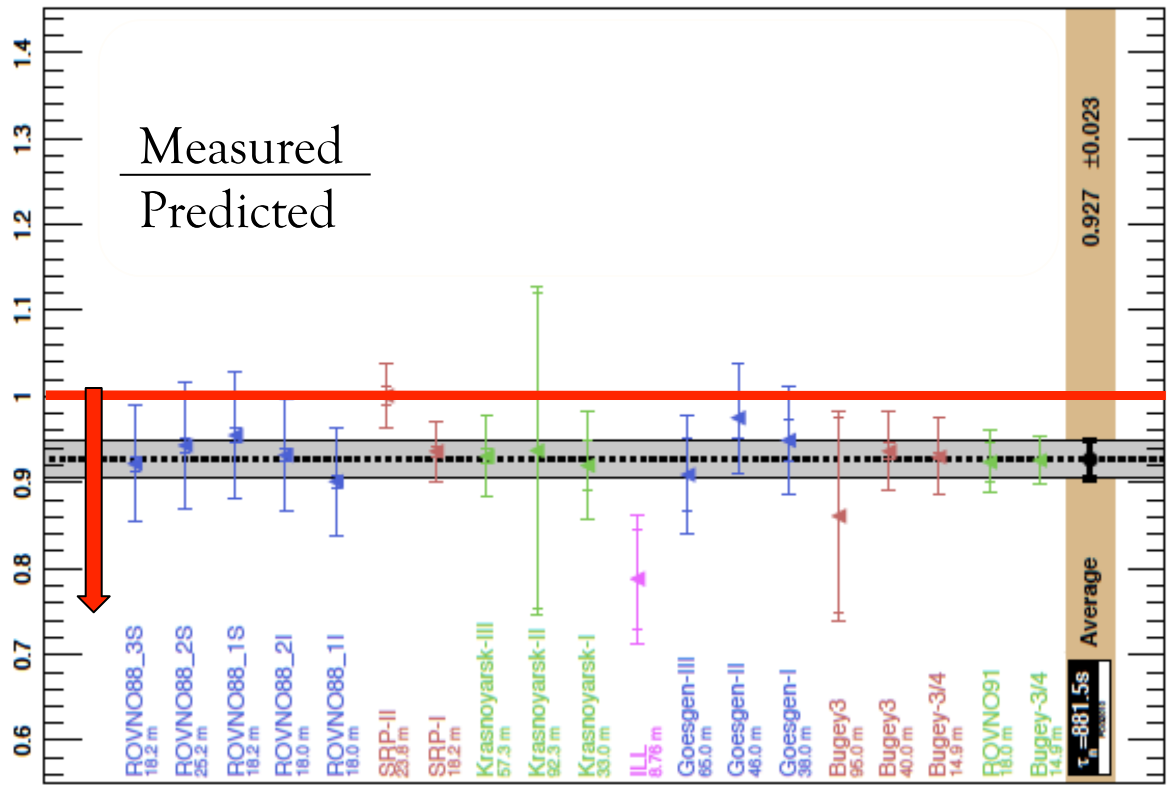
- Many experiments have studied neutrinos from reactors



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{ee} \sin^2(1.27\Delta m^2 \frac{L}{E})$$

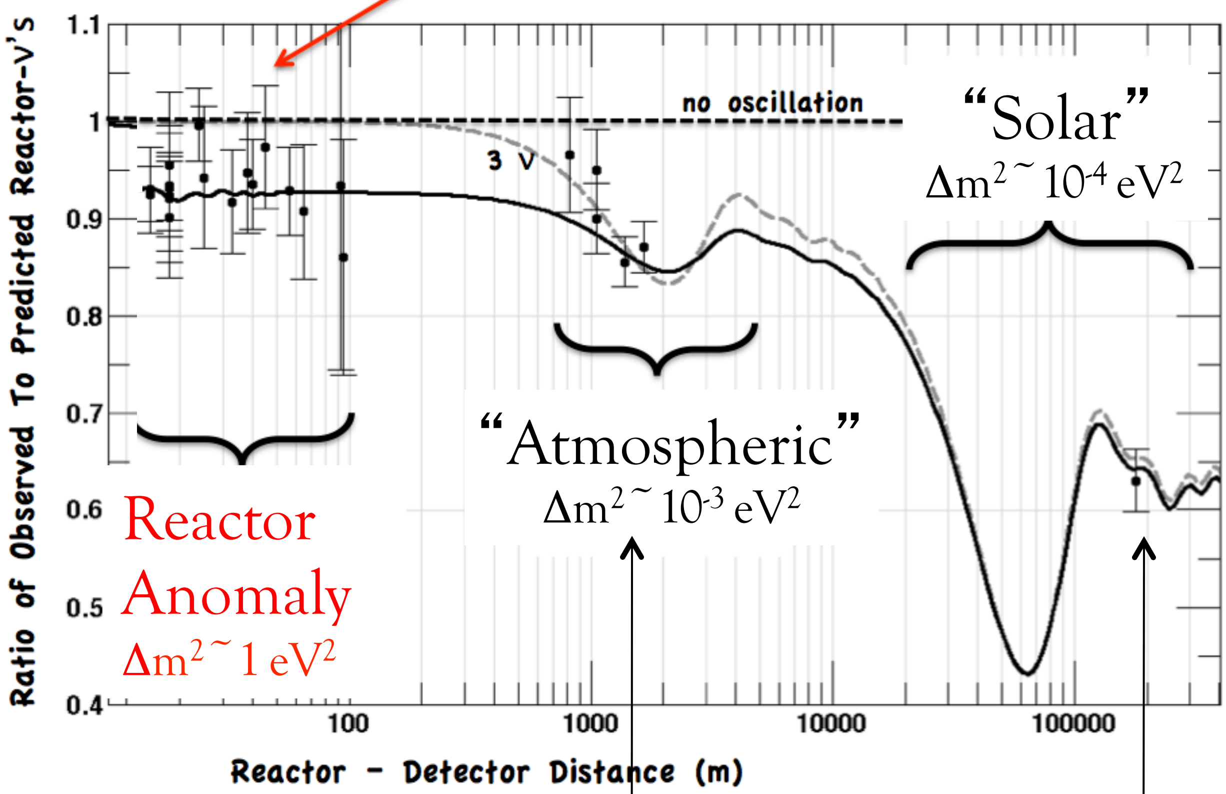
This L/E → "short baseline" reactor experiments (10s of meters)
We used to think these experiments showed no oscillation…

Then, in 2010, the predicted neutrinos/fission was updated
to reflect modern data…
and all of the points moved down!



$\bar{\nu}_e$ disappearance at reactors

- Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)



Daya Bay, et al

KamLAND

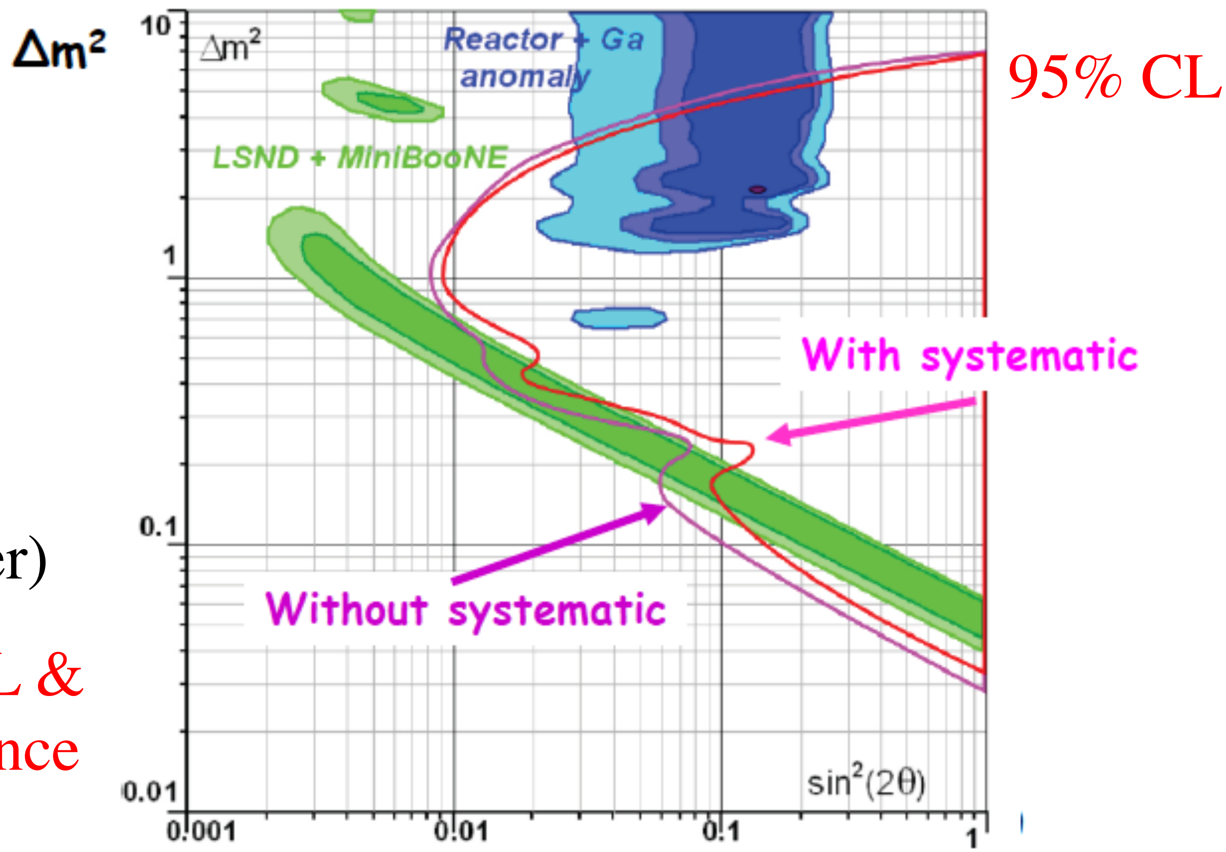
BUT REMEMBER!
THERE IS A STRANGE
FLUX BUMP! TAKE CARE!

New from Neutrino 2016 – the DANSS Experiment results are coming very soon!

Systematic effects estimated by changing E scale by 1% and by adding 1% Background (~E^{-2}) at one distance from the core

1 year of running (started April 2016, so available next summer)

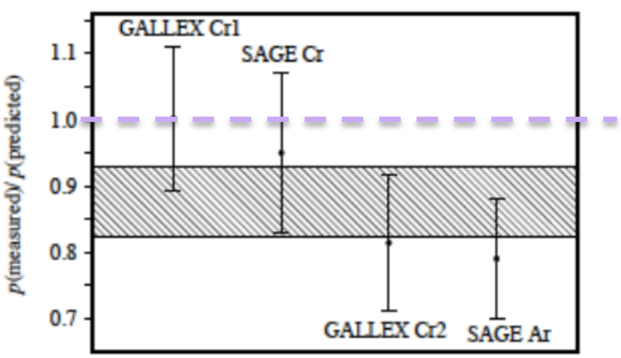
This is an L & E-dependence analysis, not just rate.

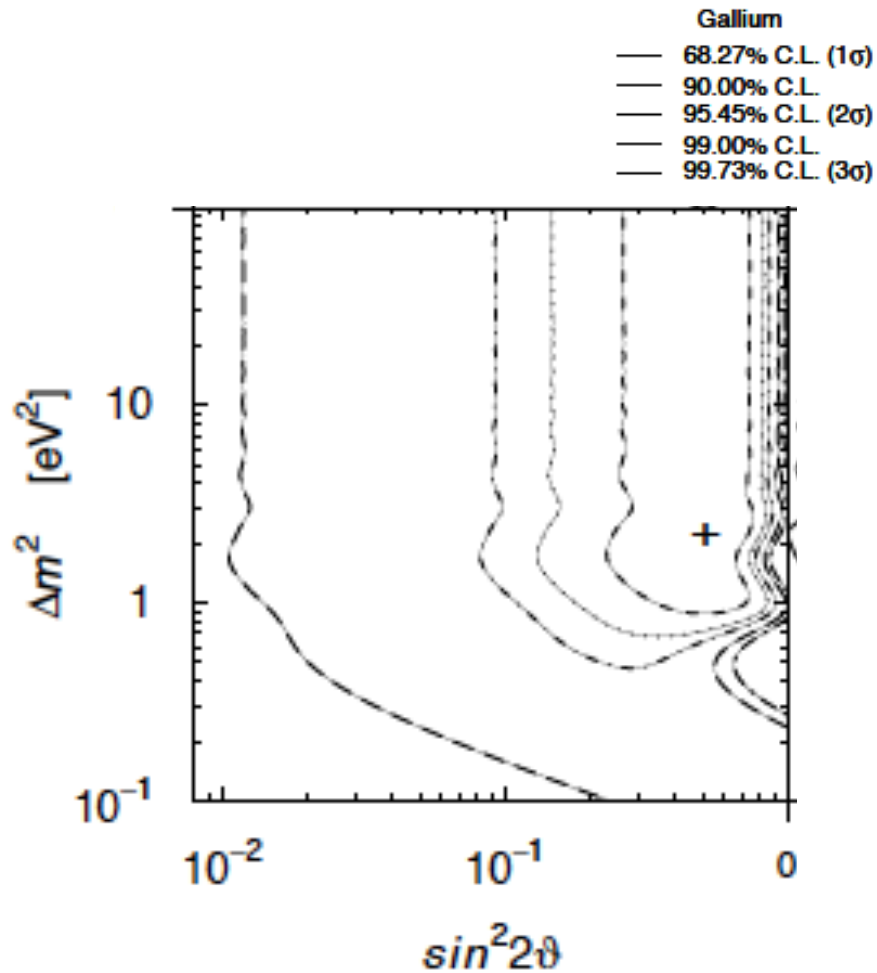


Radioactive Sources

- Cr-51 and Ar-37 sources were used to calibrate the GALLEX and SAGE solar neutrino experiments
- Very short baseline (meter scale) so sensitive to ~1 eV^2 neutrino oscillation

$\nu_e \not\rightarrow \nu_e$

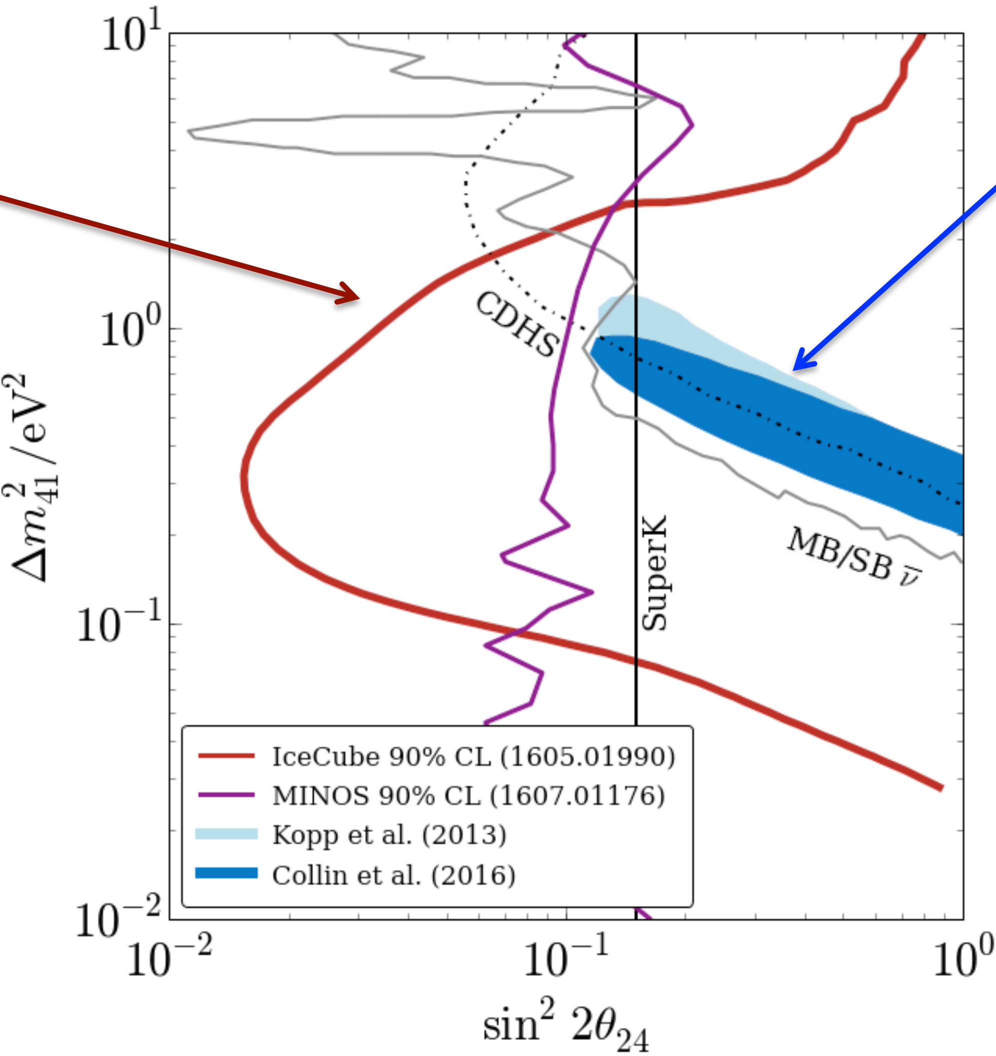




arXiv:1006.3244

Also from Neutrino 2016: New IceCube Results

90% CL Icecube

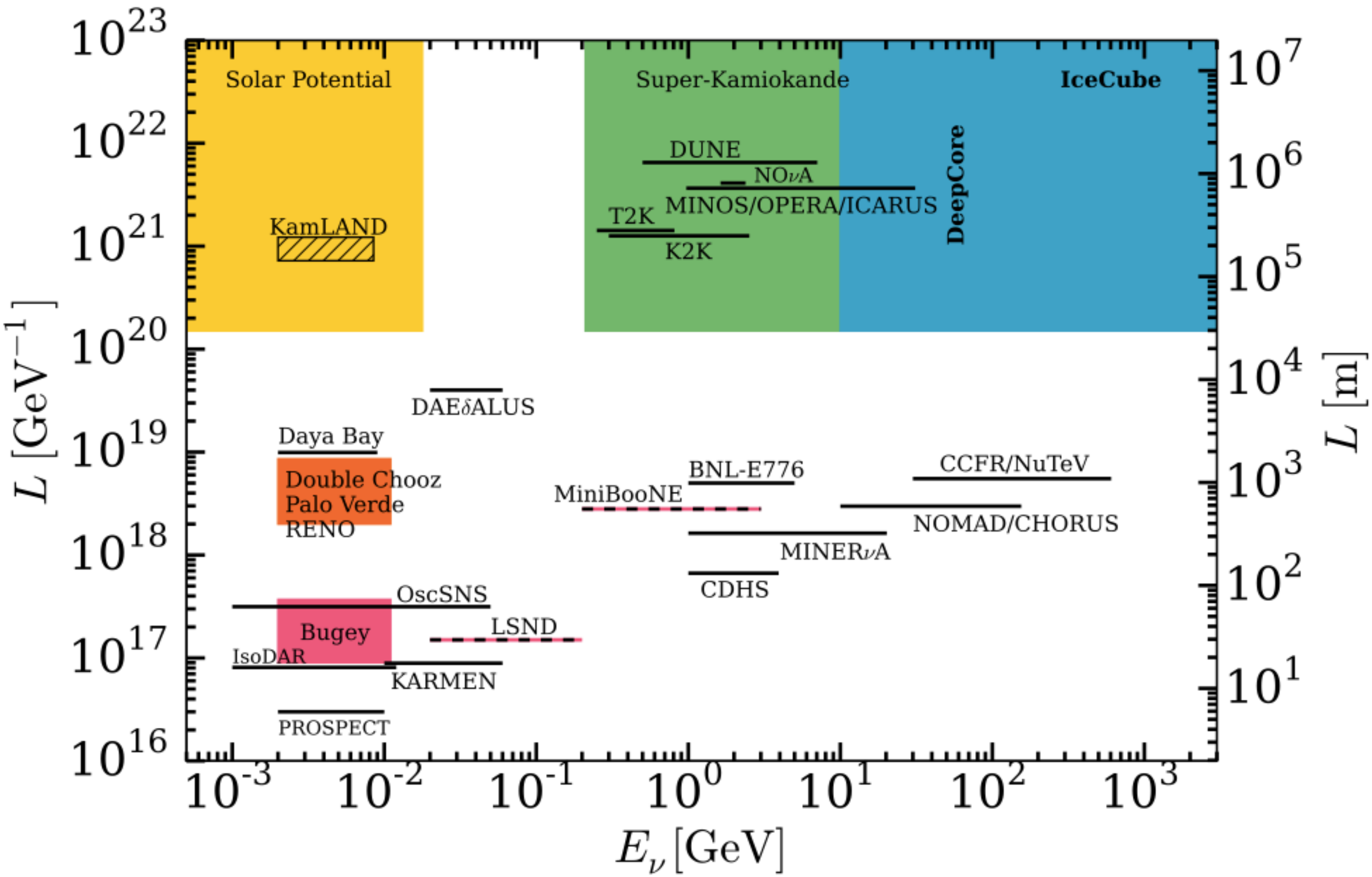


Allowed region for all appearance experiments (mu-flavor to e-flavor) in a 3+1 model

How can we make a model with appearance and ν_e disappearance but without ν_μ disappearance?

Looking for a topic that would make a good paper?

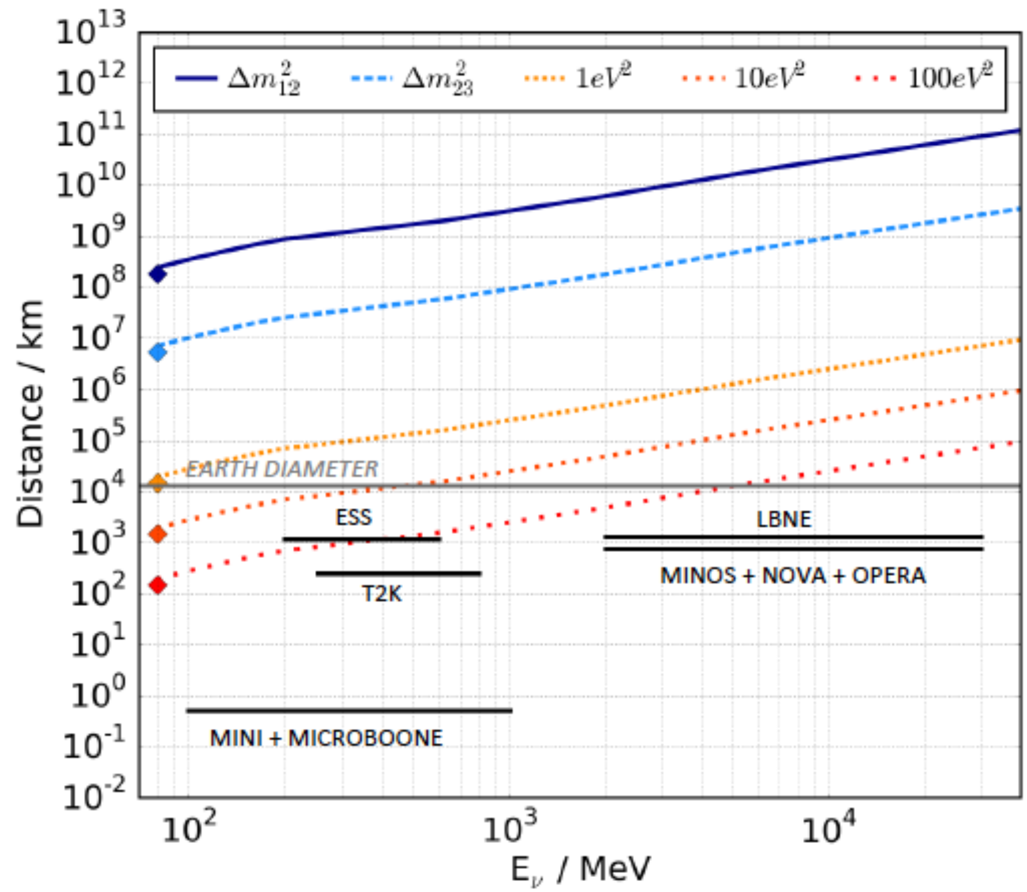
Can you motivate other trajectories?



Ideas people have looked at:
Neutrino Decay, Lorentz Violation, NonStandard Interactions, Neutrino Decoherence…

… that last one doesn't work as an explanation!

But it might be interesting physics for a proposed experiment in Sweden, called ESS



arXiv.org > hep-ph > arXiv:1412.2264

High Energy Physics – Phenomenology

Dynamical Pion Collapse and the Coherence of Conventional Neutrino Beams

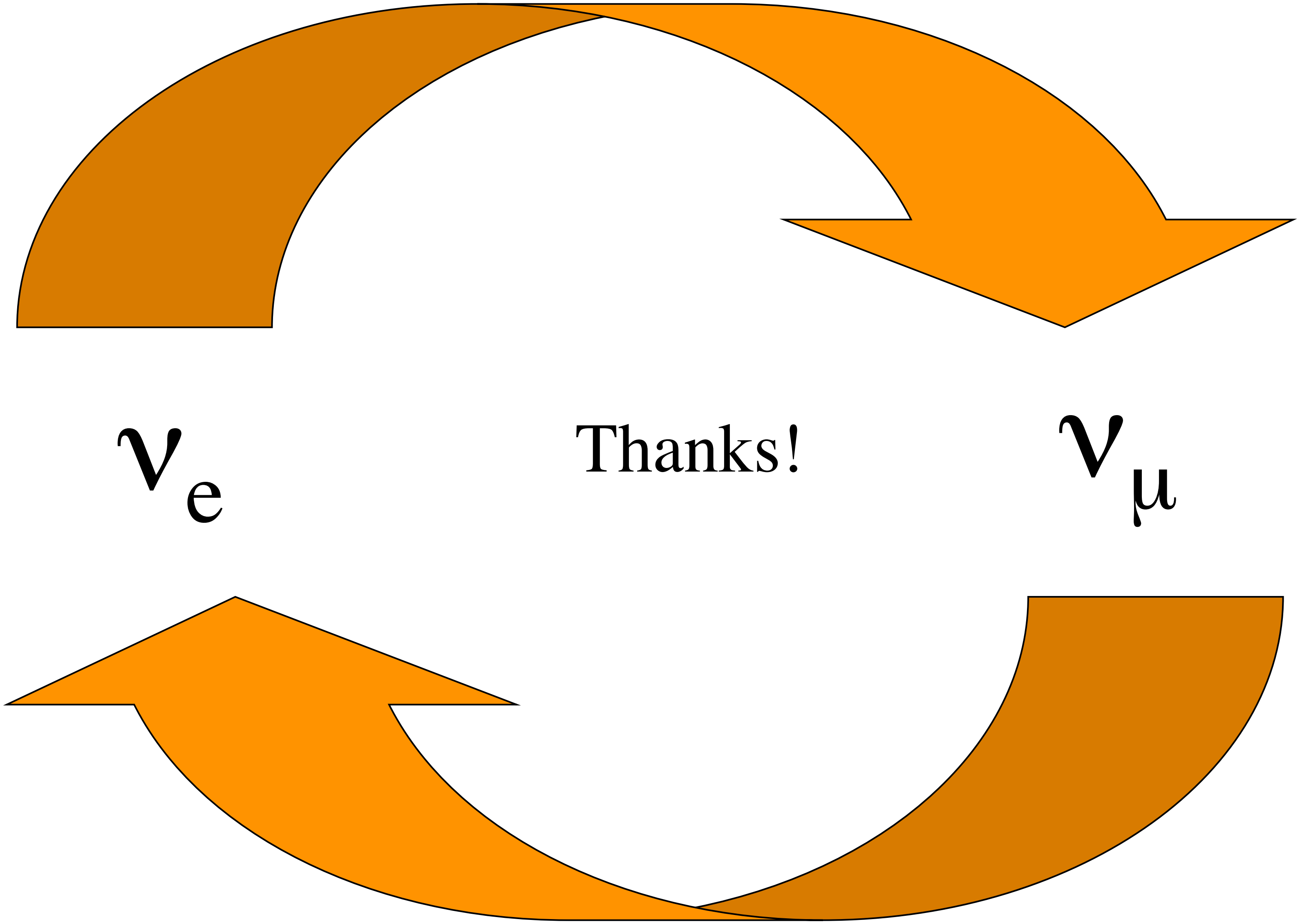
B.J.P. Jones   Phys. Rev. D 91, 053002 (2015)

A last thought

There are more examples!

Neutrino physics offers a lot of questions and a lot of opportunities.

Pursue your ideas!!! 


ν_e
Thanks!
ν_μ