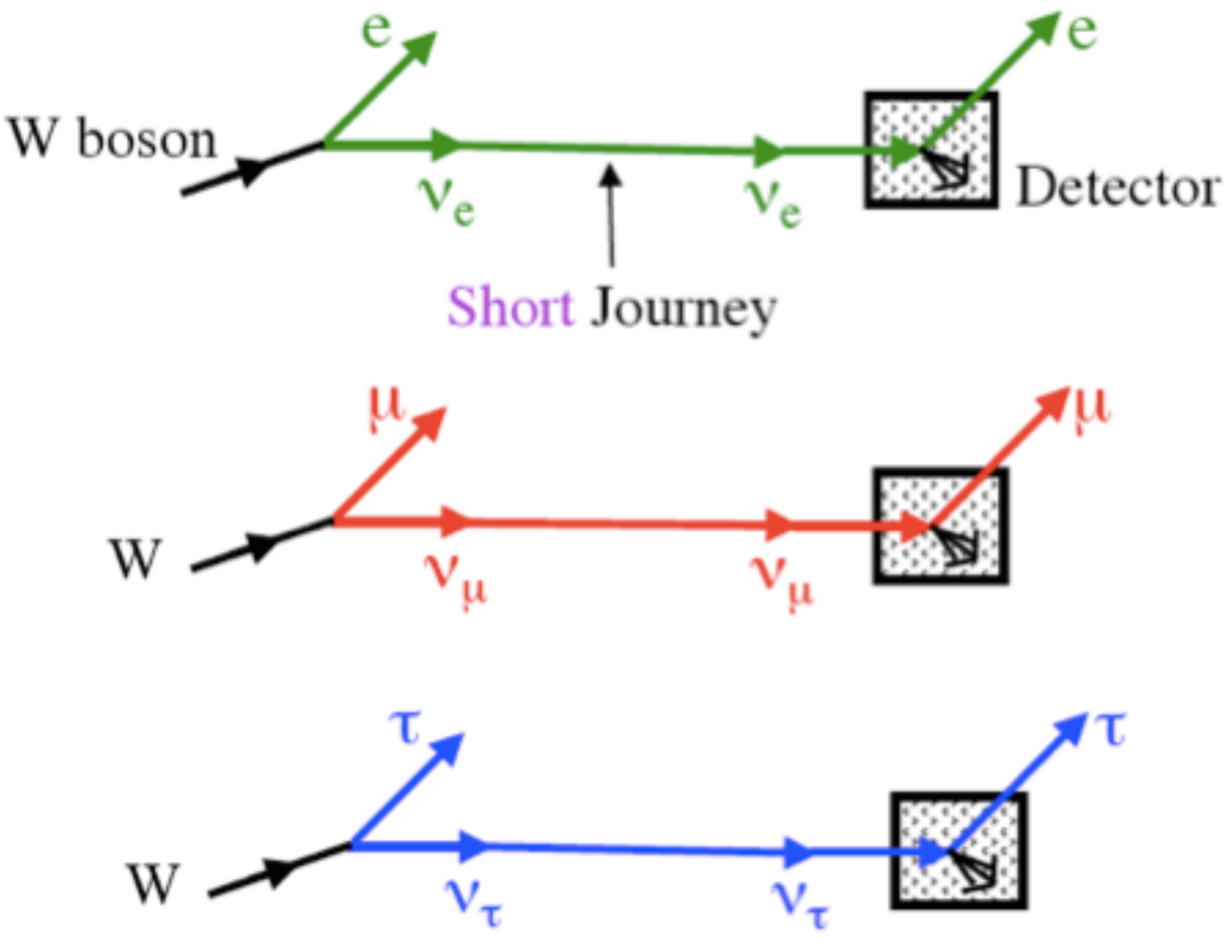
Sterile neutrino search

20151101
Koun Choi

What we Knew of Neutrinos: End of the 20th Century

↓3 generations of active neutrino - confirmed by Z decay, LEP



- come in three flavors (see figure);
- interact only via weak interactions ($W^{\pm}, Z^0$);
- have ZERO mass – helicity good quantum number;
- ν_L field describes 2 degrees of freedom:
  - left-handed state ν,
  - right-handed state $\bar{\nu}$ (CPT conjugate);
- neutrinos carry lepton number:
  - $L(\nu) = +1$,
  - $L(\bar{\nu}) = -1$.

Massless neutrinos

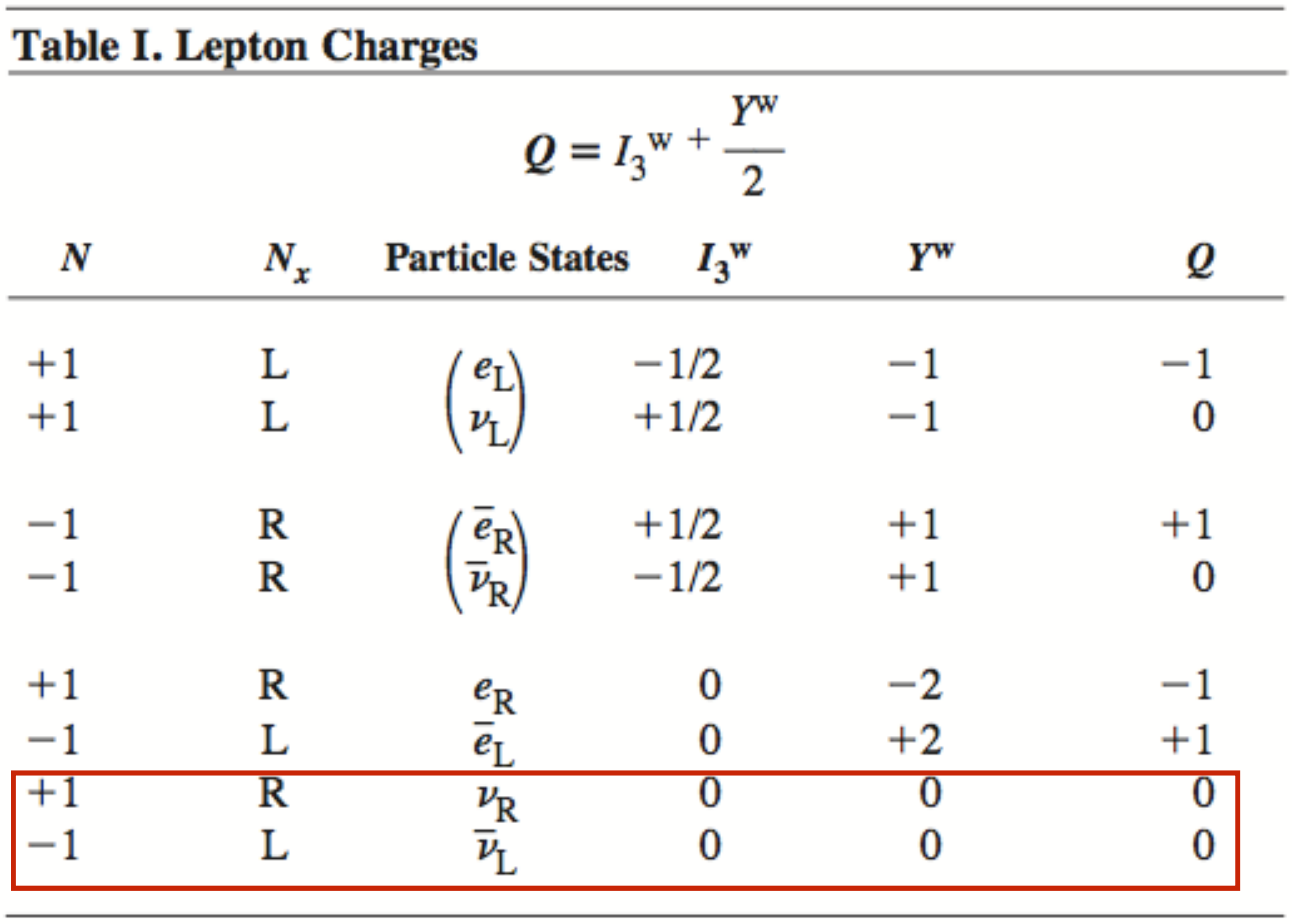


Table I. Lepton Charges

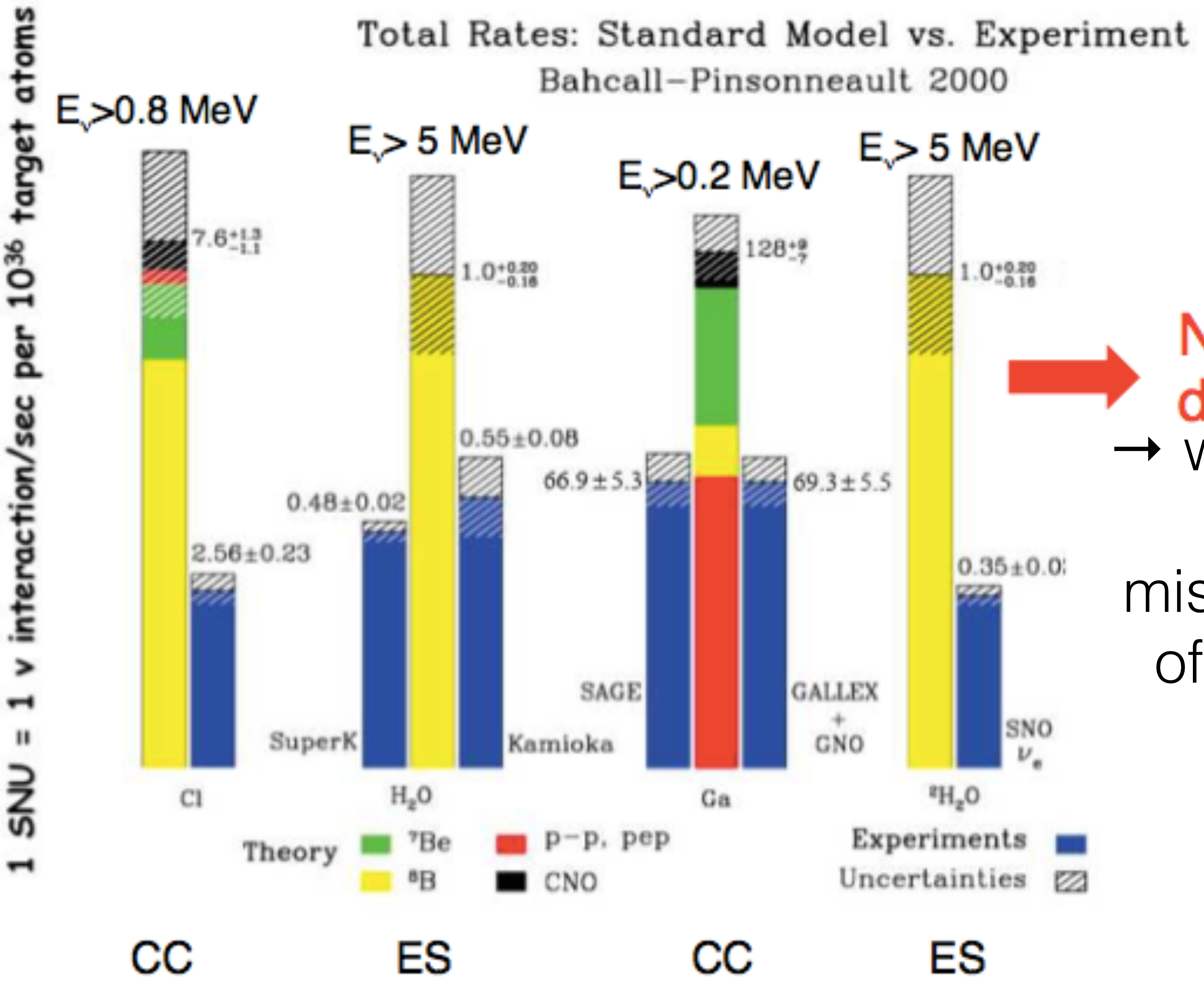
$$Q = I_3^{w} + \frac{Y^{w}}{2}$$

N	N_x	Particle States	I_3^{w}	Y^{w}	Q
+1	L	e_L	−1/2	−1	−1
+1	L	ν_L	+1/2	−1	0
−1	R	$\bar{e}_R$	+1/2	+1	+1
−1	R	$\bar{\nu}_R$	−1/2	+1	0
+1	R	e_R	0	−2	−1
−1	L	$\bar{e}_L$	0	+2	+1
+1	R	ν_R	0	0	0
−1	L	$\bar{\nu}_L$	0	0	0

- Only left-handed (LH) neutrino has been observed
- SM neutrinos are massless (no higgs coupling)
- Right-handed (RH) neutrinos are Isospin singlet, with Q=0 -> Y=0.

  -> there was no motivation to include RH neutrinos from the particle budget until …

First ‘anomaly’ observed: **solar neutrino problem**



Neutrino disappearance

→ was regarded to be due to misunderstanding of solar physics or…

Neutrino oscillation

For massive neutrinos, one can introduce in analogy to the quark mixing a mixing matrix describing the relation between mass and flavor states:

Indication of oscillation → indication of mass

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

Pontecorvo-Maki-Nakagawa-Sakata matrix

vα = Uαi vi

vi = Uiα vα = U*αi vα

Massive neutrinos develop differently in time.

$$|\nu_i(t)\rangle = |\nu_i(0)\rangle e^{-iE_i t} = |\nu_i(0)\rangle e^{-i\left(p_i + \frac{m_i^2}{2p_i}\right)}$$

for masses $m_i << E_i$:

$$E_i = \sqrt{p^2 + m_i^2} = p_i + \frac{m_i^2}{2p_i}$$

→ there will be a mixing of the flavor states with time.

$$|\nu(t)\rangle_\alpha = \sum_i U_{\alpha i} e^{-iE_i t} |\nu_i(0)\rangle = \sum_{i,\beta} U_{\alpha i} U^*_{\beta i} e^{-iE_i t} |\nu_\beta\rangle$$

Two flavor oscillations (in vacuum) : simplicity applicable when one of the mixing dominates

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Time development for an initially pure $|\nu_\alpha>$ beam:

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

$$= \left[\cos^2\theta\, e^{-iE_1 t} + \sin^2\theta\, e^{-iE_2 t}\right]\cdot|\nu_\alpha\rangle$$

$$+ \left[\cos\theta\sin\theta\left(e^{-iE_1 t} - e^{-iE_2 t}\right)\right]\cdot|\nu_\beta\rangle$$

Definite momentum p; same for all mass eigenstate components

$$E_i = \sqrt{p^2 + m_i^2} = p + \frac{m_i^2}{2\mathrm{p}}$$

$$E_2 - E_1 = \frac{m_1^2 - m_2^2}{2\mathrm{p}} \approx \frac{\Delta m^2}{2E} \qquad \Delta m^2 \equiv \Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

(assuming p_i is the same)

$t = \mathrm{L}/\beta$ w/ $\beta \approx 1$:

$$(E_2 - E_1)\, t = \frac{\Delta m^2}{2E} L$$

Mixing probability:

$$P(\nu_\alpha \to \nu_\beta, t) = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2 = 2(\cos\theta\sin\theta)^2\left[1 - \cos^2\frac{E_2 - E_1}{2} t\right]$$

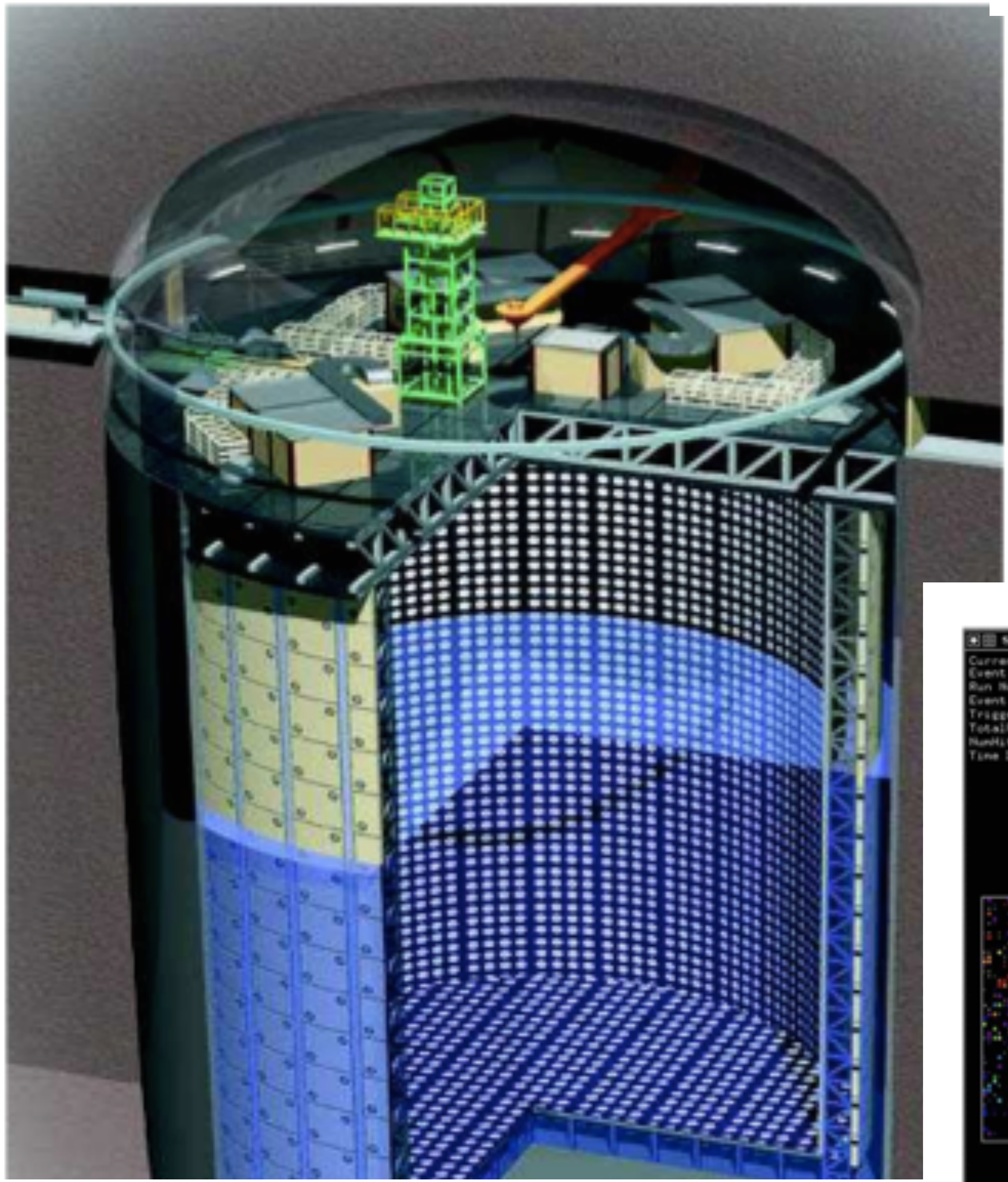
$$\boxed{P(\nu_\alpha \to \nu_\beta, t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)} = \sin^2 2\theta \sin^2\left(\frac{1.27 \cdot \Delta m^2[eV]}{4E[GeV]} L[km]\right)$$

θ_{12} ← solar neutrinos,
θ_{23} ← atmospheric neutrinos,
θ_{13} ← reactor neutrinos

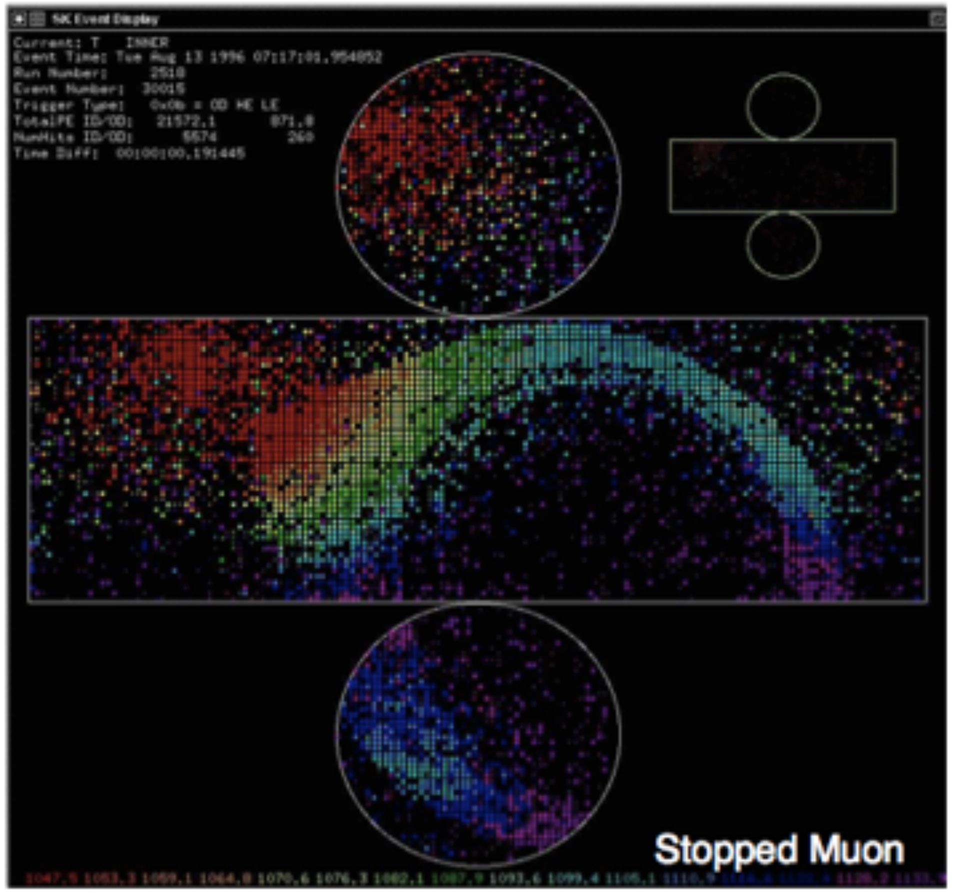
Super-Kamiokande

(means large as well as with outstanding photo coverage)

- Largest artificial water detector (50 kt), 41 m height and 39 m diameter
- Until the 2001 accident:
  11000 PMTs (50 cm tubes!): 40% of surface covered with photo-cathode
- Cherenkov radiation (directionality, energy and particle ID)



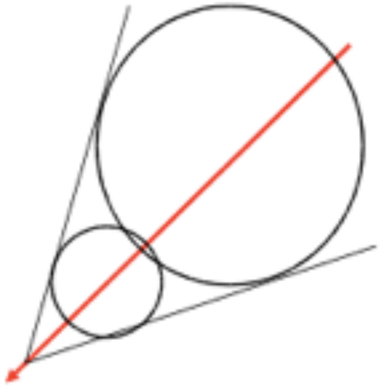
<water cherenkov detectors>
IMB, Kamiokande -> SuperKamiokande
SNO : with heavy water
ANTARES->KM3NeT : with salty water
BAIKAL : in the Baikal lake
AMANDA -> IceCube : with ice



```
Current: T   INNER
Event Time: Tue Aug 13 1996 07:17:01.954052
Run Number:      2510
Event Number:  30015
Trigger Type:   0x0b = OD HE LE
TotalPE ID/OD:   21572.1       871.0
NumHits ID/OD:      5574         260
Time Diff:  00:00:00.191445
```

Stopped Muon

Electrons suffer multiple interactions – fuzzy ring.
Muons fly straight through – sharp edge ring.



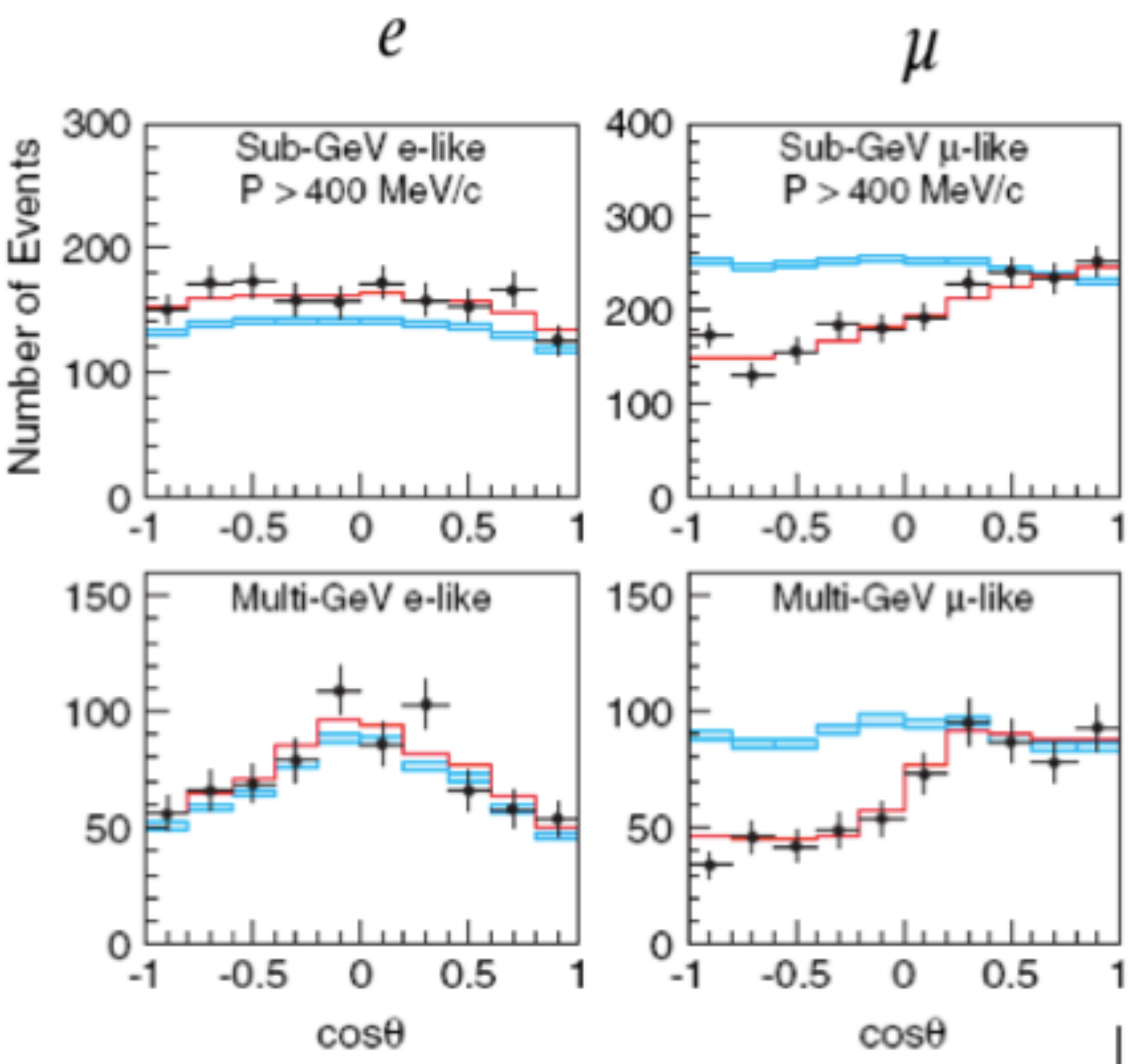
Cherenkov cone:

$$\cos\theta = \frac{1}{\beta n}$$

$$\Leftrightarrow \theta = 42^{o}\,(\beta = 1)$$

Experiment can distinguish electron and muon events, and can measure energy

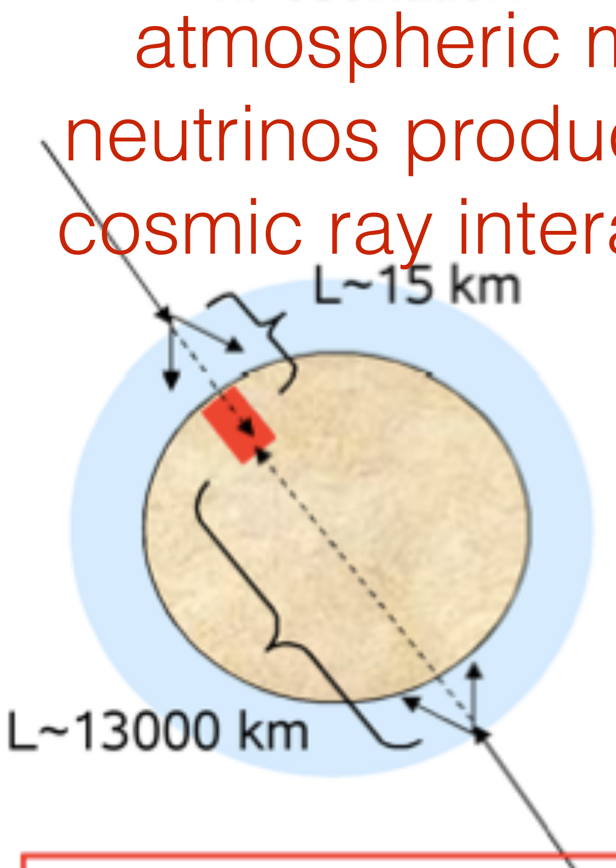
Zenith angle dependence of the neutrino flux



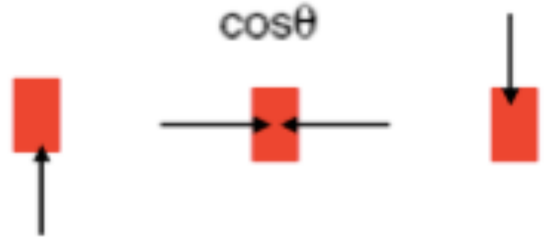
Theoretical predicton

🟦 w/o oscillation

🟥 w/ oscillation



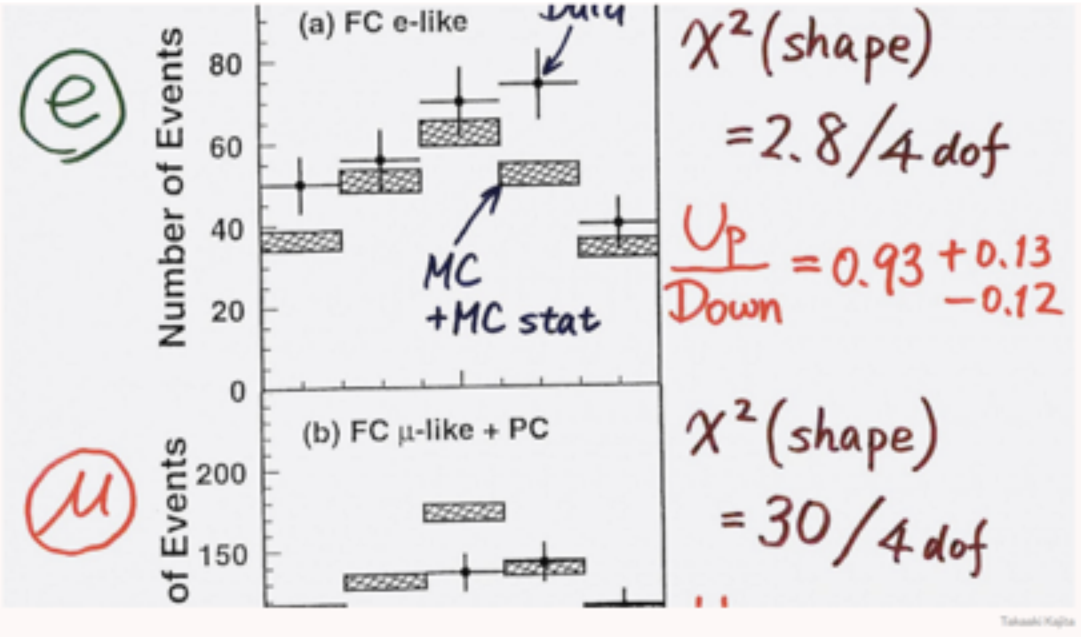
atmospheric muon neutrinos produced by cosmic ray interactions



ν_μ deficit depends on angle

ν_e flux okay

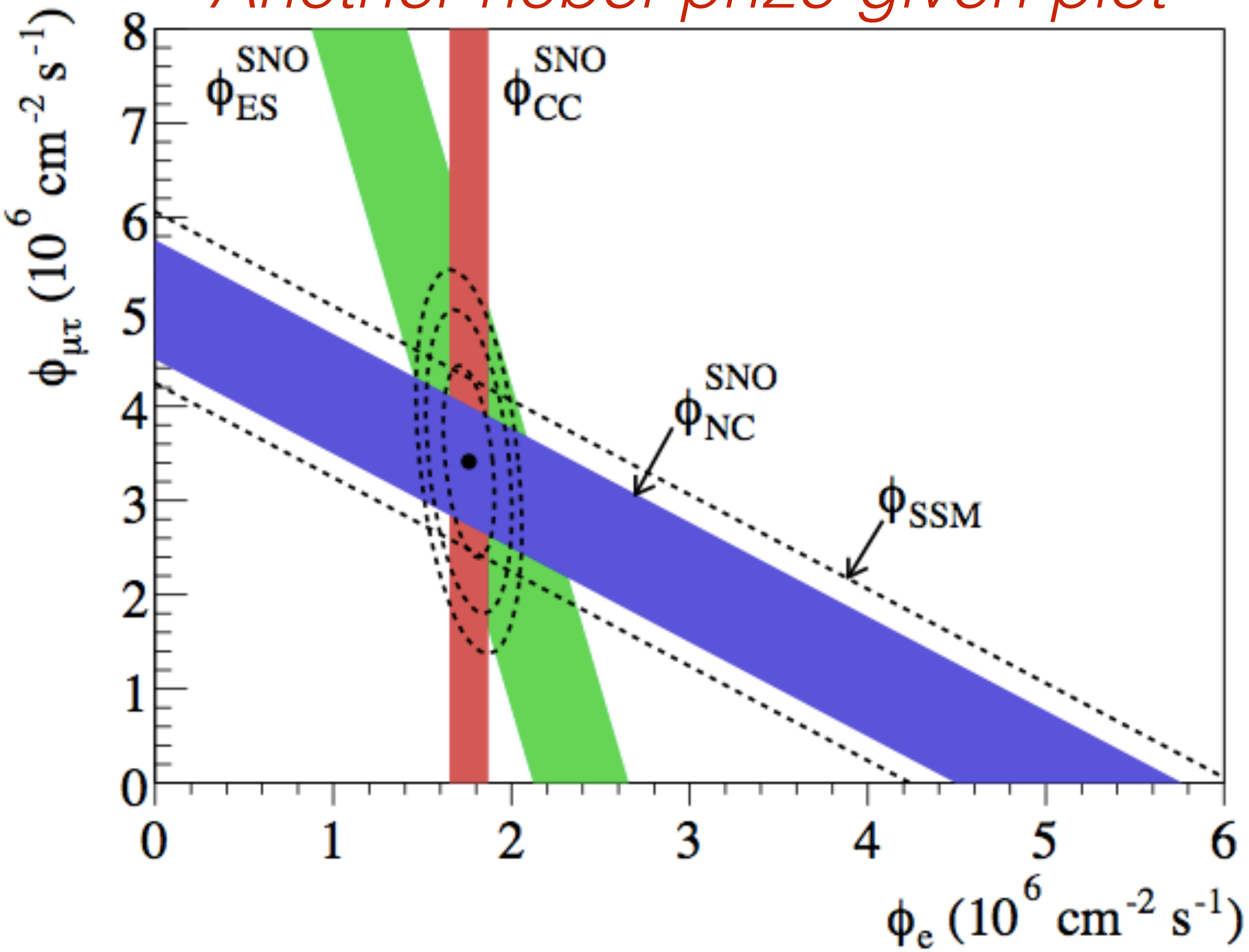
Oscillation: $\nu_\mu \leftrightarrow \nu_\tau$



← Mr. Kajita's plot in 1998 which gave the Super-Kamiokande second nobel prize!

The SNO Experiment: conclusive evidence for flavor change

Another nobel-prize given plot



SNO Measures:

$[CC]\ \nu_e + {}^2H \rightarrow p + p + e^-$

$[ES]\ \nu + e^- \rightarrow \nu + e^-$

$[NC]\ \nu + {}^2H \rightarrow p + n + \nu$

different reactions sensitive to different neutrino flavors.

Electron neutrino flux is too low:

$$P_{\nu e \nu e} = (35 \pm 2)\,\%$$

Total flux of neutrinos is correct.

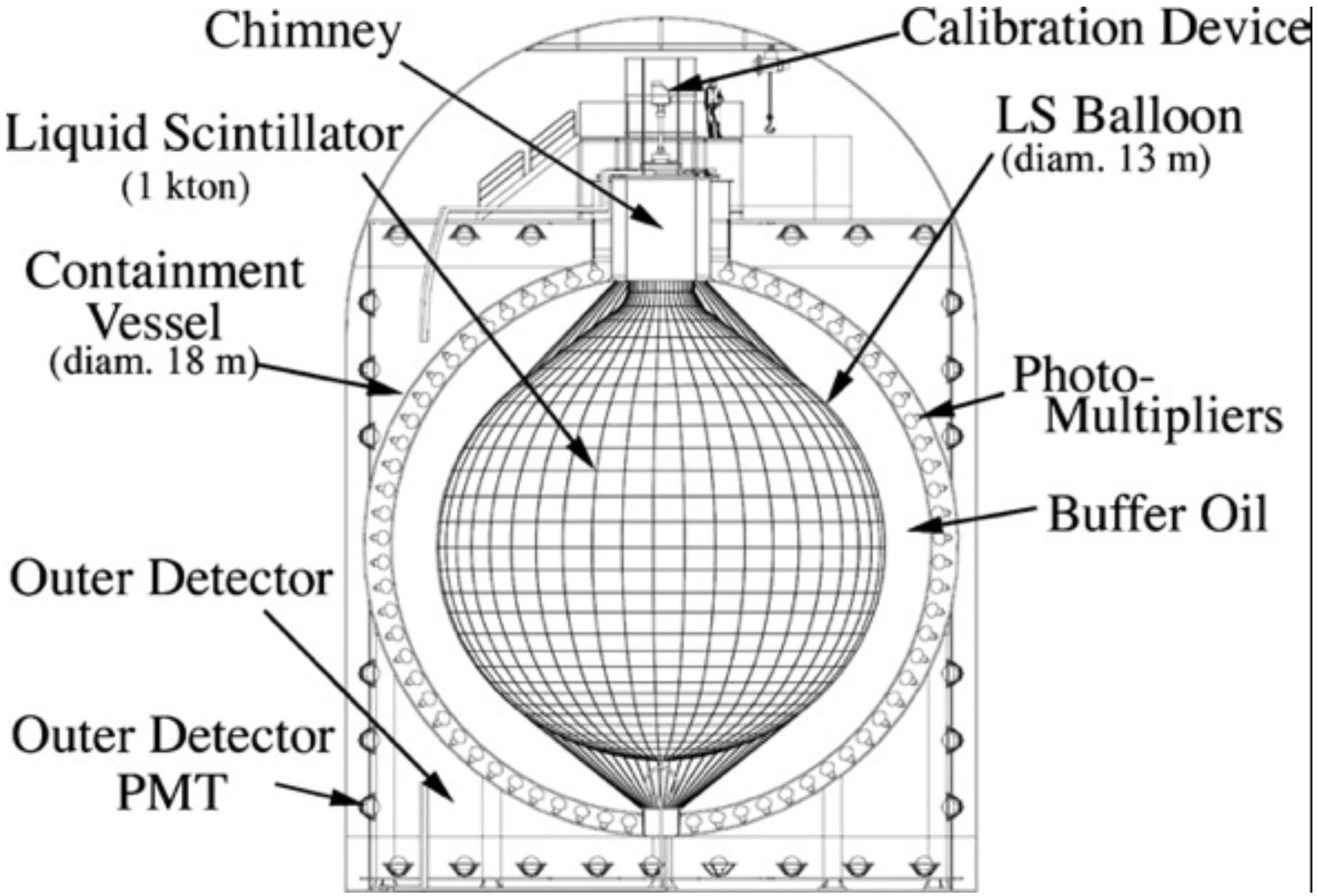
→ Interpreted as $\nu_e \leftrightarrow \nu_\mu$ or ν_τ oscillation

Scintillators : KamLaND and Borexino

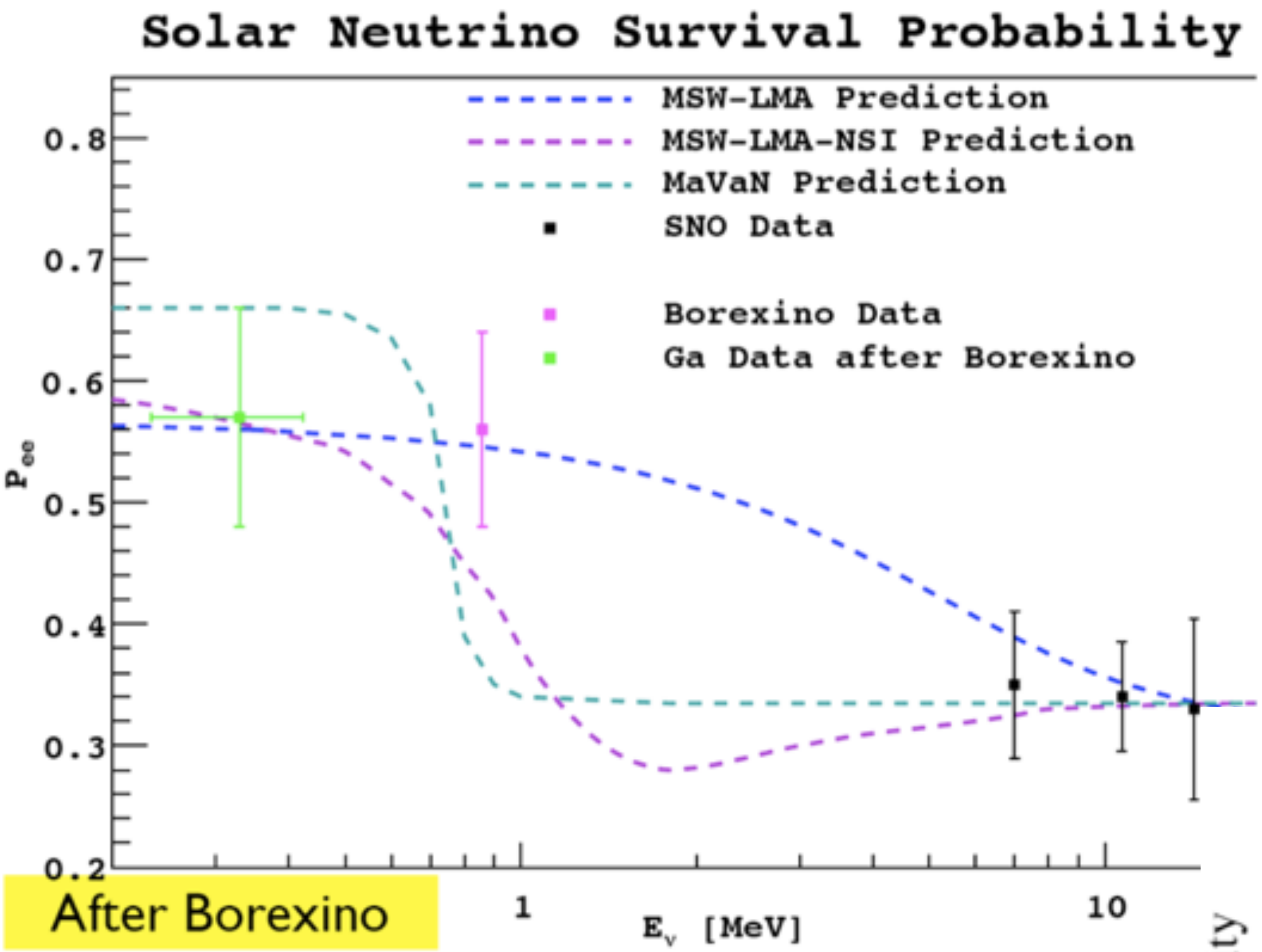
sensitive to neutrino-electron scattering $\nu + e^- \rightarrow \nu + e^-$

and inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

compared to water cherenkov detector, lower E threshold but harder tracking (therefore worse directionality)



KamLaND (Borexino looks similar)

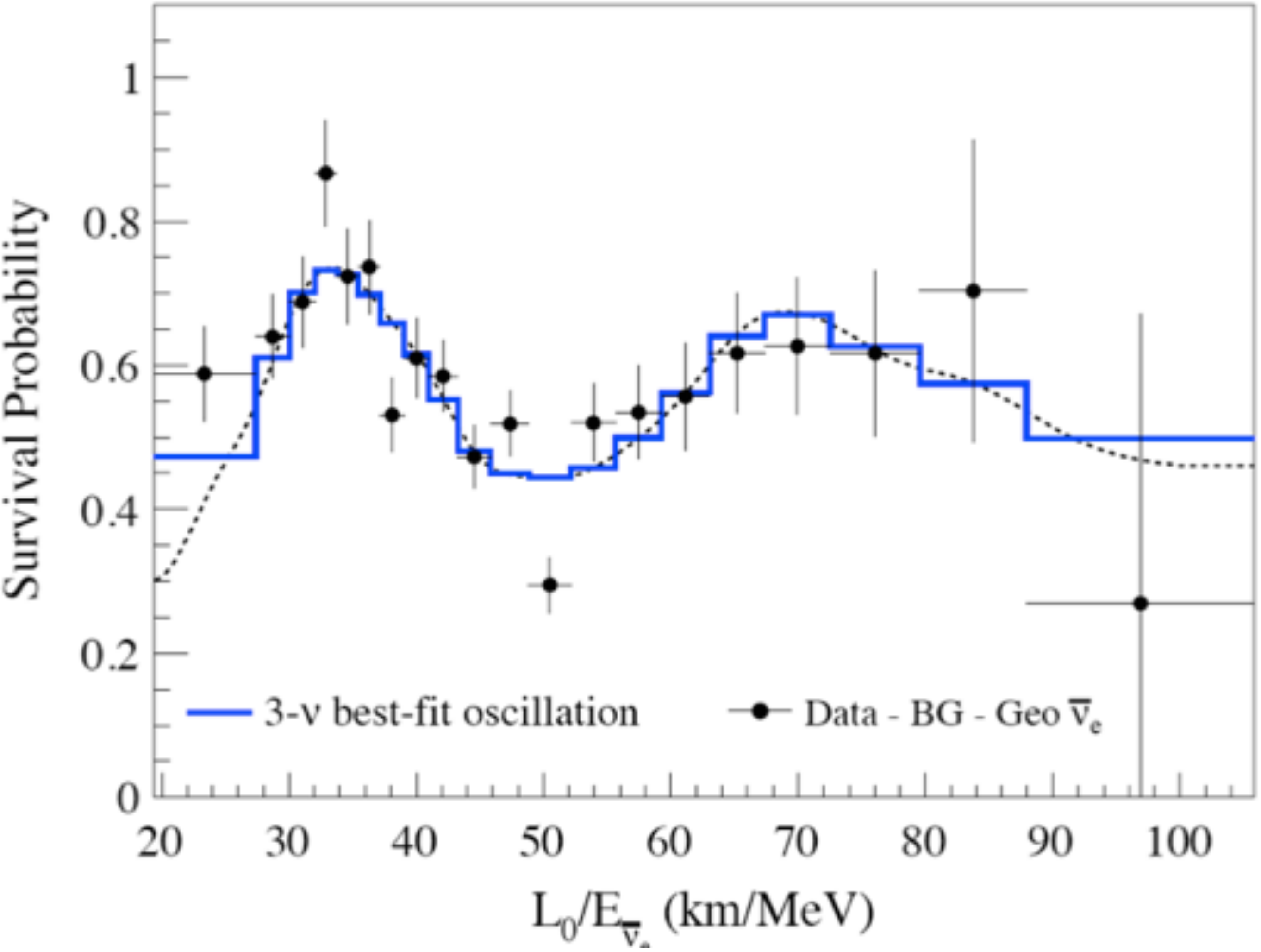


After Borexino

$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

electron-neutrino disappearance $\nu_e \leftrightarrow \nu_a$

Solar neutrino result was confirmed by reactor experiment : KamLaND with oscillatory behaviour observed



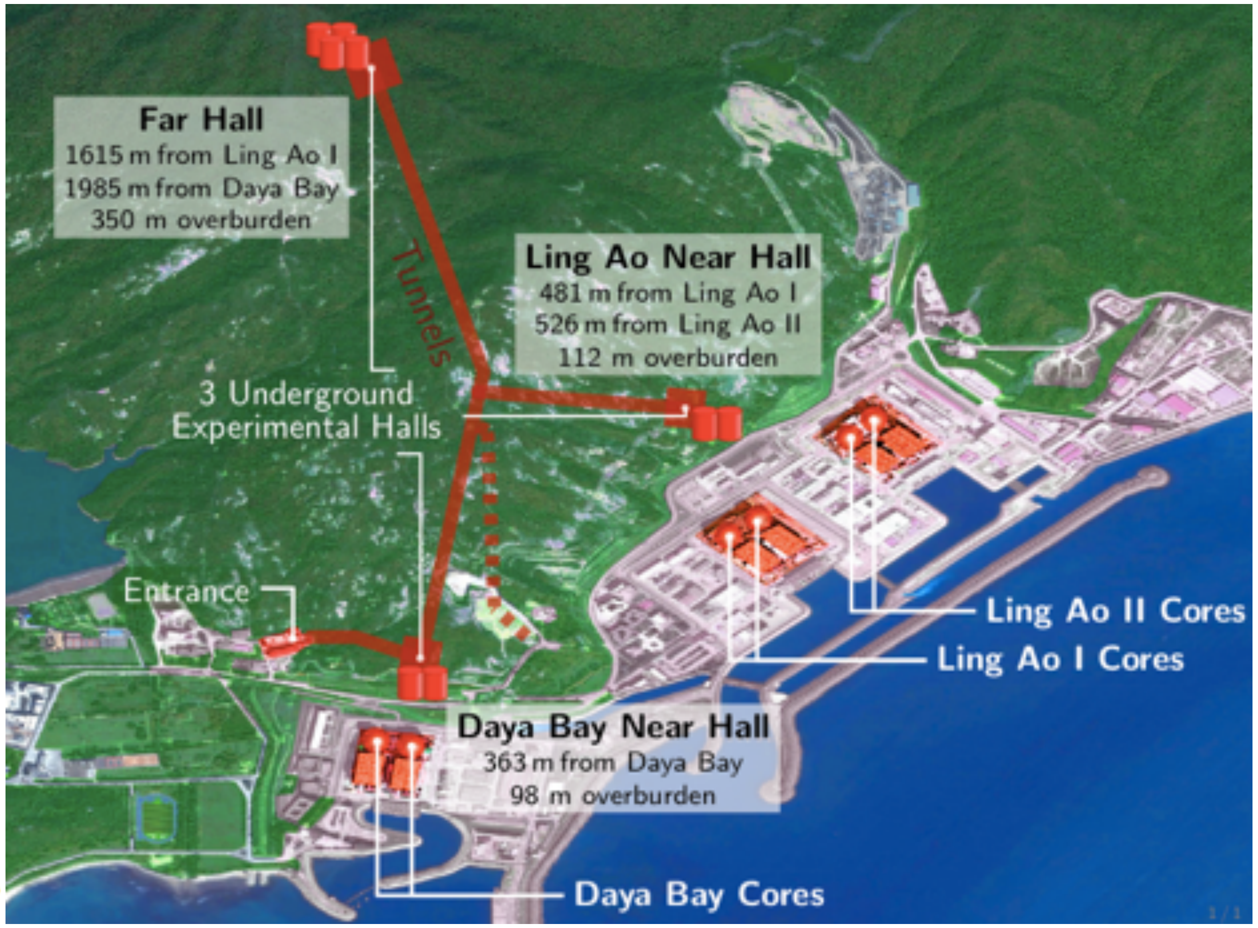
Reactors : Daya Bay, double Chooz, RENO

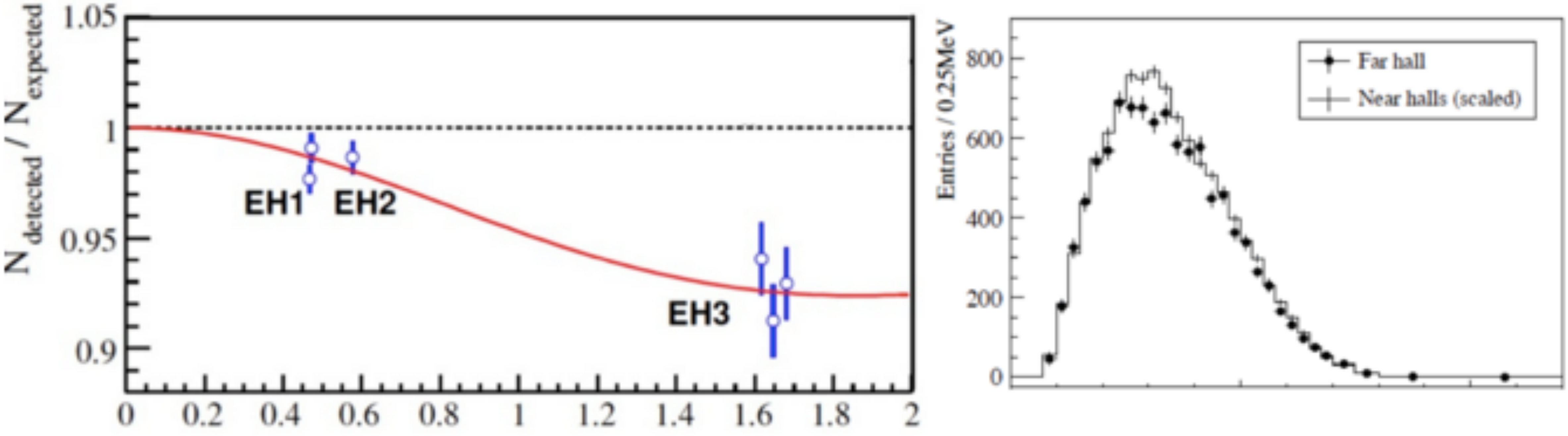
Long or short baseline to reactors

To detect anti-neutrinos by inverse beta decay in scintillators

Near-far detectors in different distance

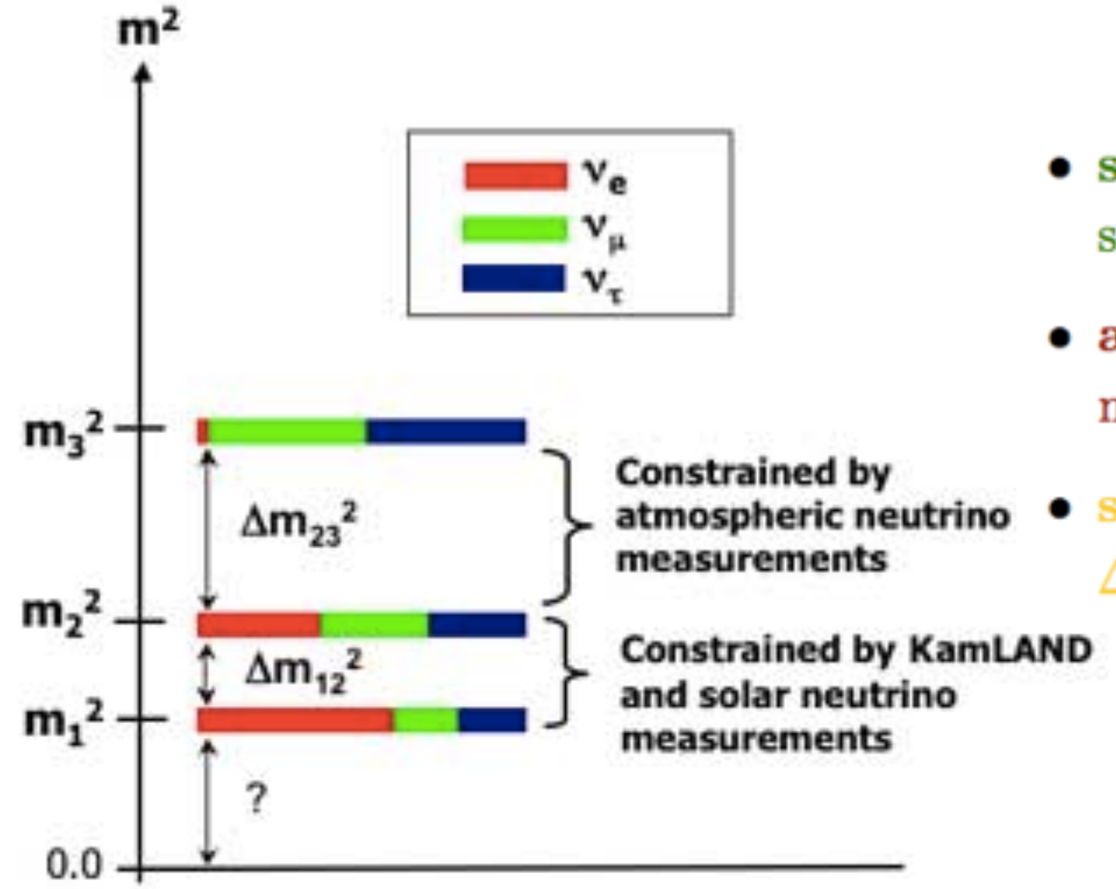
$$P_{\text{sur}} \approx 1 - \sin^2 2\theta_{13} \sin^2(1.267\Delta m^2_{31} L/E)$$





Daya Bay result on non-zero θ_{13} (2012)

So, what we know about neutrinos now?



Note: Because we don't know the signs of the mass differences or the values of the masses themselves , the true spectrum may be inverted from what is shown here.

- **solar:** $\nu_e \leftrightarrow \nu_a$ (linear combination of ν_μ and ν_τ): $\Delta m^2 \sim 10^{-4}$ eV^2, $\sin^2\theta \sim 0.3$. (θ_{12})
- **atmospheric:** $\nu_\mu \leftrightarrow \nu_\tau$: $\Delta m^2 \sim 10^{-3}$ eV^2, $\sin^2\theta \sim 0.5$ ("maximal mixing"). (θ_{23})
- **short-baseline reactors:** $\nu_e \leftrightarrow \nu_a$ (linear combination of ν_μ and ν_τ): $\Delta m^2 \sim 10^{-3}$ eV^2, $\sin^2\theta \sim 0.02$. (θ_{13})

- all 3 flavor are confirmed to oscillate to each other
- neutrinos have mass and their mass difference (actually difference between mass-squares) is known with good precision

* mass hierarchy is yet unknown

And what we want to know further?

- absolute mass : observation of oscillations only tells us about the mass-square difference.
from cosmology (thermal history) - mass < ~0.2 MeV
from particle experiments (kinematics) : < ~ 2 MeV

- cp phase in PMNS matrix, mass hierarchy (long base line - experiments and larger atmospheric neutrino experiments)
Majorana or not (neutrino-less double beta decay)

- and many more things depending on what properties will be revealed first…

Indication of oscillation → indication of mass

But from where does the mass come from…?
- without RH neutrino, no higgs coupling for neutrinos -> no Dirac mass term $m_\nu \nu_e^c \nu_e$
- for LH neutrinos, Majorana mass term $\frac{1}{2}\mu_\nu \nu_e \nu_e$ is forbidden (combination of weak isospin singlet and doublet).

→ no way to do it in SM frame

1) first simplest remedy : introduce RH neutrinos

-> introduce Dirac mass term through Higgs mechanism.

-> but another question arises : why neutrino's coupling to Higgs is 500,000 times smaller than electron's?

2) another simple remedy : introduce RH neutrinos, and write down Majorana mass term for them

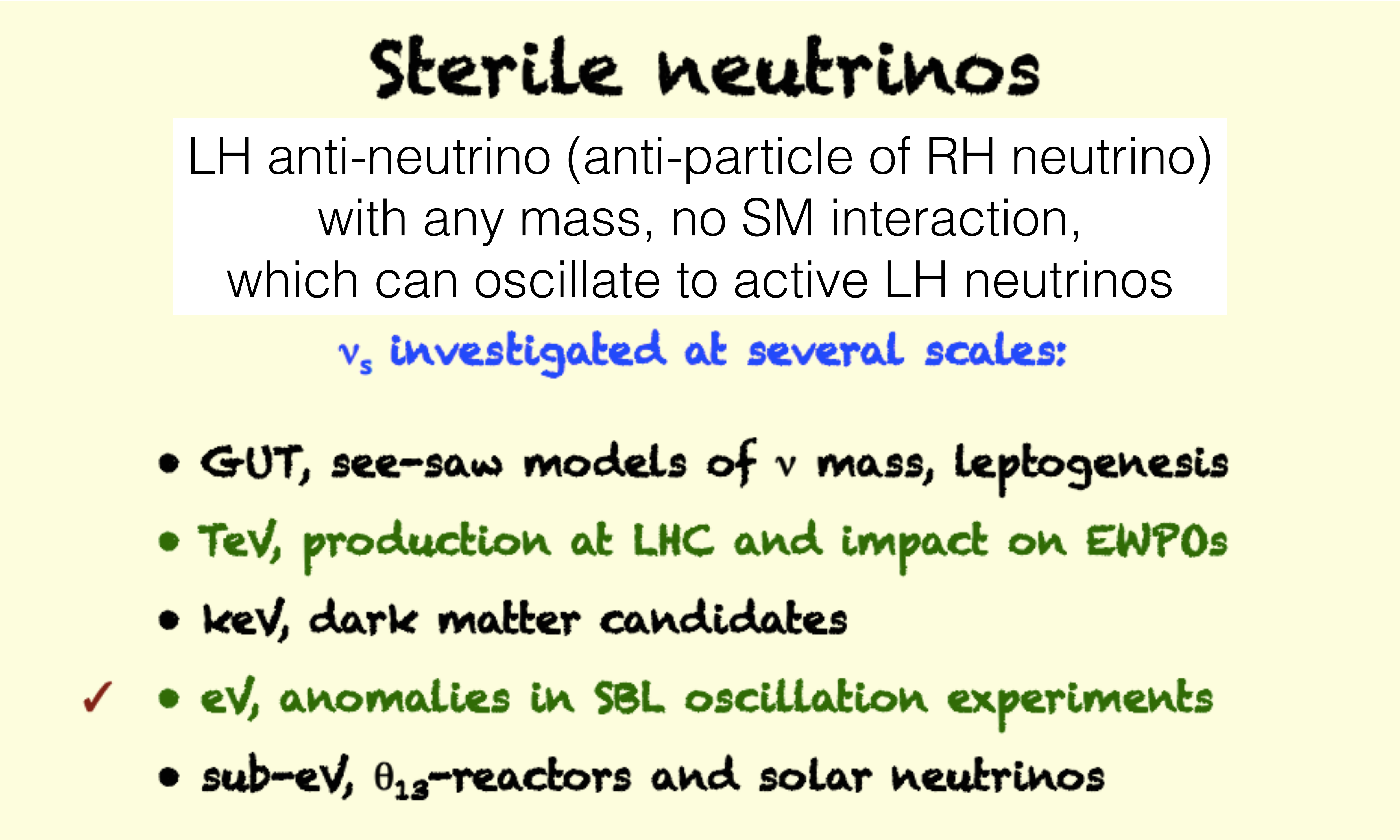
$$\mathcal{L}_{\nu_e \text{ mass}} = m_{\nu_e} \nu_e {\nu_e}^{\mathrm{c}} + \frac{1}{2} M {\nu_e}^{\mathrm{c}} {\nu_e}^{\mathrm{c}}$$

$$1/2(\nu_e \quad {\nu_e}^{\mathrm{c}}) \begin{pmatrix} 0 & m_{\nu_e} \\ m_{\nu_e} & M \end{pmatrix} \begin{pmatrix} \nu_e \\ {\nu_e}^{\mathrm{c}} \end{pmatrix}$$

$$\mu_{\text{heavy}} \approx M \quad \mu_{\text{light}} \approx \frac{m_{\nu_e}^2}{M}$$

-> Clever way to give mass without breaking weak isospin symmetry, as well as to explain such small mass : so-called "See saw mechanism" (The heavier heavy neutrino is, the lighter light neutrino is)

Typically, M ~ GUT scale and m_ve ~ m_e gives m_light ~ 500,000 times smaller m_e



Sterile neutrinos

LH anti-neutrino (anti-particle of RH neutrino)
with any mass, no SM interaction,
which can oscillate to active LH neutrinos

ν_s investigated at several scales:

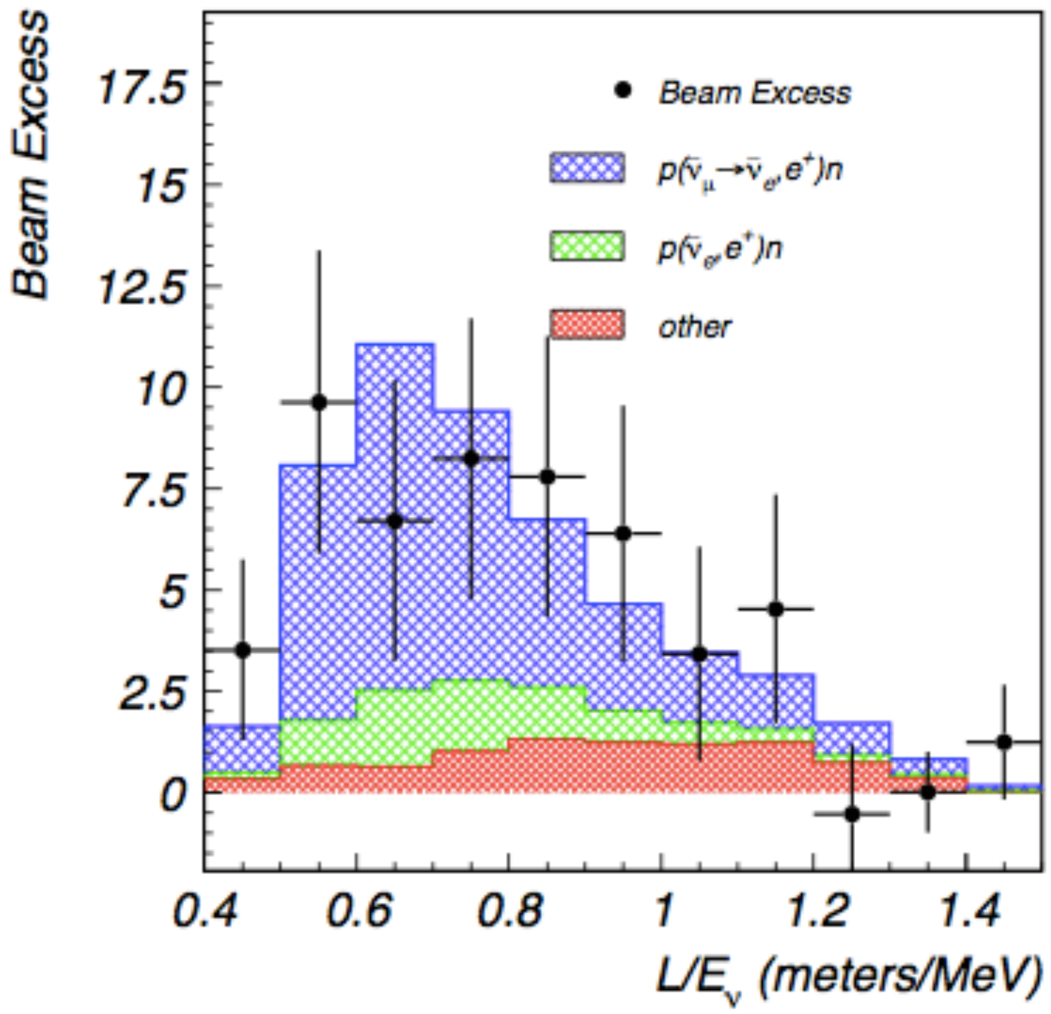
- GUT, see-saw models of ν mass, leptogenesis
- TeV, production at LHC and impact on EWPOs
- keV, dark matter candidates
- ✓ eV, anomalies in SBL oscillation experiments
- sub-eV, θ_{13}-reactors and solar neutrinos

O(eV) sterile neutrinos are:
- motivated experimentally (will be explained in following pages)
- accessible to oscillation experiments

Sterile neutrino anomalies

LSND : old (~1998) liquid scintillator detected neutrinos coming from accelerator - access of anti v_e was observed from anti v_mu beam

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 30\,\text{m}$ $20\,\text{MeV} \lesssim E \lesssim 200\,\text{MeV}$

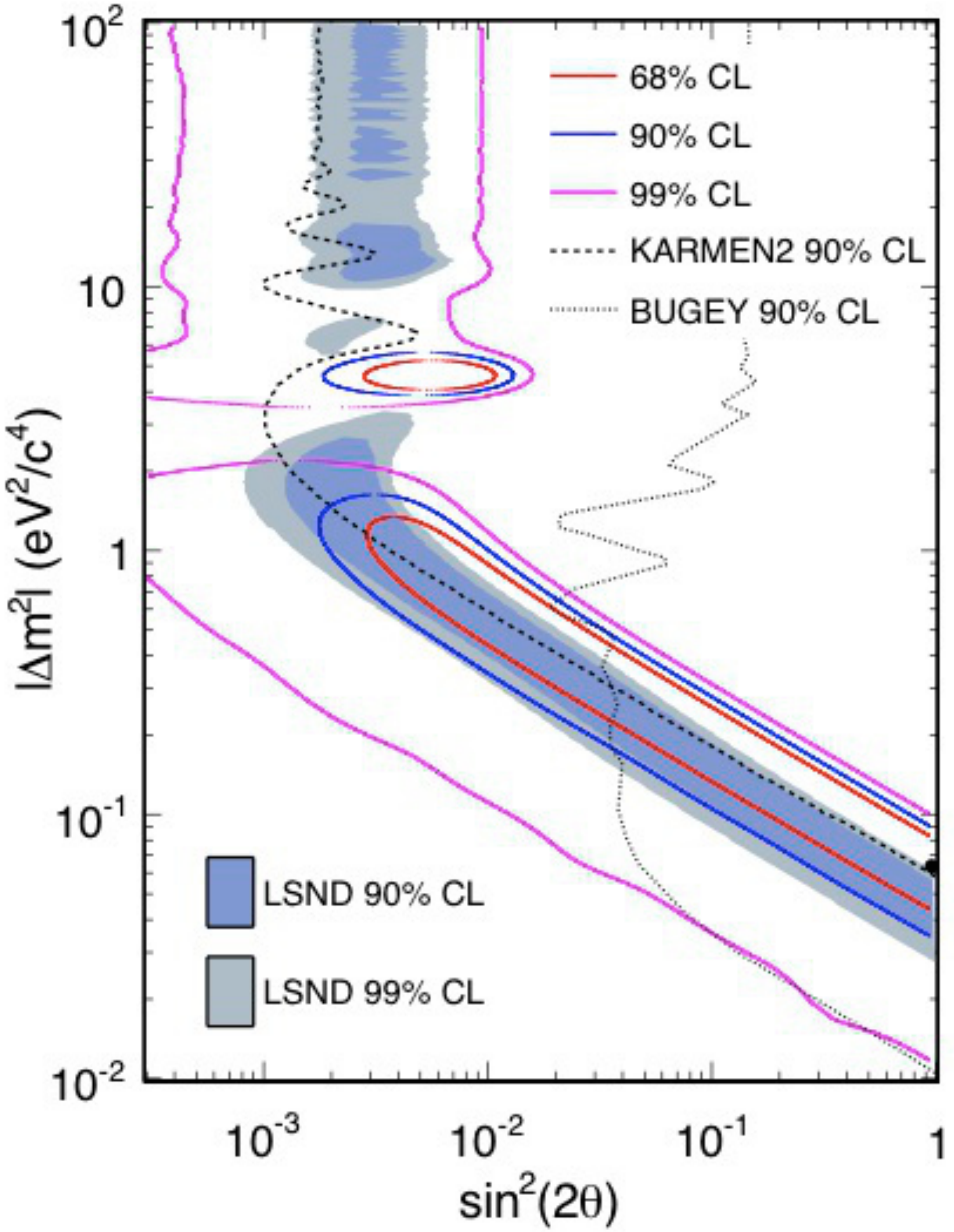


Attempt to explain with 2 flavor oscllation
(as it was old time) but :

$$\Delta m^2_{\text{LSND}} \gtrsim 0.2\,\text{eV}^2$$

the large mixing angle conflicts with all the following experiments -> but may be explained with sterile neutrino!

Another experiment MiniBooNE was followed to examine the LSND result and :

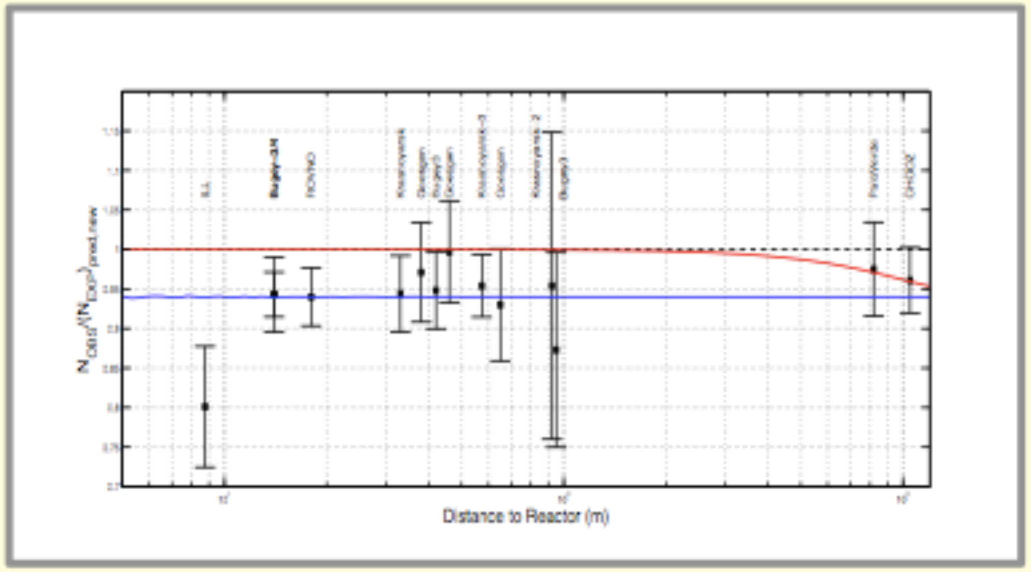


Agreement with LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal!

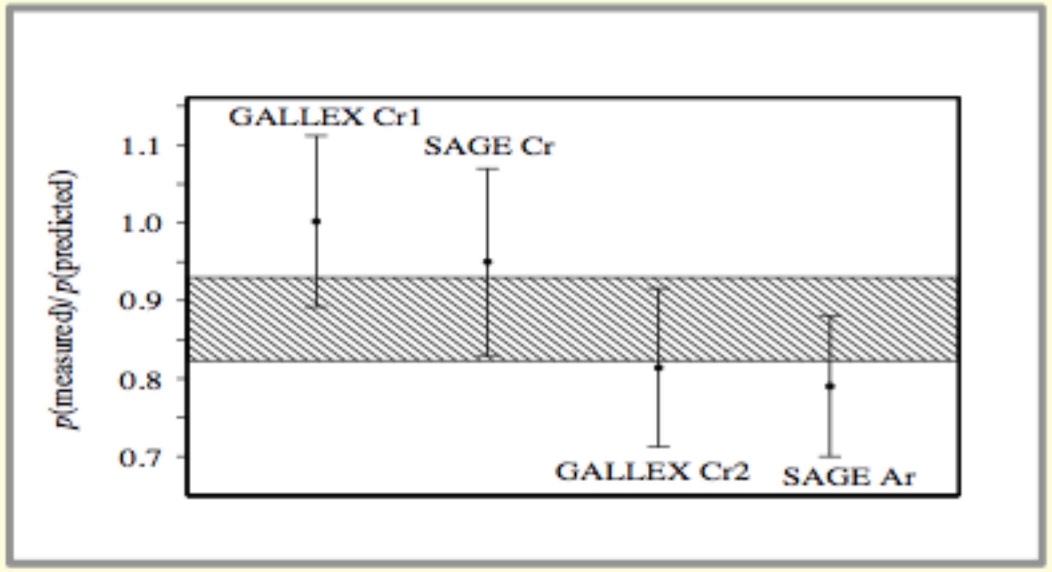
Similar L/E but different L and E $\Longrightarrow$ Oscillations!

The reactor and gallium anomalies

(unexplained ν_e disappearance)



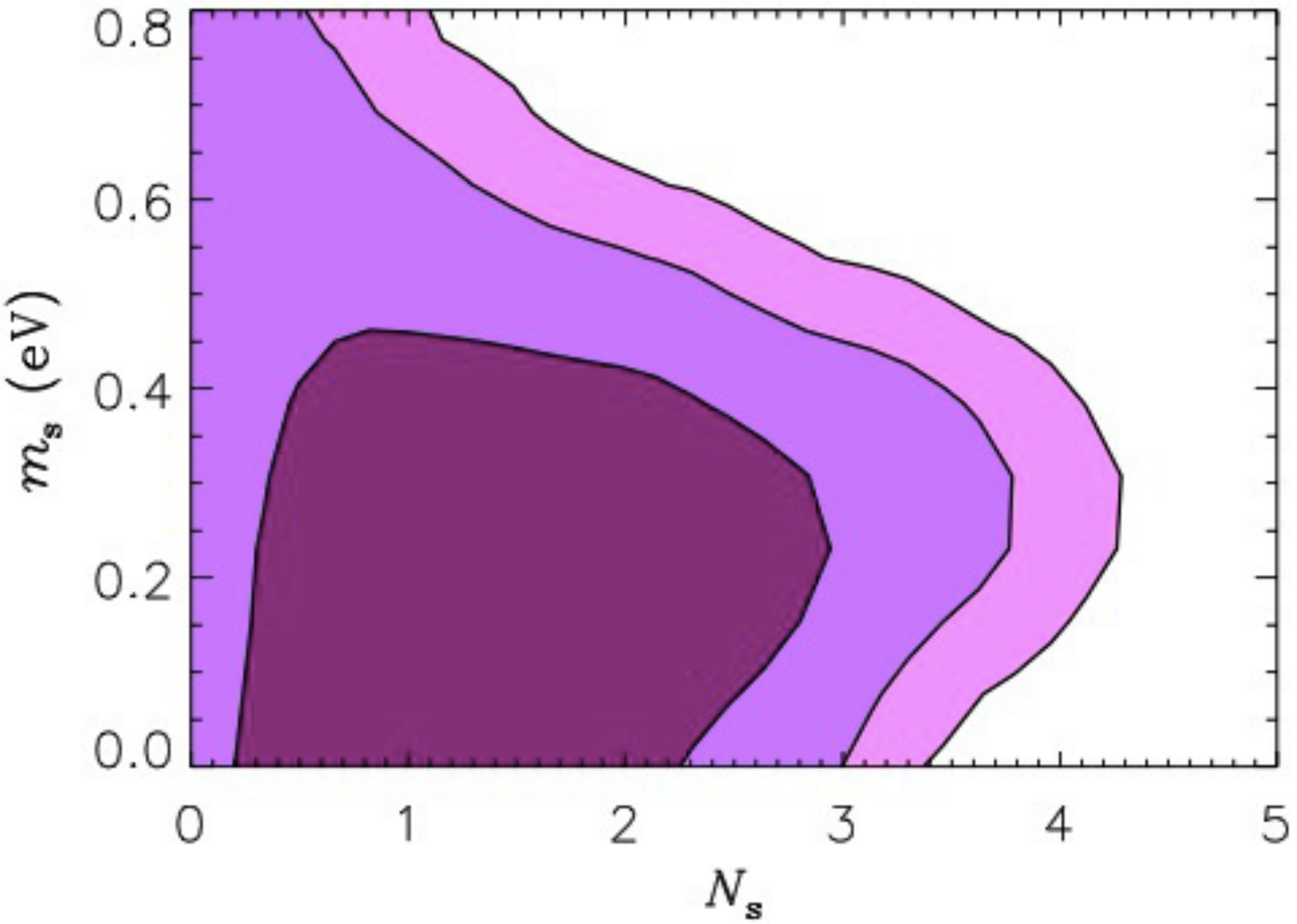
Mention et al. arXiv:1101:2755 [hep-ex]



SAGE coll., PRC 73 (2006) 045805

Warning: both are mere normalization issues

The culprit may be in hidden systematics

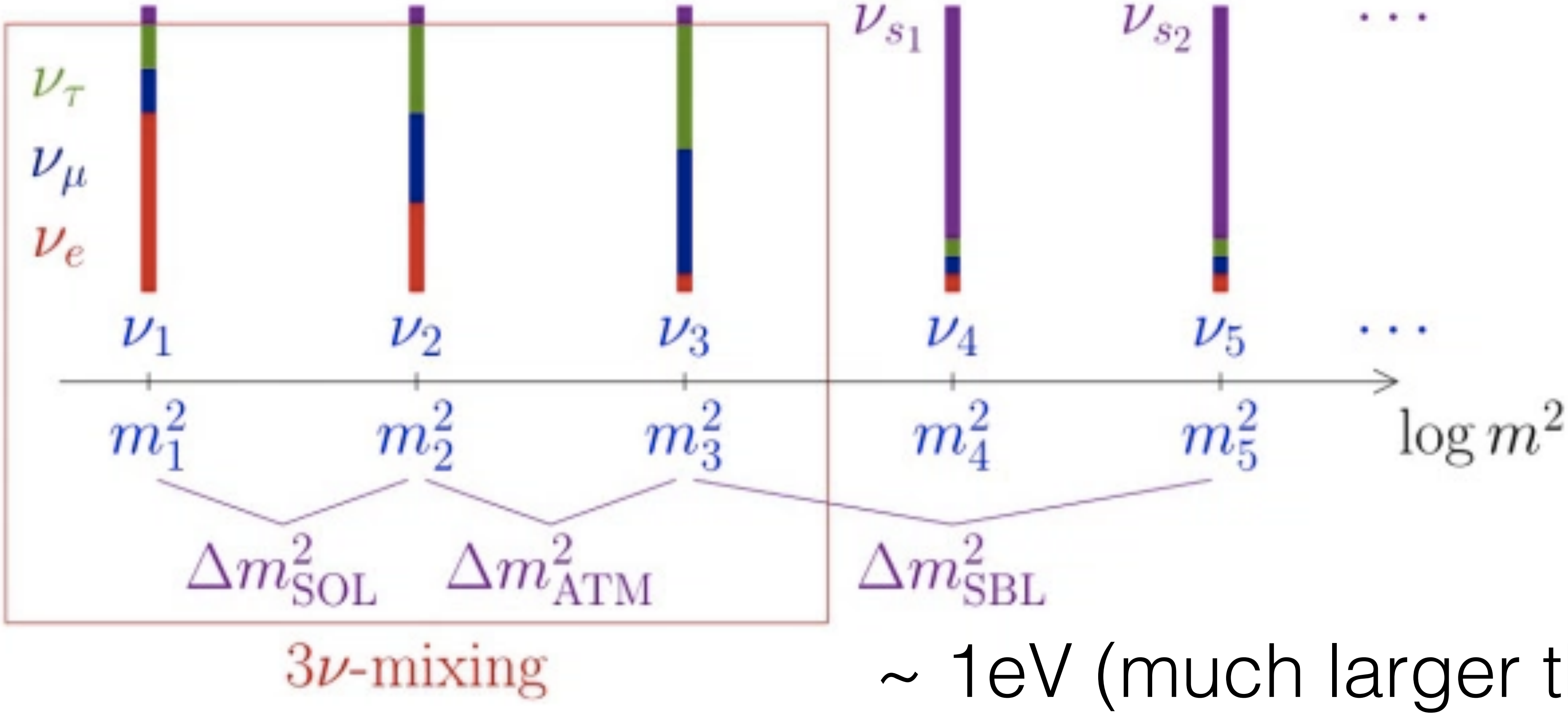


At 95% CL, N_s=1.61+- 0.92 with a bound on the masses of m < 0.70 eV.

* Cosmology also favors # of sterile neutrinos (Ns) = 0.8 ~ 1.6, and confines its mass Ms < 0.3 ~ 0.7 eV (too low for LSND, though)

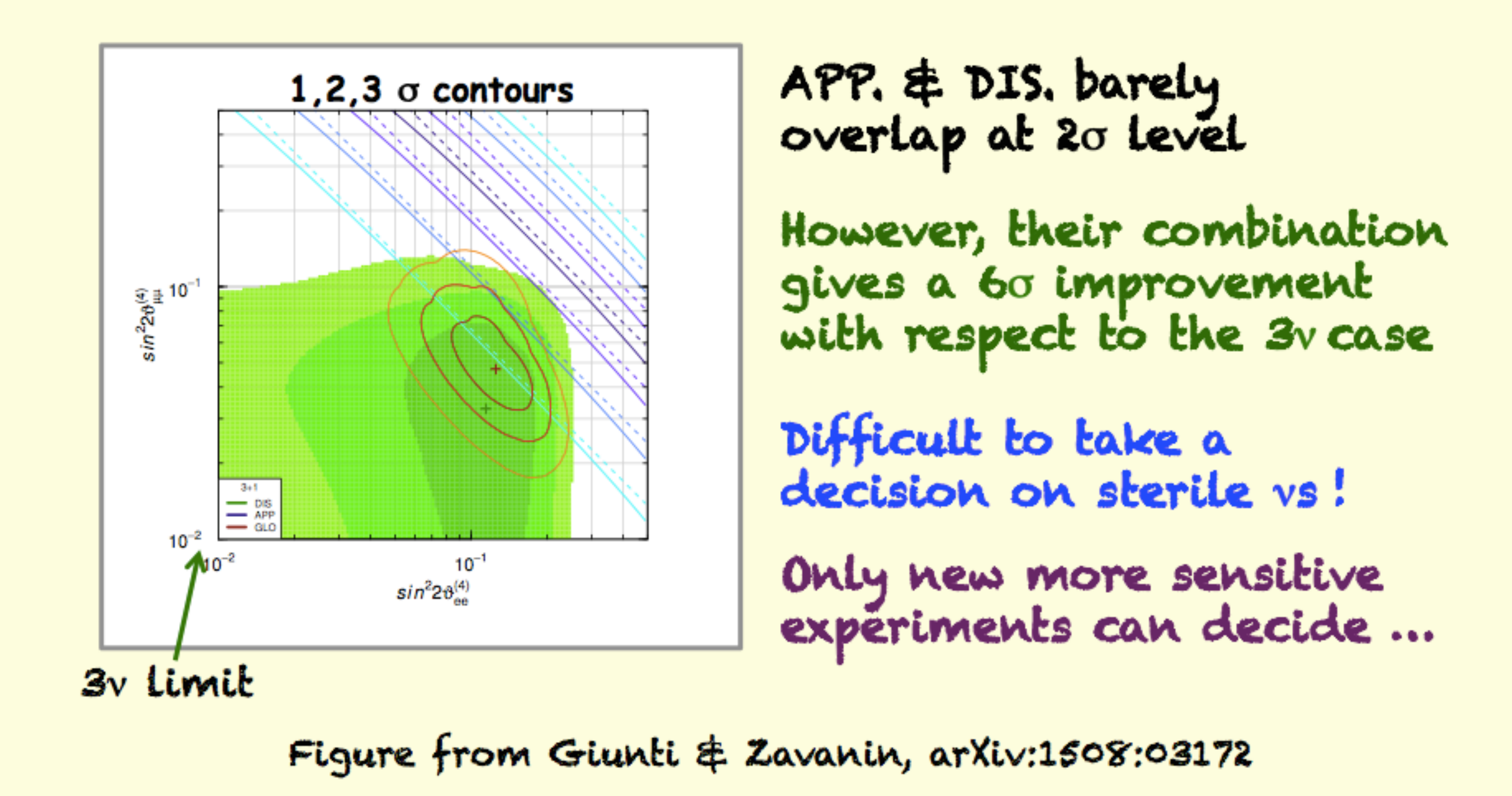
Idea:

- Introduce extra neutrino flavor ν_s, mixing with the active ones
- $\nu_e \rightarrow \nu_s$ oscillations explain Gallium anomaly
- $\bar{\nu}_e \rightarrow \bar{\nu}_s$ oscillations explain reactor anomaly
- $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_s \rightarrow \overset{(-)}{\nu}_e$ oscillations explain LSND + MiniBooNE



~ 1eV (much larger than other two angles)

Then, will all the anomalies agree in a certain parameter region?
- in combined (global) analysis . . .



APP. & DIS. barely overlap at 2σ level

However, their combination gives a 6σ improvement with respect to the 3ν case

Difficult to take a decision on sterile νs !

Only new more sensitive experiments can decide ...

Figure from Giunti & Zavanin, arXiv:1508:03172

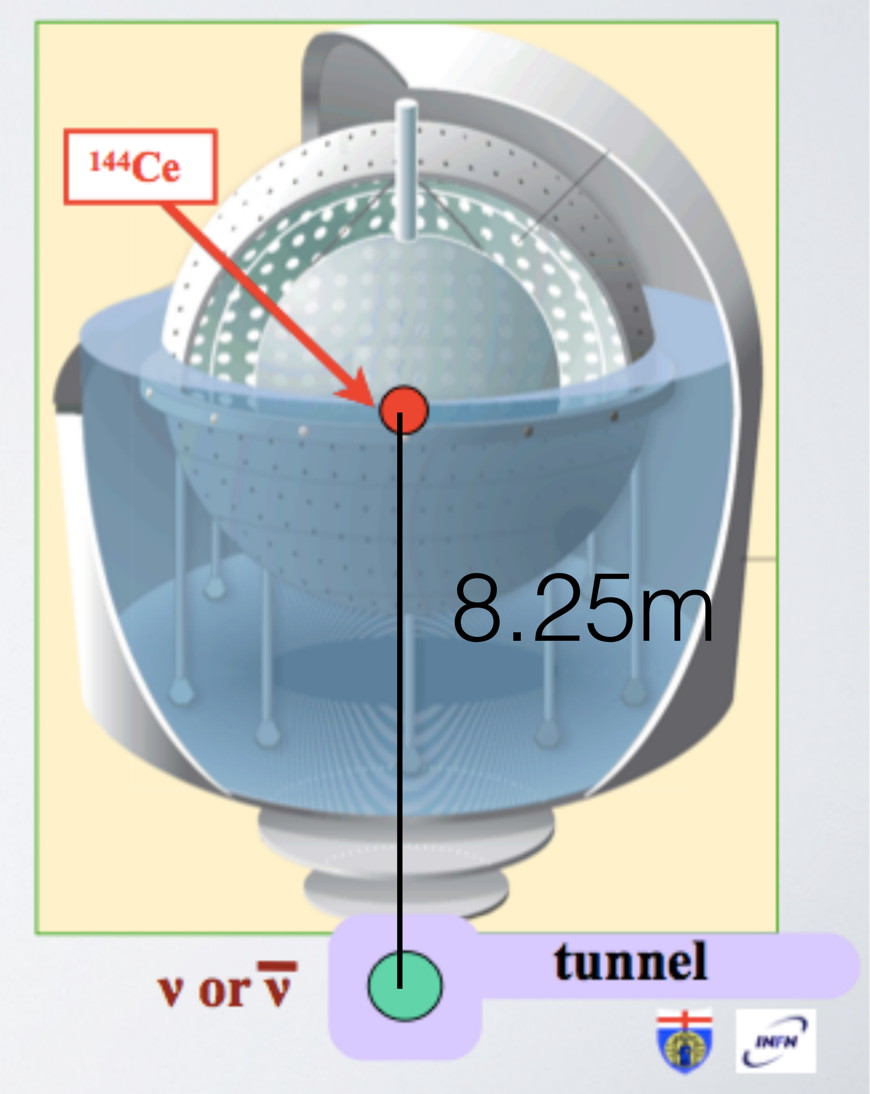
Looks like a situation in dark matter anomalies…
(though here, lack of strong theoretical motivation such as SUSY WIMP)

SOX: SHORT DISTANCE OSCILLATIONS WITH BOREXINO (I)

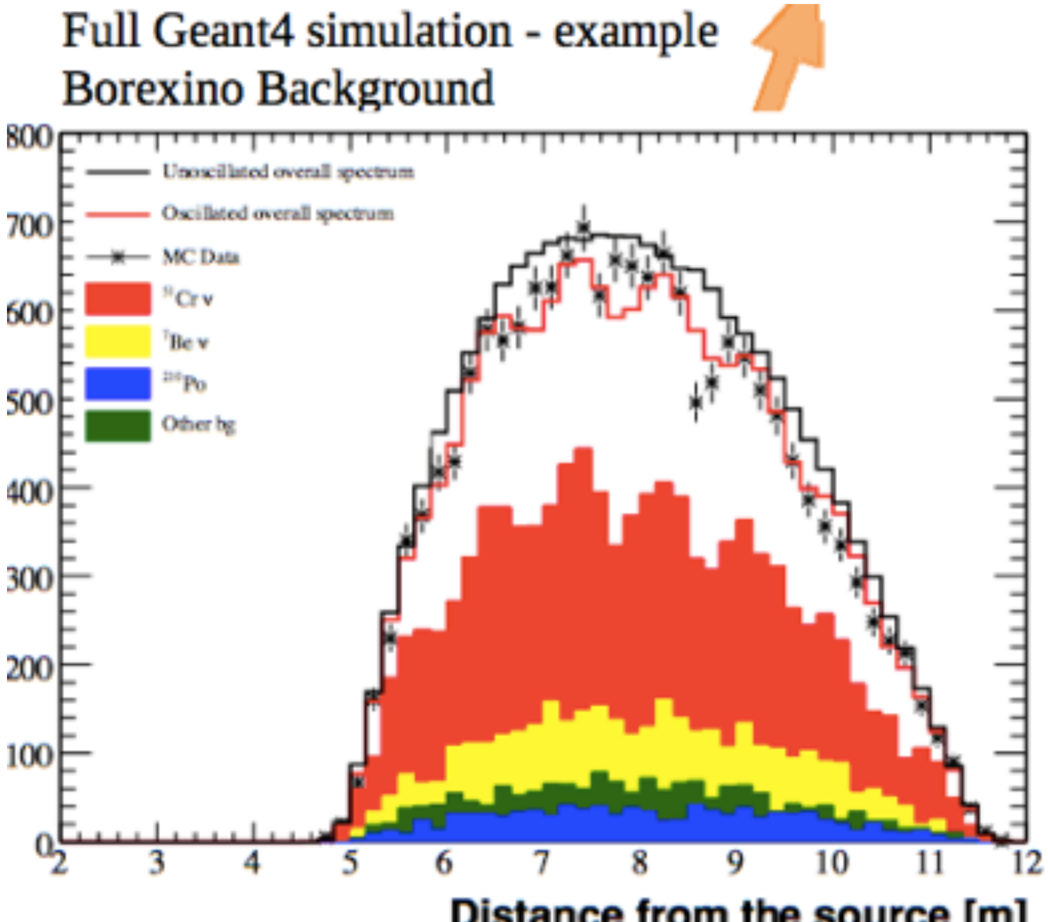
Measure ve / anti-ve disappearance
Deploy ve / anti-ve source inside/
outside the detector

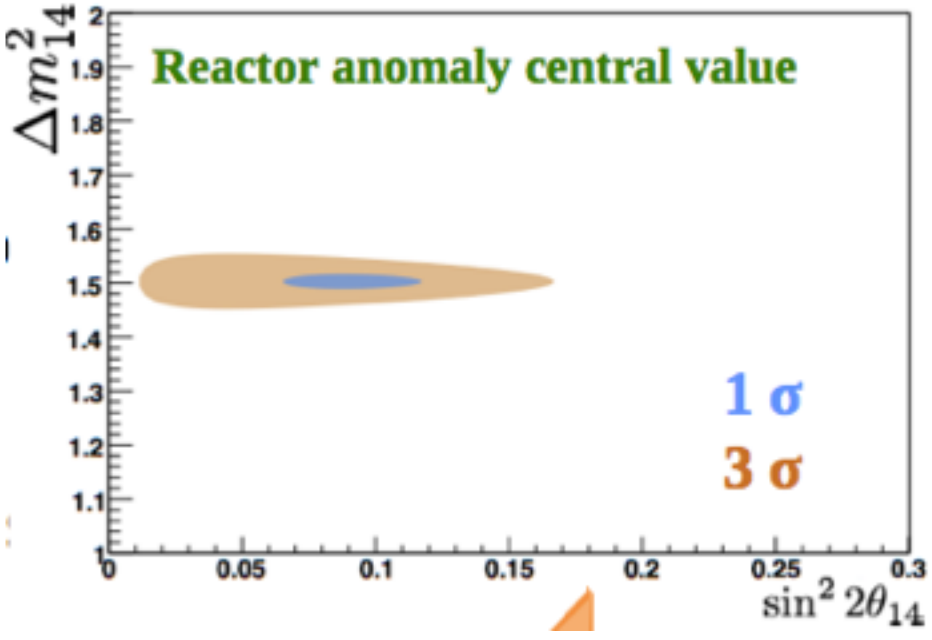
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{ee}) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

can clearly see the short baseline
oscillation pattern

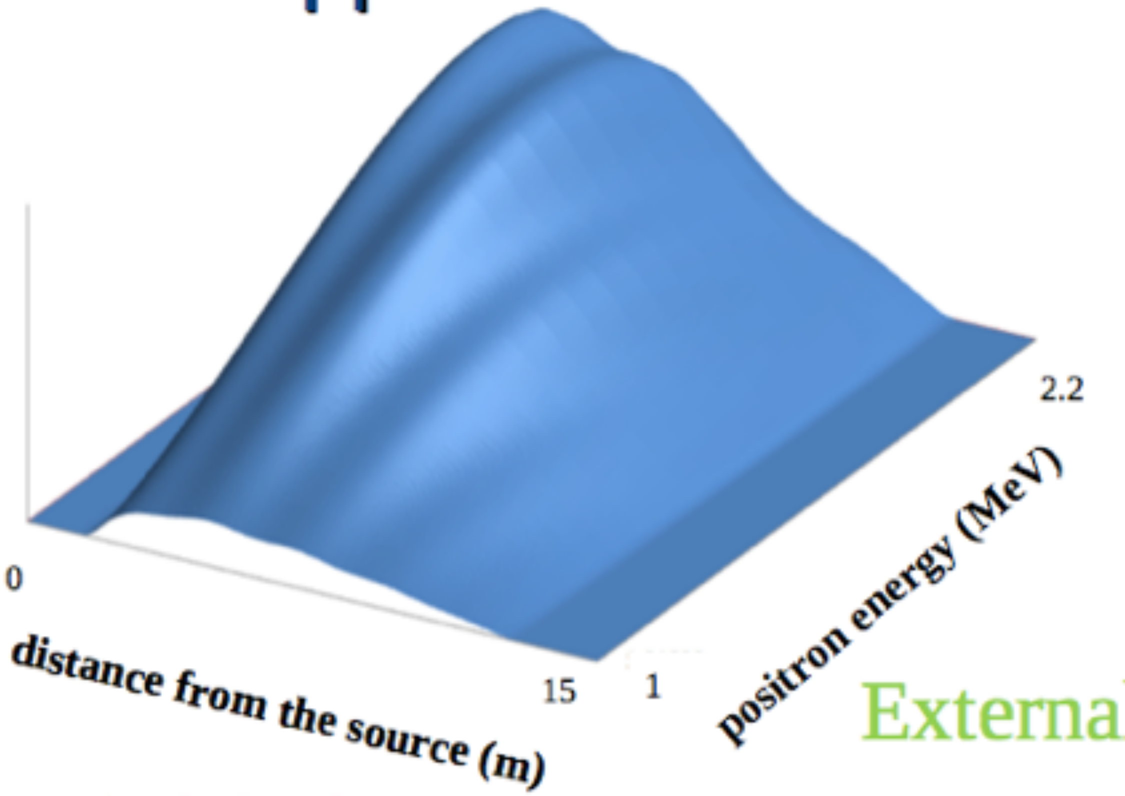


Full Geant4 simulation - example
Borexino Background

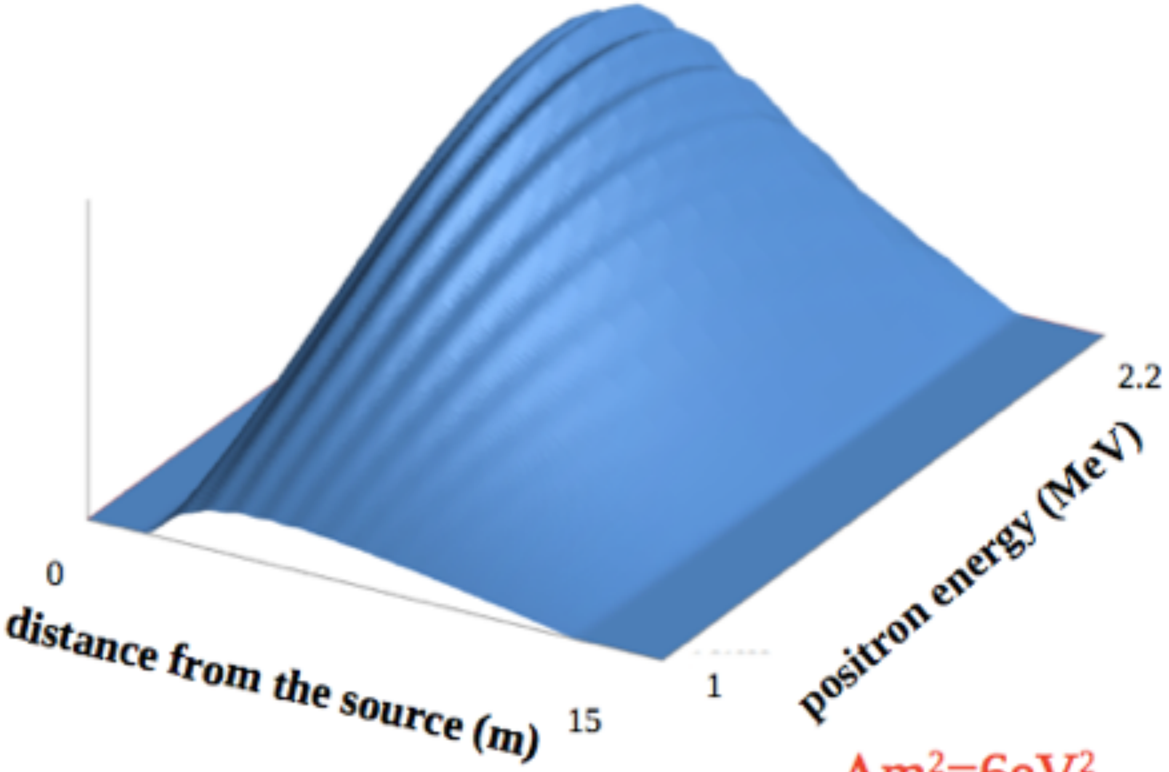




More examples of space-energy patterns for ^{144}Ce-^{144}Pr

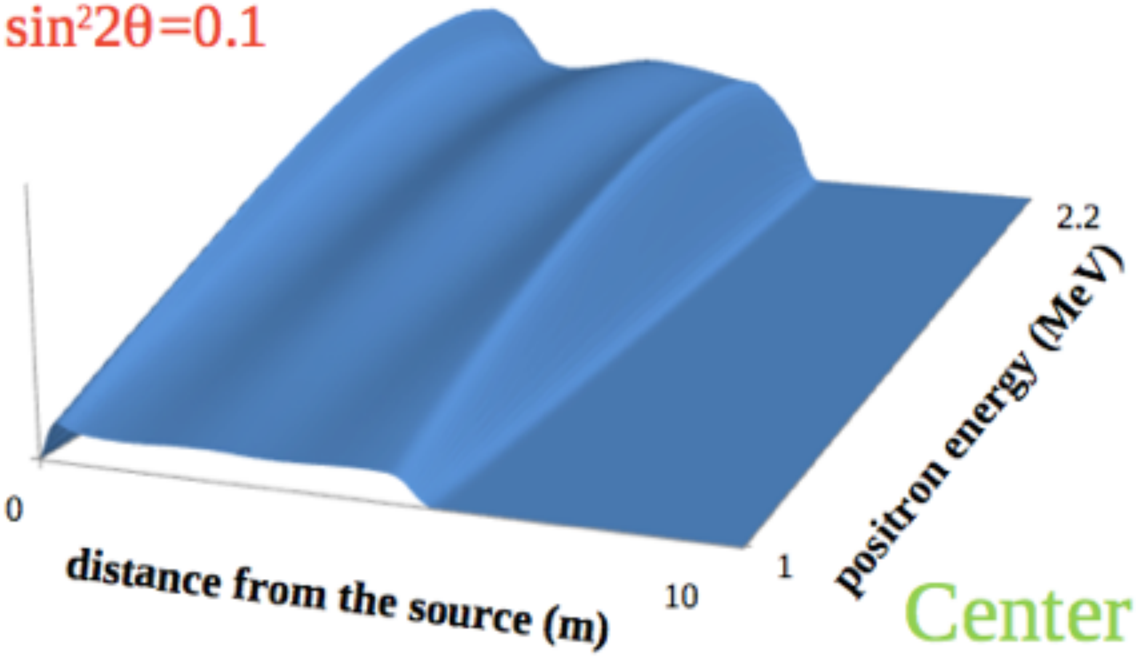


External

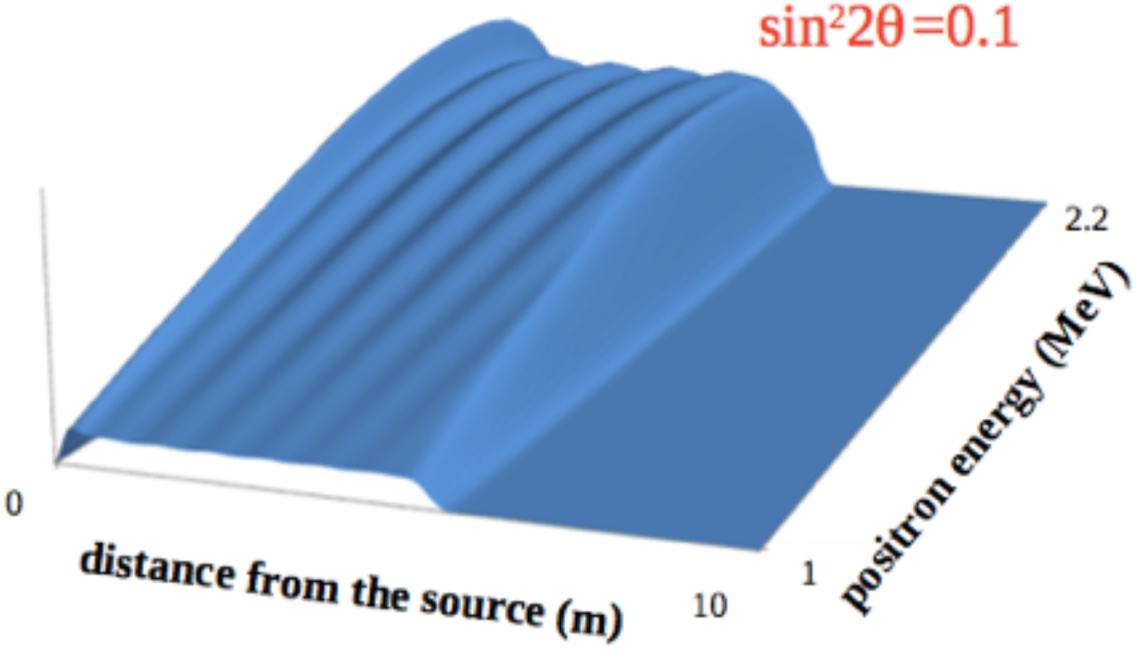


$\Delta m^2 = 2 eV^2$
$\sin^2 2\theta = 0.1$

$\Delta m^2 = 6 eV^2$
$\sin^2 2\theta = 0.1$

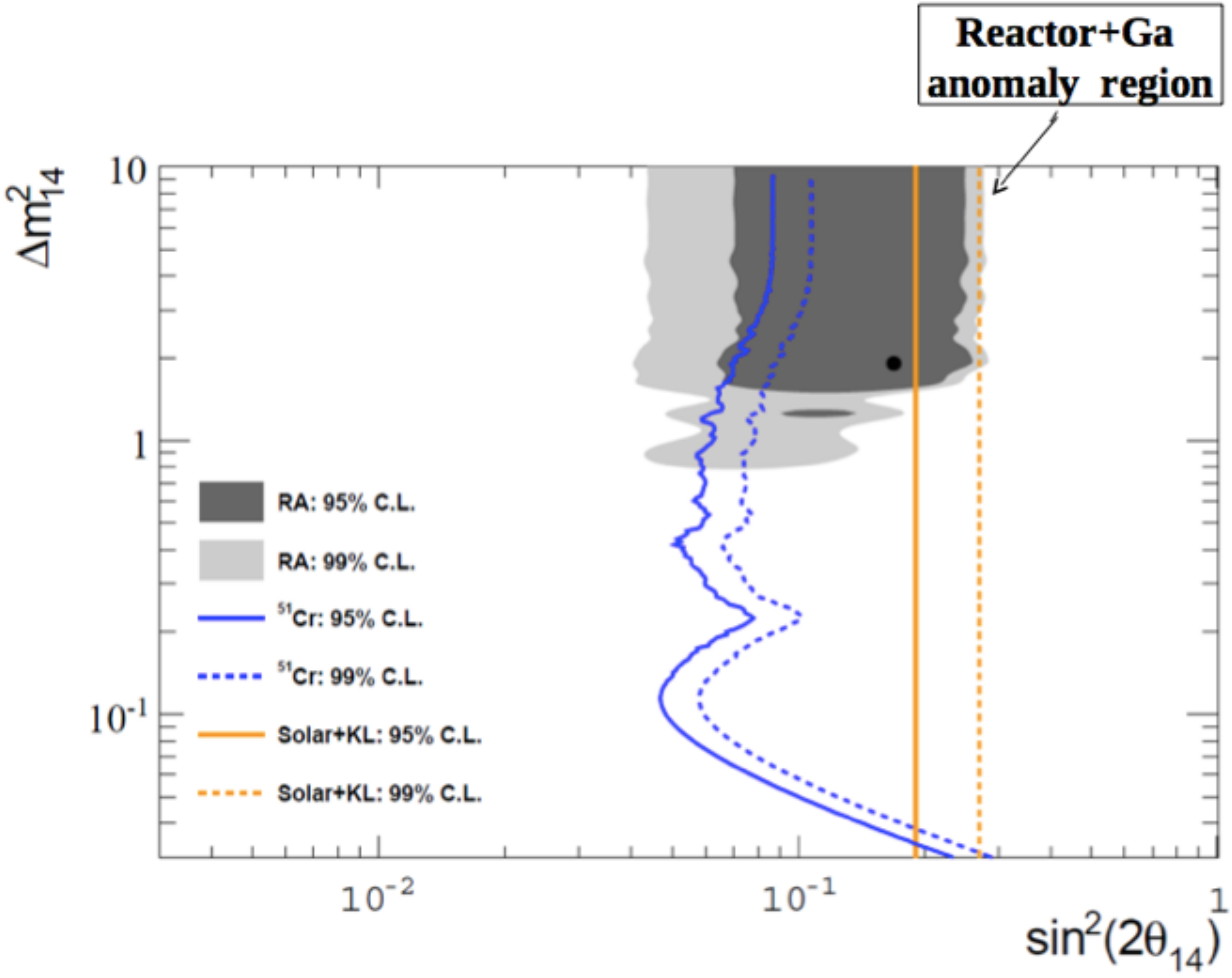


Center



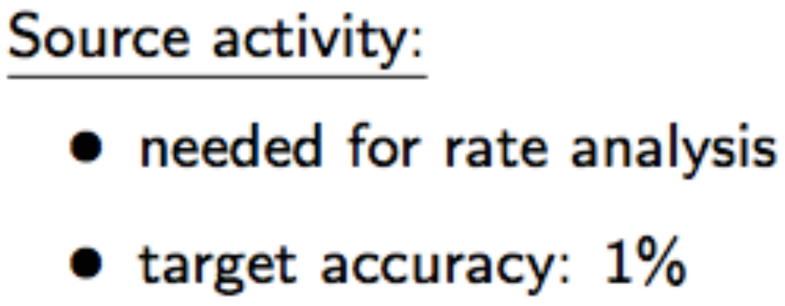
SOX-A sensitivity

- **SOX-A:**
  - ^{51}**Cr** source at **8.25 m** from the center
  - **10 MCi**
  - 1% precision in source activity
  - 1% in FV determination



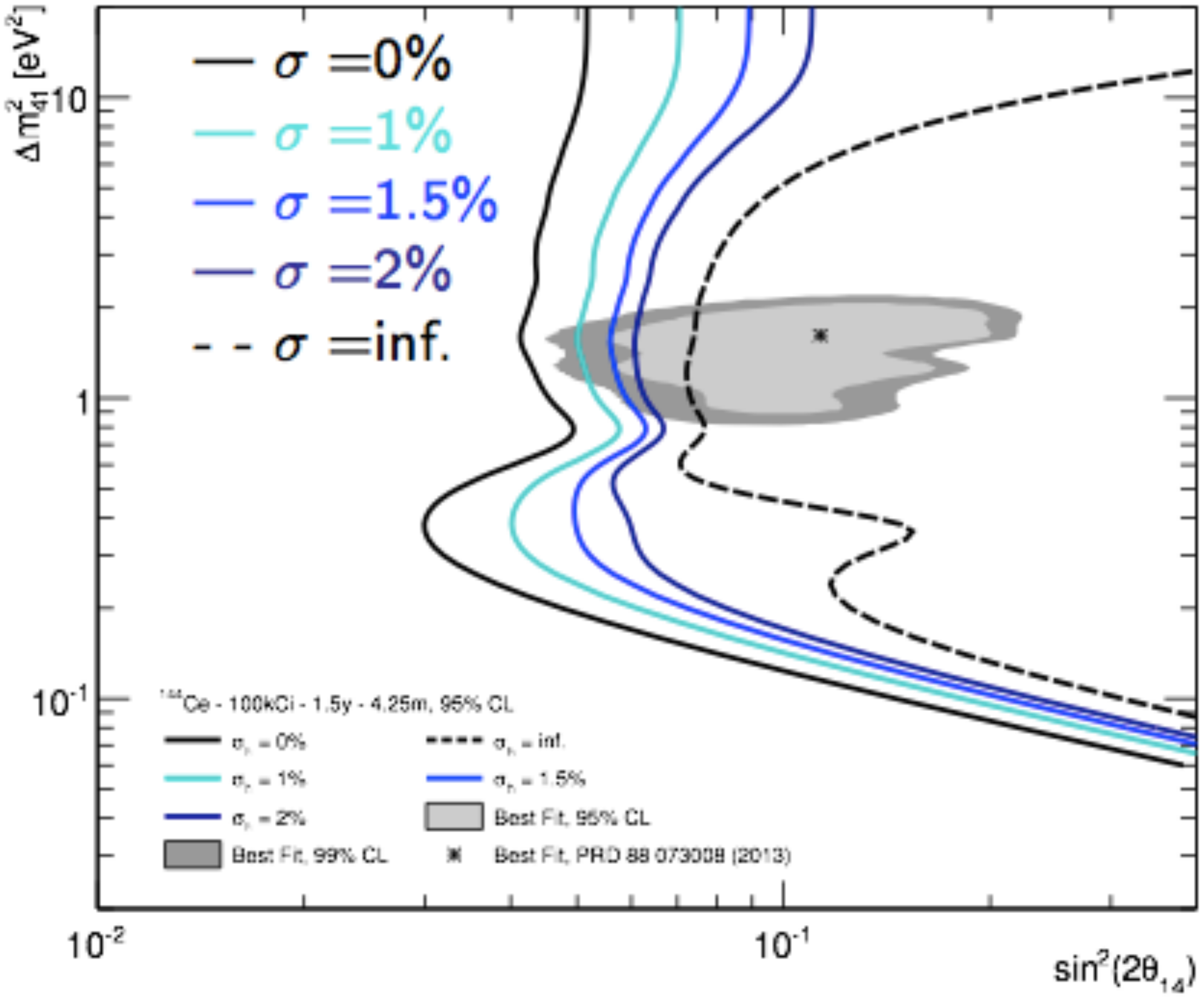
1.5 years data taking

Experimental challenge



Source activity:

- needed for rate analysis
- target accuracy: 1%



Source activity will be calibrated with calorimetric measurement, but not only source activity, but detector FV uncertainty (due to deformed vessel, leakage of scintillator outside the vessel, etc.) can also give similar result.

Conclusion

- SOX experiment will start data taking in late 2016
  - if systematics can be controlled < 1%, can examine most of the region where anomalies are claimed

- Another projects are also on-going :
  - MicroBooNE (data taking started 2015. July ~) : to verify LSND/MiniBooNE anomaly with new technology (liquid Argon time projection chamber)
  - Daya Bay, SNO+ …

- Prove of sterile neutrinos - starting point of questioning (as in DM search)