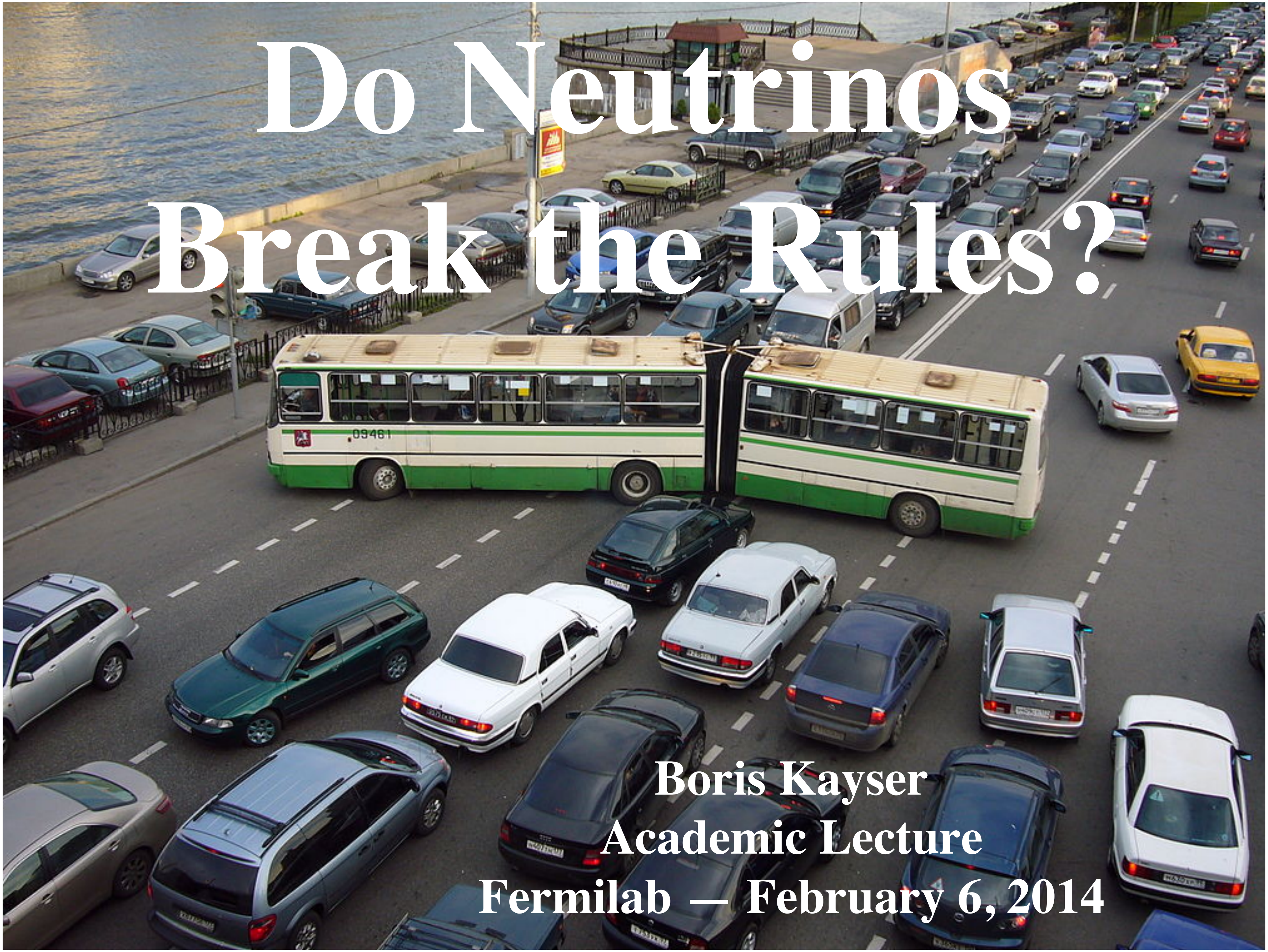
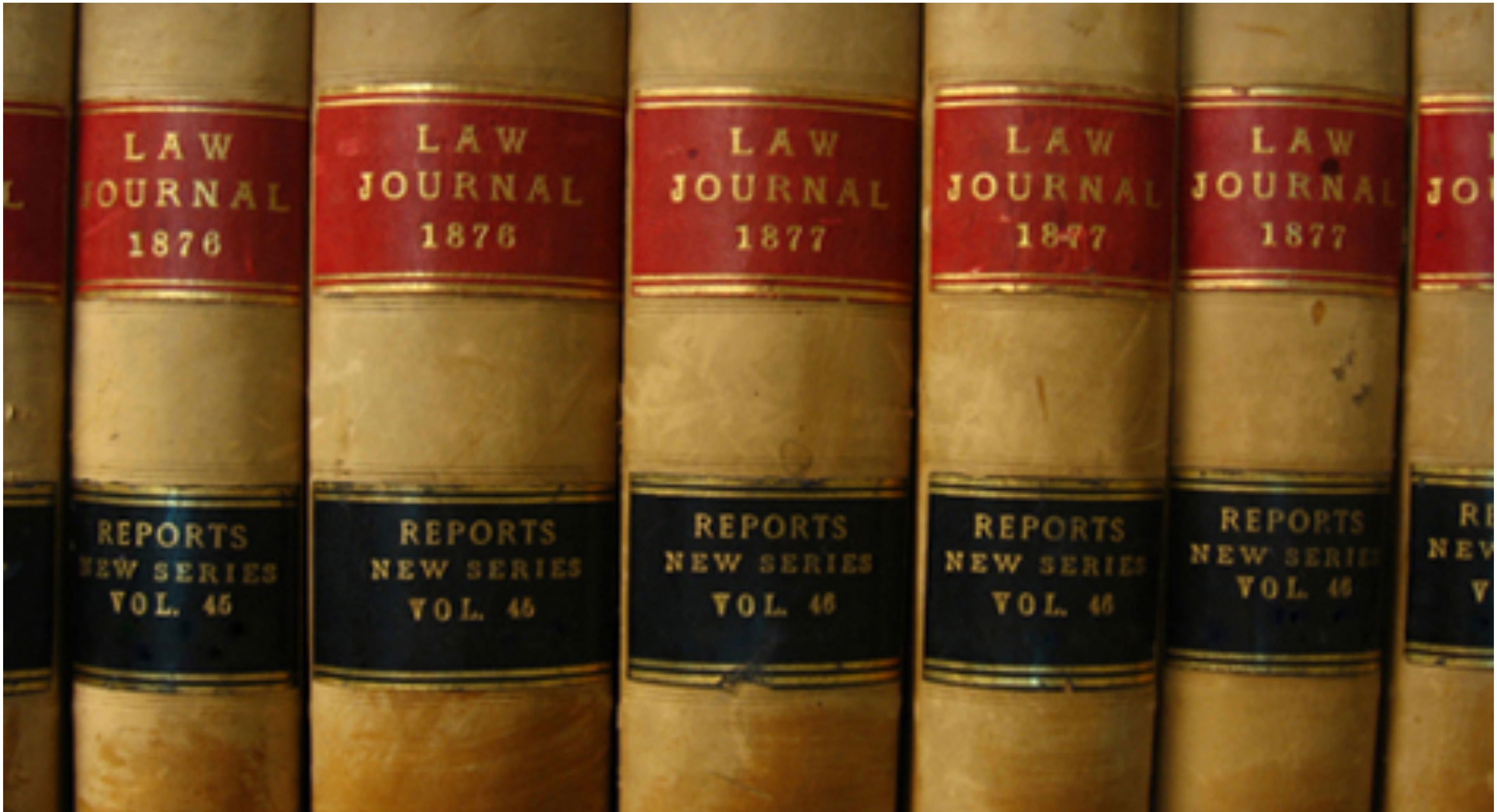


Do Neutrinos Break the Rules?

Boris Kayser

Academic Lecture

Fermilab — February 6, 2014



What rules are we talking about?

The Standard Neutrino Model (SνM) makes many assumptions (*The Rules*), some taken for granted and not even mentioned.

These assumptions include —

- **Quantum mechanics**
- **Special relativity**
- **A spectrum with only 3 neutrino mass eigenstates with masses less than ~ 1 TeV**
- **Neutrino interactions that are as predicted by the Electroweak Standard Model (SM), and the neglegibility of any non-SM interactions (NSI)**
- **Consequences of this last assumption include —**

  CPT invariance

  No anomalously big neutrino dipole moments or rapid neutrino decays

  Decoherence of interfering neutrino amplitudes only from kinematical effects

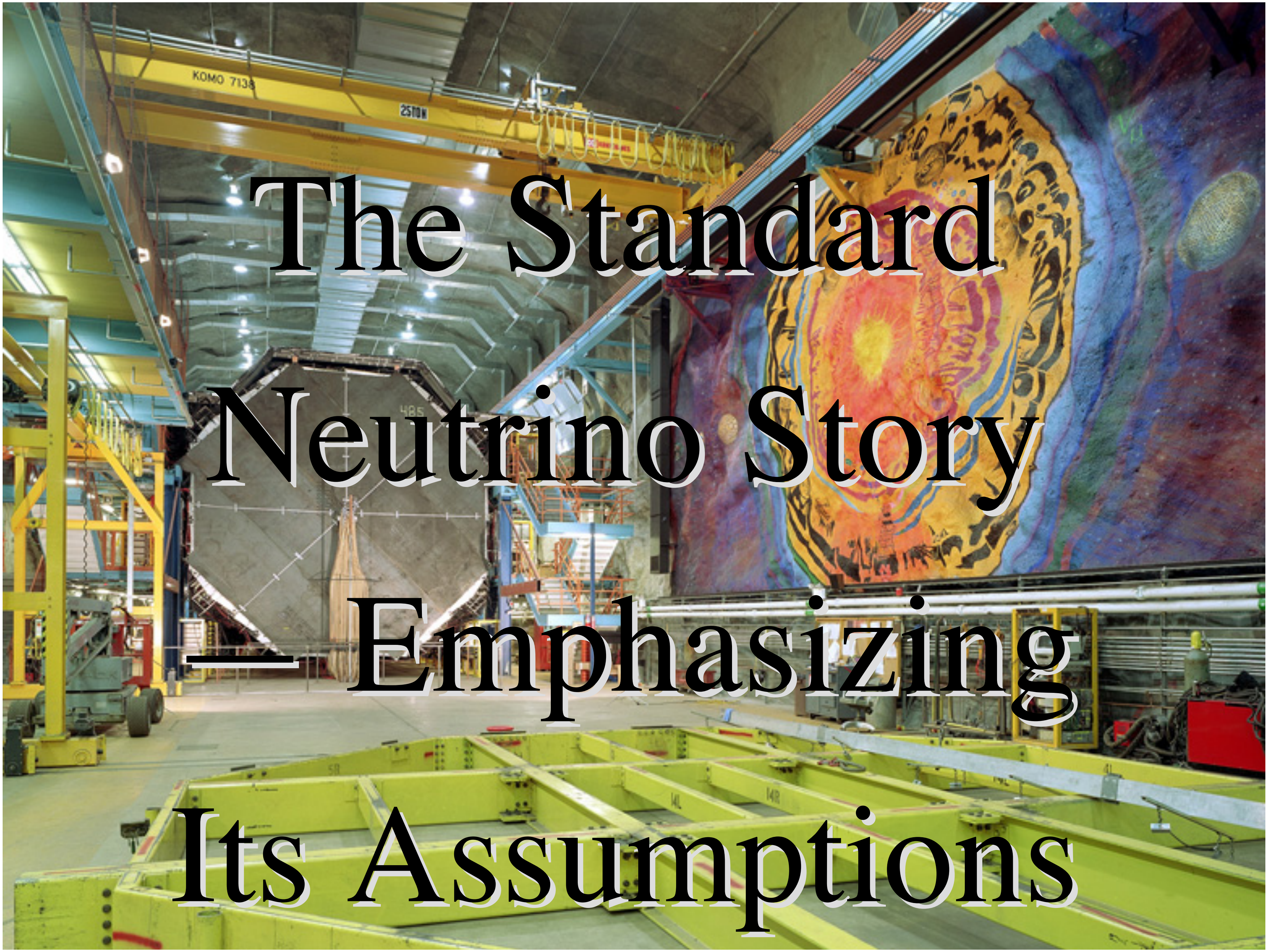
Q: Are *Neutrinos* More Likely Than Other Particles To Break the Rules?

A: *Neutrinos* Are *special* !

- **Weakest SM interactions of any known particles, so any non-SM interactions may be more visible**
- **Lightest known massive particles by far**
- **Oscillations can be very sensitive probes of tiny effects**
- **Only electrically neutral fermionic constituents of matter**
- **Only known candidates for Majorana masses, which are non-SM**

Neutrino experiments should always be on the lookout for behavior outside the SνM.

The Standard Neutrino Story — Emphasizing Its Assumptions



The Assumed SM W – Lepton Couplings

Semi-weak coupling

Left-handed

Charged lepton

$$\mathcal{L}_{SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \left(\bar{\ell}_{L\alpha} \gamma^{\lambda} \nu_{L\alpha} W_{\lambda}^{-} + \bar{\nu}_{L\alpha} \gamma^{\lambda} \ell_{L\alpha} W_{\lambda}^{+} \right)$$

$$= -\frac{g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \left(\bar{\ell}_{L\alpha} \gamma^{\lambda} U_{\alpha i} \nu_{Li} W_{\lambda}^{-} + \bar{\nu}_{Li} \gamma^{\lambda} U_{\alpha i}^{*} \ell_{L\alpha} W_{\lambda}^{+} \right)$$

CPT invariance is a consequence

Mass eigenstate

3 x 3 unitary leptonic mixing matrix

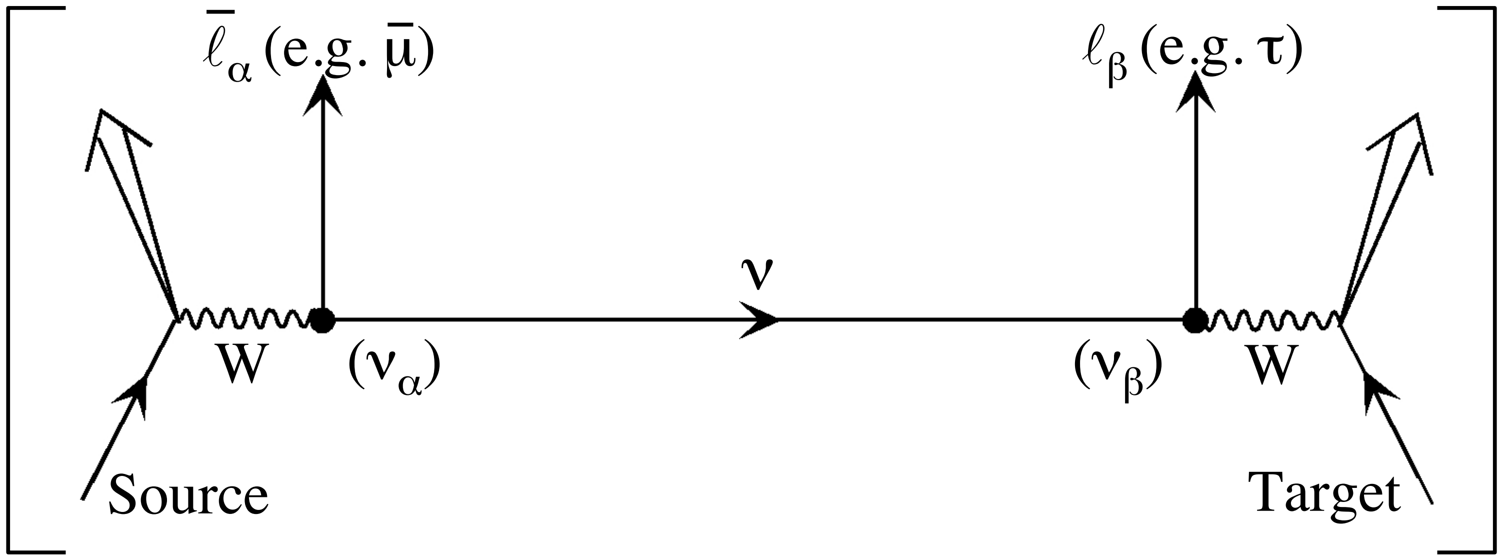
Taking mixing into account

$$\mathrm{Amp}\left(W^{+} \to \ell_{\alpha}^{+} + \nu_{i}\right) = \frac{g}{\sqrt{2}} U_{\alpha i}^{*} \qquad \mathrm{Amp}\left(\nu_{i} \to \ell_{\beta}^{-} + W^{+}\right) = \frac{g}{\sqrt{2}} U_{\beta i}$$

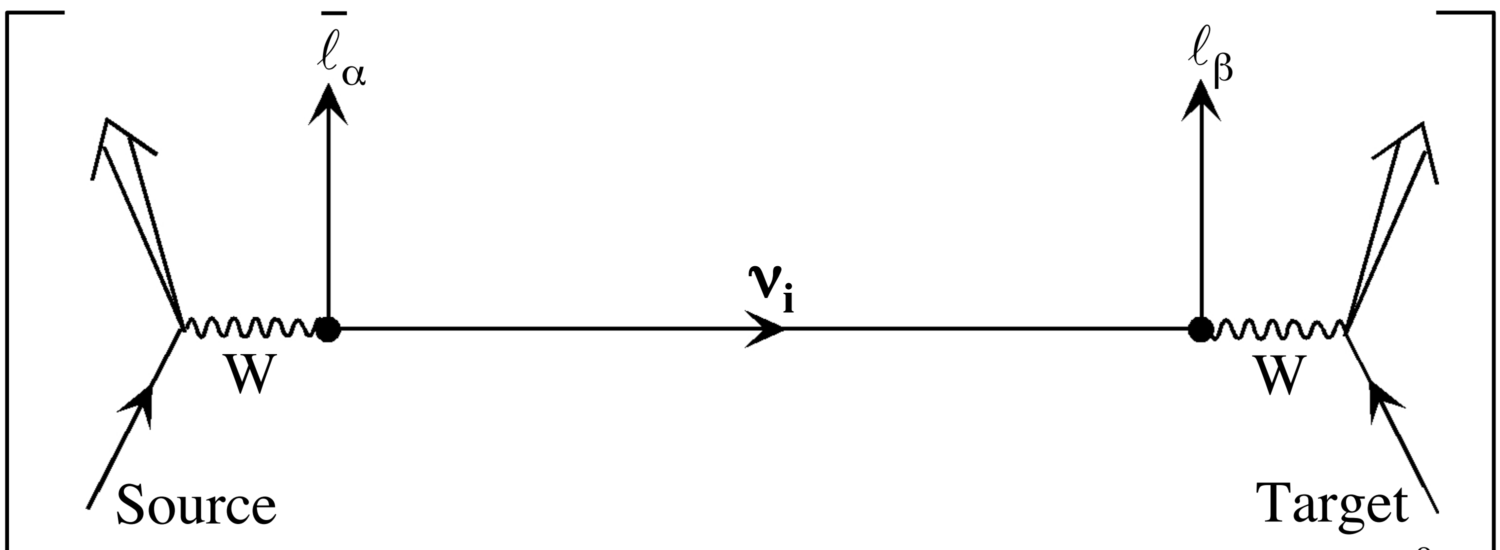
The Oscillation $\nu_\alpha \rightarrow \nu_\beta$

Quantum Mechanics

Amp

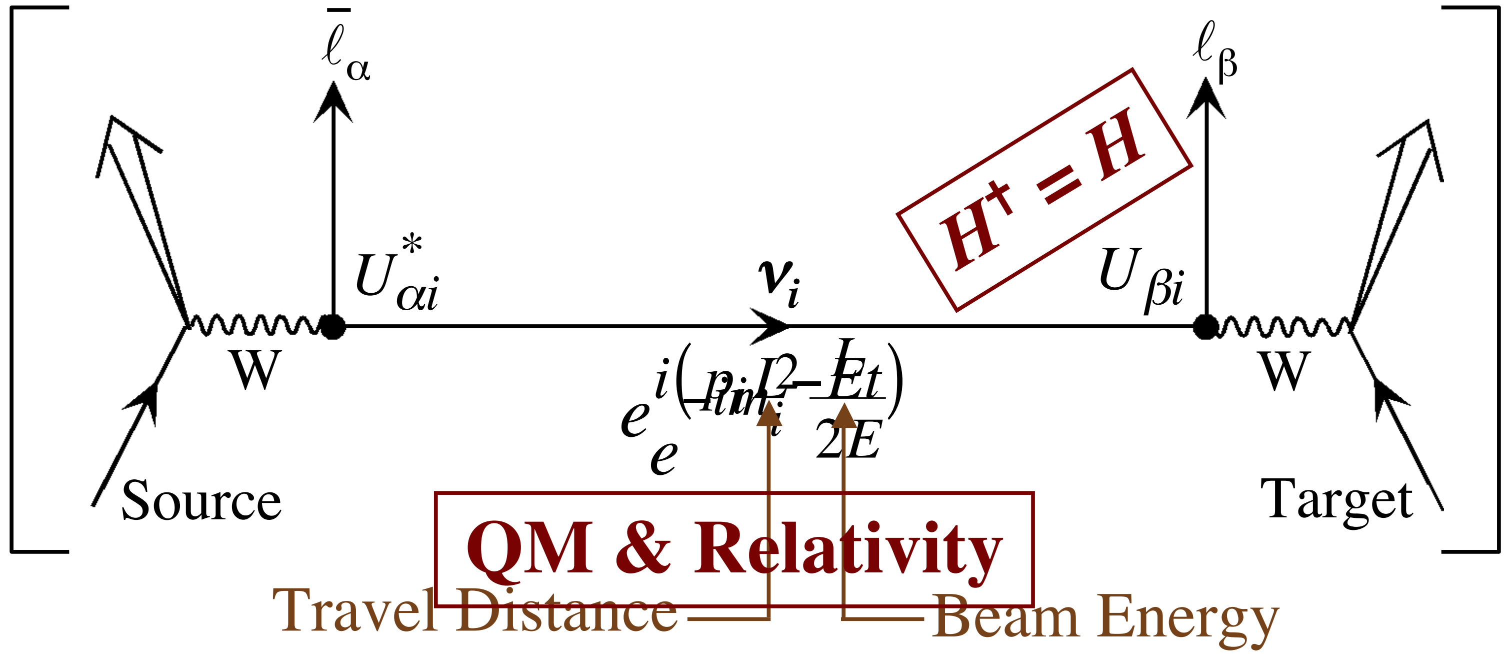


$= \sum_{\mathbf{i}}$ Amp



$$\mathrm{Amp}(\nu_\alpha \to \nu_\beta)$$

$$= \sum_{\mathbf{i}} \mathrm{Amp}$$



$$= \sum_i U^*_{\alpha i}\, e^{-im_i^2 \frac{L}{2E}}\, U_{\beta i}$$

$$P(\nu_\alpha \to \nu_\beta) = \left|\mathrm{Amp}(\nu_\alpha \to \nu_\beta)\right|^2 \qquad \boxed{\textbf{QM}}$$

Probability

Antineutrinos vs. Neutrinos

Because the neutrinos we encounter in the lab. are always of left-handed helicity, while the antineutrinos are always of right-handed helicity,

$$\bar{\nu}_\alpha \to \bar{\nu}_\beta = \mathrm{CP}\left(\nu_\alpha \to \nu_\beta\right)$$

Similarly,

$$\bar{\nu}_\alpha \to \bar{\nu}_\beta = \mathrm{CPT}\left(\nu_\beta \to \nu_\alpha\right)$$

If CPT-invariance holds,

$$P\left(\bar{\nu}_\alpha \to \bar{\nu}_\beta\right) = P\left(\nu_\beta \to \nu_\alpha\right)$$

In particular,

$$P\left(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha\right) = P\left(\nu_\alpha \rightarrow \nu_\alpha\right)$$

Hence,

$$P\left(\bar{\nu}_\alpha \rightarrow \bar{\nu}_{\not\alpha}\right) = P\left(\nu_\alpha \rightarrow \nu_{\not\alpha}\right)$$

Even if there are CP-violating differences,

$$P\left(\bar{\nu}_\alpha \rightarrow \bar{\nu}_{\beta \neq \alpha}\right) \neq P\left(\nu_\alpha \rightarrow \nu_{\beta \neq \alpha}\right) \ ,$$

between individual ***appearance*** probabilities,
if CPT-invariance holds, the ***disappearance*** probabilities
for a neutrino of a given flavor and its antineutrino
must be equal.

However —

An experiment that thinks it is measuring a disappearance probability may actually be measuring something else.

More later ………

If CPT-invariance is violated, we can have —

$$\boxed{\mathrm{Mass}(\bar{\nu}_i) \neq \mathrm{Mass}(\nu_i)}$$

and

$$\boxed{\text{Mixing matrix (Antileptons)} \neq \text{Mixing matrix (Leptons)}}$$

The SνM assumes that neither of things happens, and that the W – lepton couplings are given by the SM, with the result that —

In the SνM —

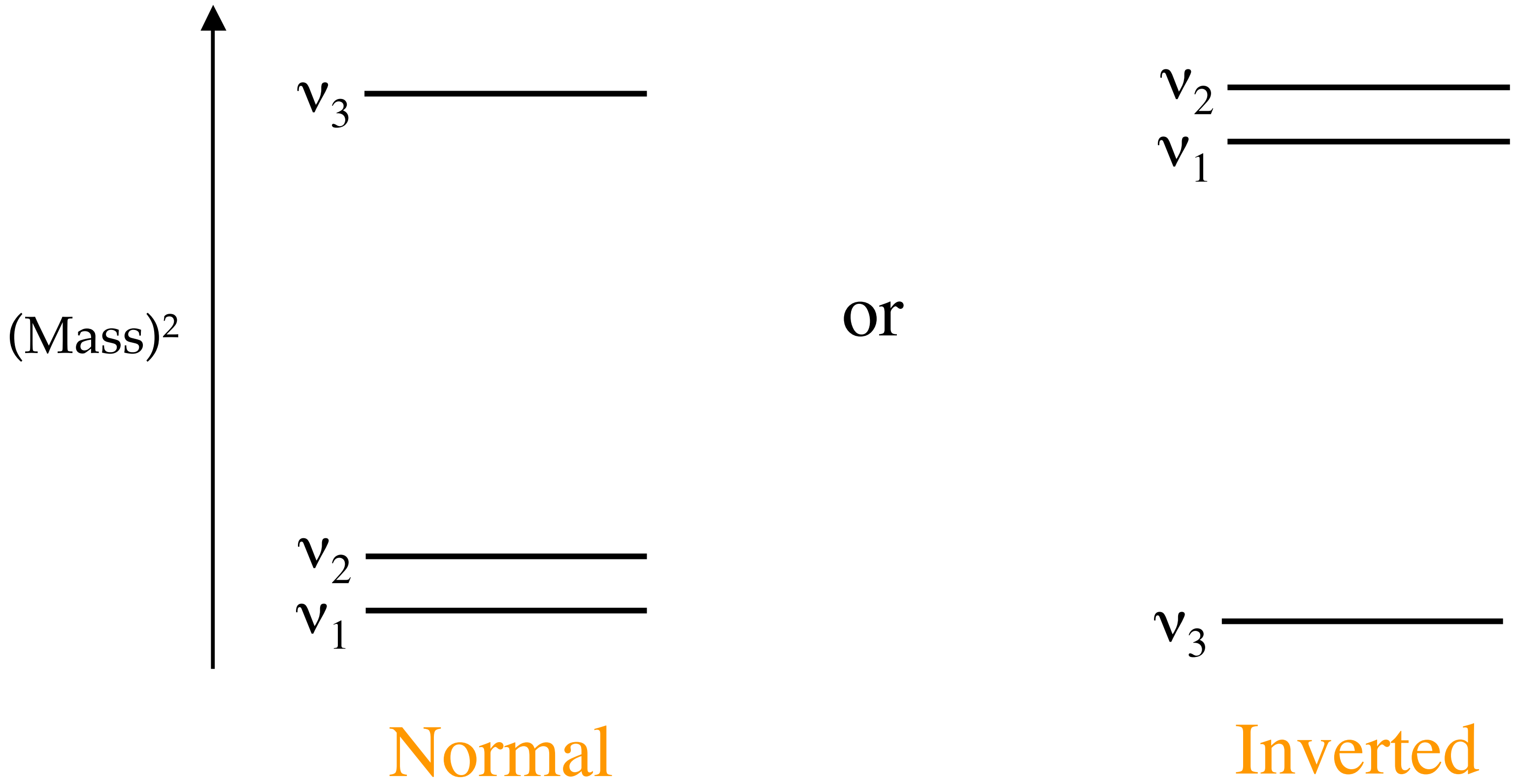
$$P\left(\overset{(-)}{\nu}_\alpha \rightarrow \overset{(-)}{\nu}_\beta\right) =$$

$$\delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}\right) \sin^2\left(1.27\,\Delta m_{ij}^2\left(\mathrm{eV}^2\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

$$\overset{(-)}{+} 2\sum_{i>j} \mathrm{Im}\left(U_{\alpha i}^{*} U_{\beta i} U_{\alpha j} U_{\beta j}^{*}\right) \sin\left(2.54\,\Delta m_{ij}^2\left(\mathrm{eV}^2\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right)$$

CPT-invariance is built in.

The Single (Mass)^2 Spectrum



$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 \cong 7.5 \times 10^{-5}\ \text{eV}^2, \qquad \Delta m^2_{32} \cong 2.4 \times 10^{-3}\ \text{eV}^2$$

There might be more mass eigenstates.

The Single Unitary Lepton Mixing Matrix *U*

Not valid if there are sterile neutrinos

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

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

$\theta_{12} \approx 33°$, $\theta_{23} \approx 36\text{-}42°$ <u>or</u> $48\text{-}54°$, $\theta_{13} \approx 8\text{-}9°$

We know nothing about the phases.

Possible Rule Violations

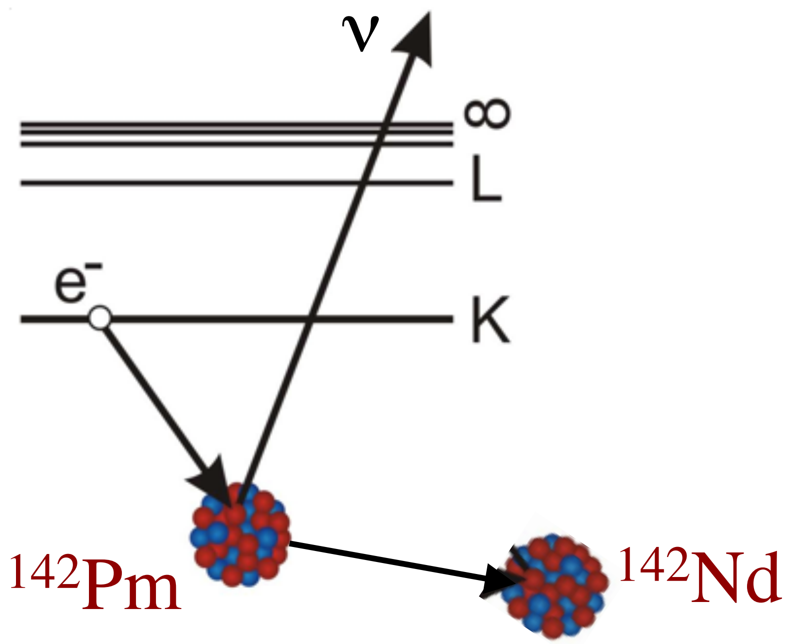
Violation of Quantum Mechanics

This would be a ***far-reaching*** discovery, to say the least!

There have been indications of oscillating ***decay rates*** that almost surely cannot behave as reported if quantum mechanics holds.

We expect that —

Electron Capture (EC) Decay

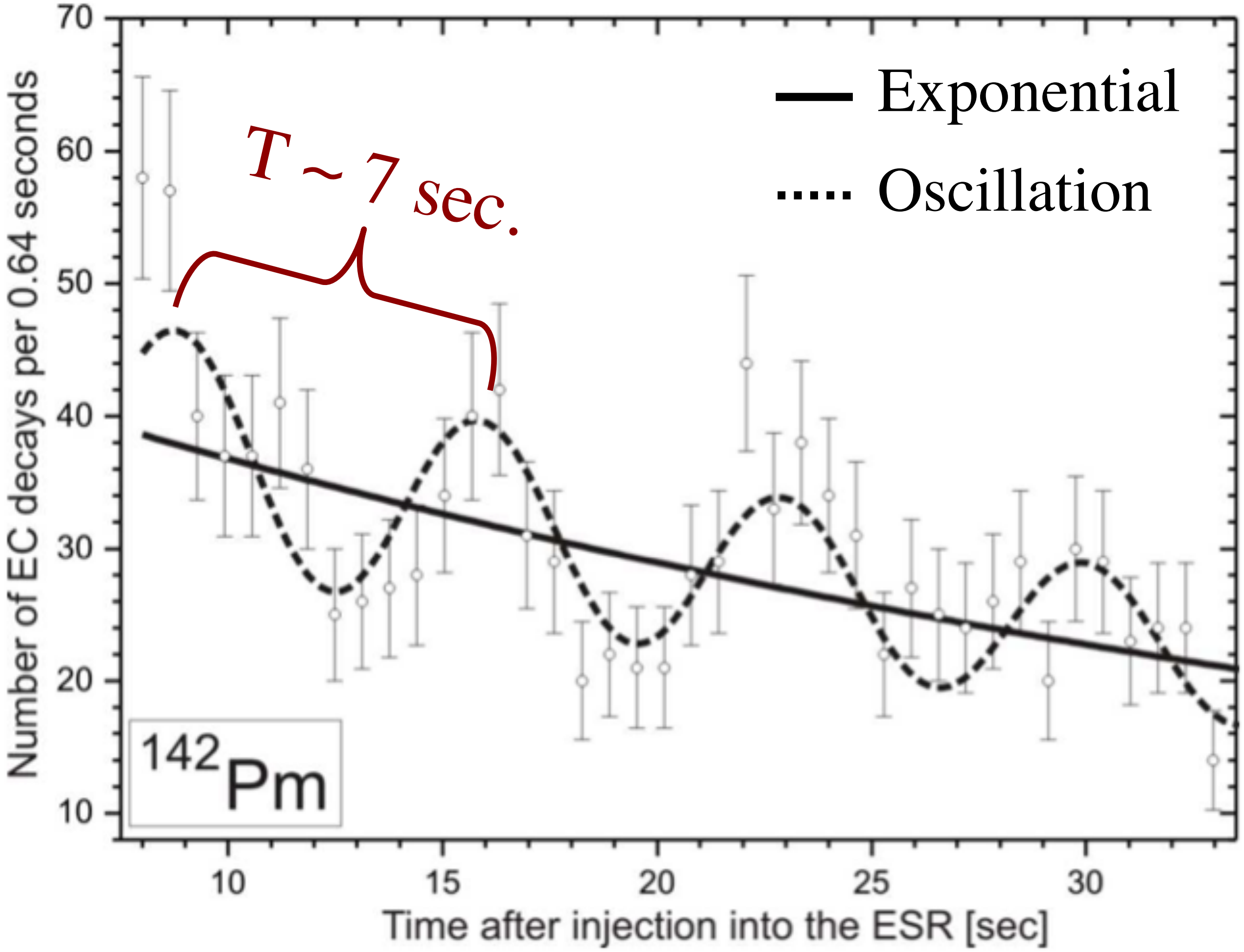


leads to —

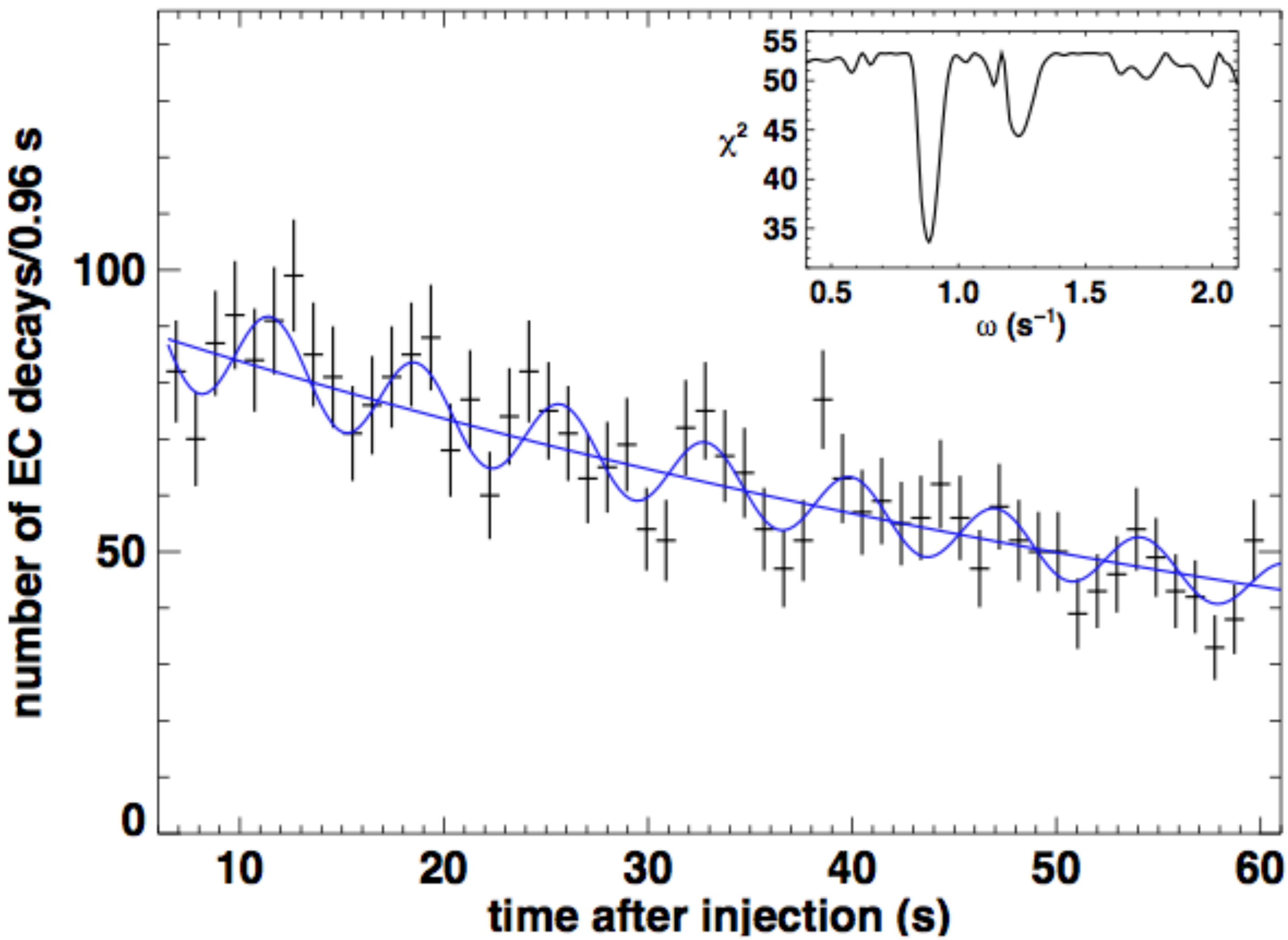
$$\frac{dN}{dt}(t) = -\frac{N(0)}{\tau} e^{-t/\tau} \quad ; \; \tau \equiv \text{meanlife}$$

But, Litvinov *et al*. report that —

EC decays of H-like ^{142}Pm, ^{140}Pr, and ^{122}I ions in a storage ring at GSI oscillate.



The effect is still present as of a few months ago.



From 1309.7294

Has GSI Observed Decay-Rate Oscillation From *Neutrino Mass*?

Never accept an observation until confirmed by theory.

— A. Eddington

Quantum mechanics and common sense:

The rates of production of ***different final states*** contribute to the total event rate ***incoherently***.

Amplitudes for the production of different final states do NOT interfere!

There are (at least) 3 neutrino mass eigenstates ν_i, with unequal masses m_i.

Thus, in electron-capture (EC) decays such as

$$H - like\ {}^{142}Pm \to {}^{142}Nd + \nu \; ,$$

in which a parent particle P decays to a daughter particle D plus a neutrino, there are 3 distinct final states:

$$P \begin{array}{l} \nearrow D + \nu_1 \\ \longrightarrow D + \nu_2 \\ \searrow D + \nu_3 \end{array}$$

Thus,

$$\frac{dN}{dt}\left(H-like\ {}^{142}Pm \rightarrow {}^{142}Nd + \nu;\, t\right)$$

$$= \sum_i \left[\frac{dN}{dt}\left(H-like\ {}^{142}Pm \rightarrow {}^{142}Nd + \nu_i;\, t\right)\right]$$

Mass eigenstate

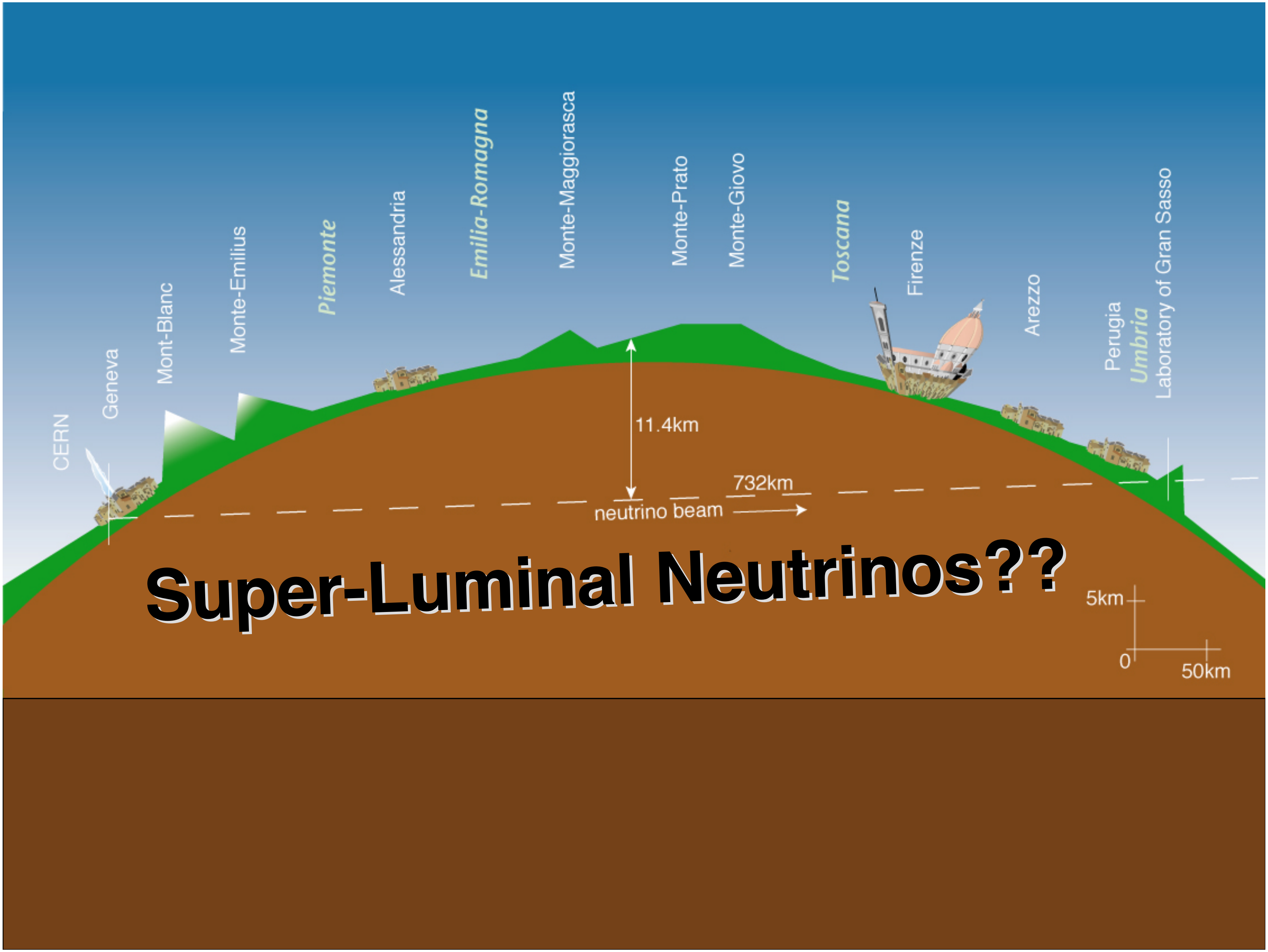
An incoherent sum

Unlike neutrino oscillation, this sum is not expected to depend on the splittings $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$.

This dependence comes from interference.

Violation of Relativity

This too would be a ***far-reaching*** discovery,
to say the least!


CERN
Geneva
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
Super-Luminal Neutrinos??
5km
0
50km

OPERA: Neutrinos from CERN arrive at Gran Sasso

$57.8 \pm 7.8\ (\text{stat})\ {}^{+8.3}_{-5.9}\ (\text{sys})$ ns before a light beam would.

$$v_{\nu} = c\ \{1 + [2.37 \pm 0.32\ (\text{stat})\ {}^{+0.34}_{-0.24}\ (\text{sys}) \times 10^{-5}]\}$$

"Extraordinary claims require extraordinary evidence."

Q: How come the neutrinos from Supernova 1987A, 168,000 light years away, did not arrive here 4 years before the light did?

A: Good point, but maybe the speed of neutrinos is energy-dependent.

Updated OPERA results obtained using a dedicated short-bunch proton beam at CERN show no significant deviation of the ν_μ velocity from the speed of light.

$$-1.8 \times 10^{-6} < (v_\nu - c)/c < 2.3 \times 10^{-6} \text{ @ } 90\% \text{ CL}$$

1212.1276

But can there be OTHER violations of relativity?

Lorentz-Invariance Violation

If a neutrino beam travels a great distance L,
a tiny (mass)^2 splitting Δm^2 can get amplified
into a visibly-large oscillation phase $\Delta m^2\, L/E$.

One can construct a Lorentz-Invariance-Violating
(LIV) model with ***massless*** neutrinos
that still leads to neutrino oscillation.

(Kostelecky & Mewes; hep-ph/0308300)

$$\mathcal{L} \supset \frac{1}{2} i\bar{L}_\alpha \gamma^\mu \overleftrightarrow{D}_\mu L_\alpha - \left(a_\mu\right)_{\alpha\beta} \bar{L}_\alpha \gamma^\mu L_\beta + \frac{1}{2} i\left(c_{\mu\nu}\right)_{\alpha\beta} \bar{L}_\alpha \gamma^\mu \overleftrightarrow{D}_\nu L_\beta$$

SM lepton doublet

LIV Numbers

$\alpha, \beta =$ e, μ, τ

This leads to the effective Hamiltonian for time evolution of a neutrino —

$$\left(H_{\text{eff}}\right)_{\alpha\beta} = |\vec{p}|\delta_{\alpha\beta} + \frac{1}{|\vec{p}|}\left[a_{\mu}p^{\mu} - c_{\mu\nu}p^{\mu}p^{\nu}\right]_{\alpha\beta}$$

The oscillation phases are controlled by aL and cEL.

If $L = 1.5 \text{ x } 10^{8}$ km, the sun – earth distance, ***very tiny*** a and c can lead to visibly-large oscillation phases.

At least at some energies, the oscillation phase can have the form ***(constant*** **x** ***L/E)***, mimicking the L and E dependence of oscillation caused by neutrino mass.

LIV, as an alternative to ν mass, is hard to rule out.

However, at some energies one expects an oscillation phase with ***non-standard E dependence***.

Also, the oscillation will depend on the ***direction*** of propagation of the oscillating beam .

The apparent moral: In neutrino experiments, one should take nothing for granted, and should measure with precision.

Light ($m \sim 1$ eV) Sterile Neutrinos

A sterile neutrino is one that does
not couple to the SM W or Z boson.

Light Sterile Neutrinos:
Theory, Evidence and Prospects

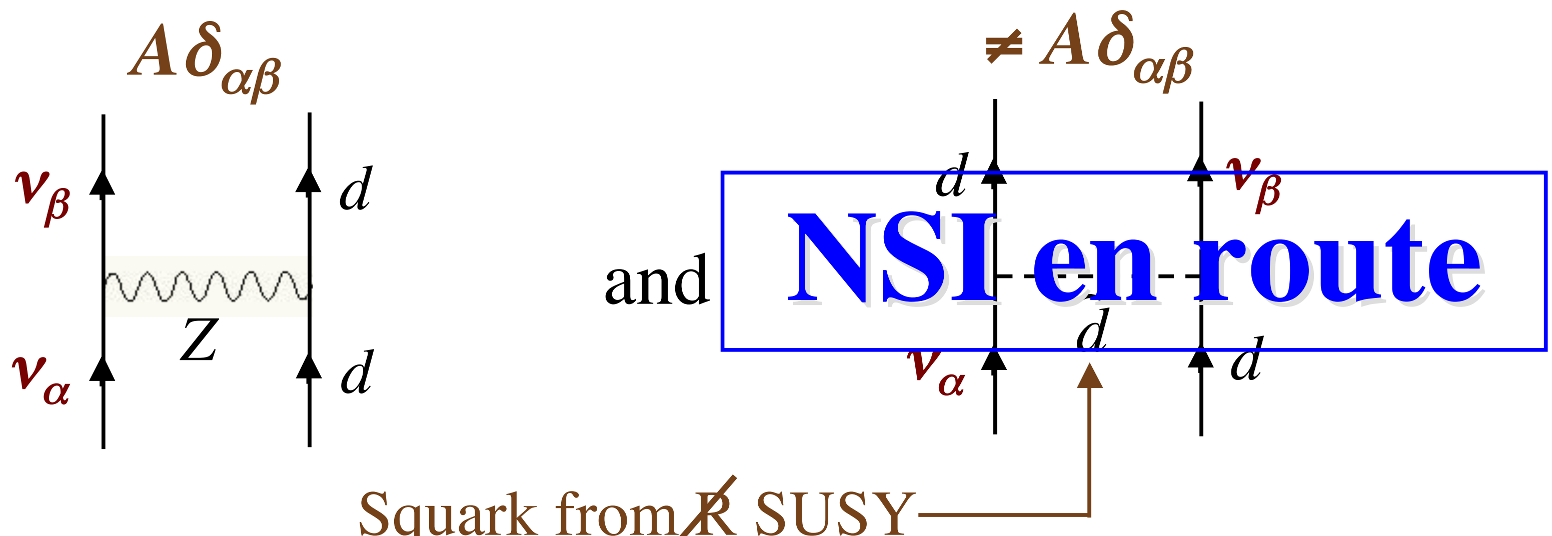
Already covered by
Andre de Gouvea
and
David Schmitz

Non–SM Neutrino Interactions (NSI)

Surely, there are new interactions beyond the SM,
and neutrinos participate in (at least some of) them.

Potentially, non-SM neutrino interactions (NSI) could have significant effects on neutrino oscillation.

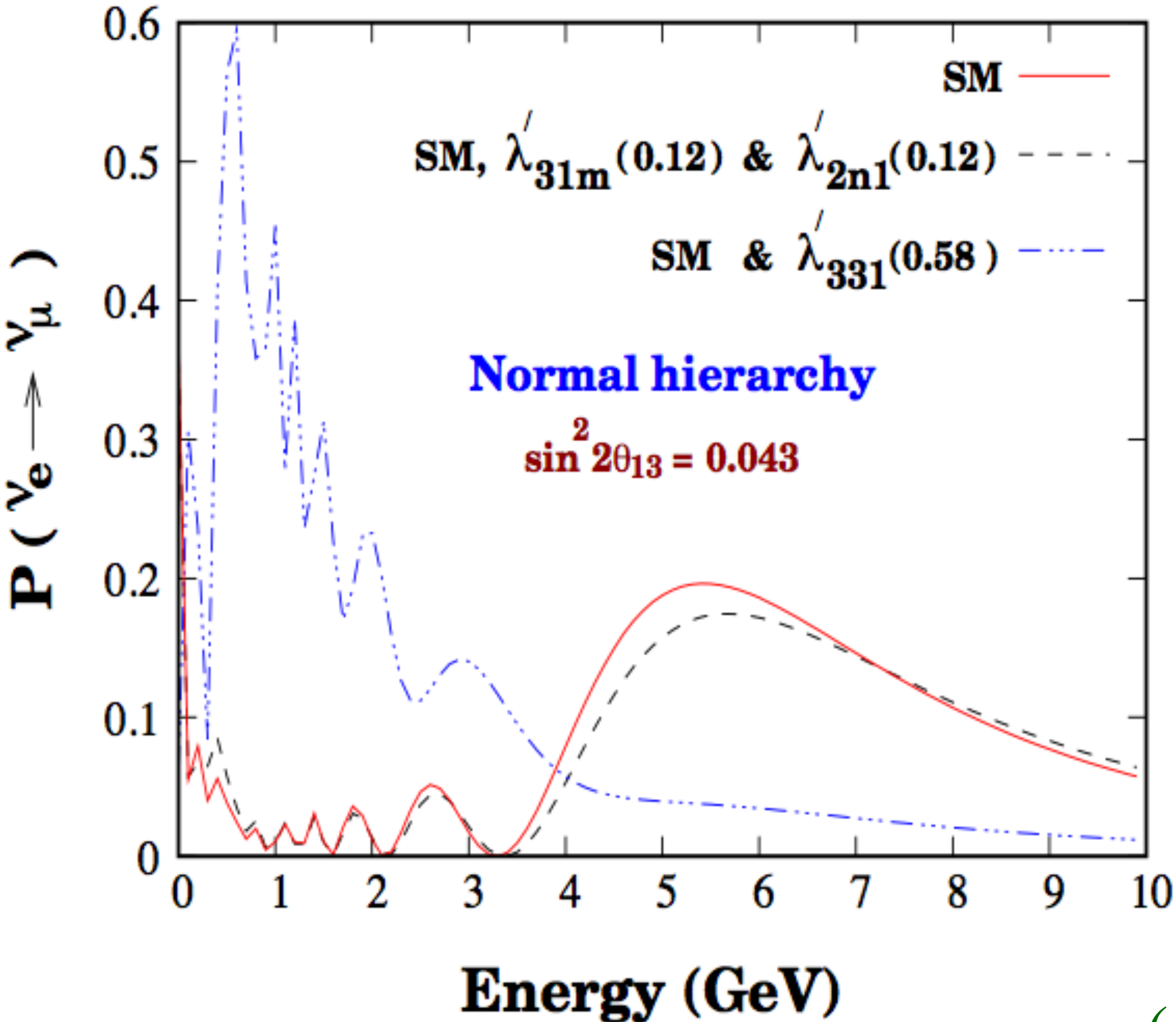
Suppose, for example, that neutrinos passing through earth matter interact with the down quarks there both through —



The SM Z exchange amplitude, $A\delta_{\alpha\beta}$, is proportional to the identity matrix in flavor space.

Any such influence on neutrino propagation will not affect ***oscillation***.

But the squark exchange does affect oscillation.

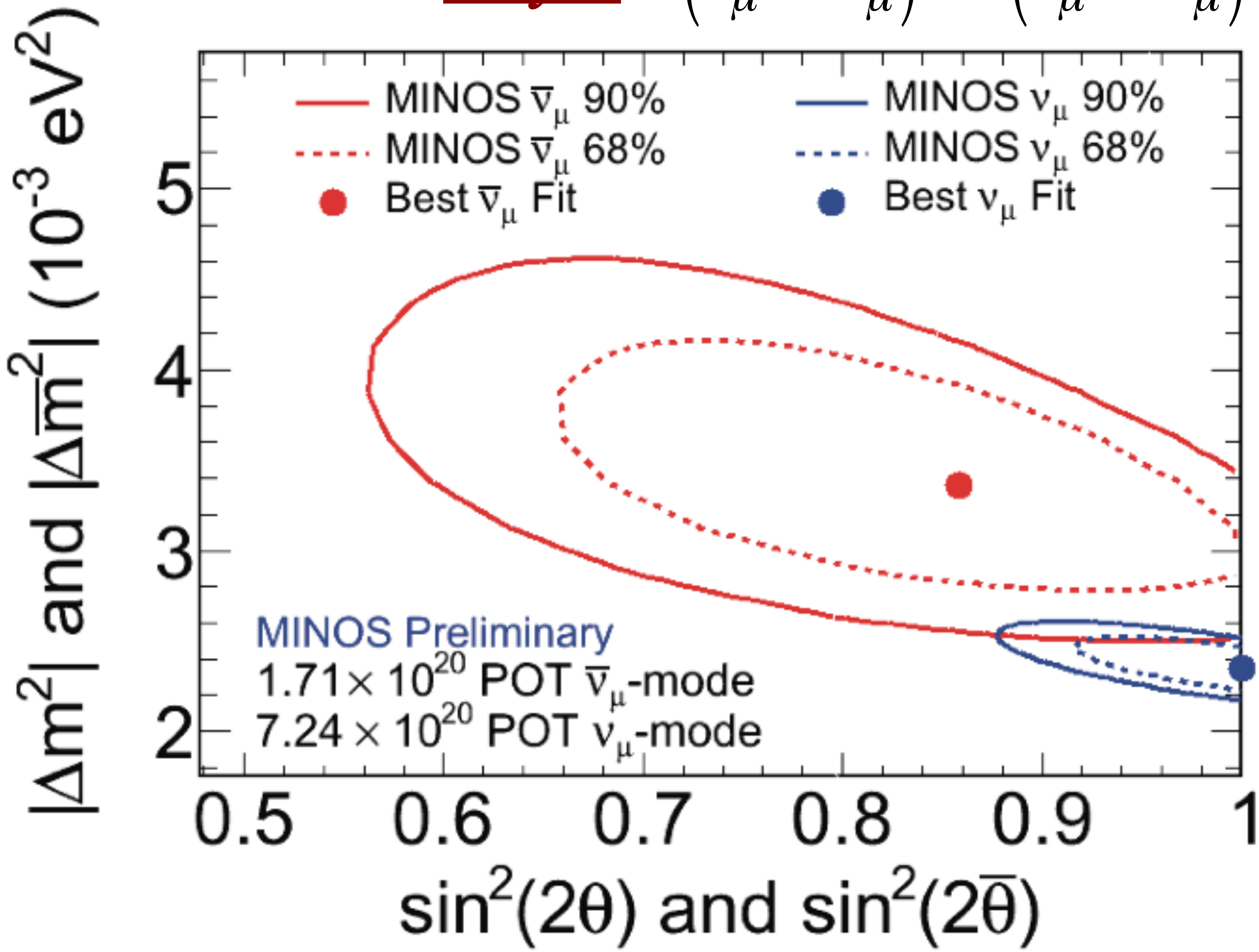


L = 7152 km

$\lambda' \equiv \not{R}$ SUSY couplings

(Adhikari et al., hep-ph/0608034)

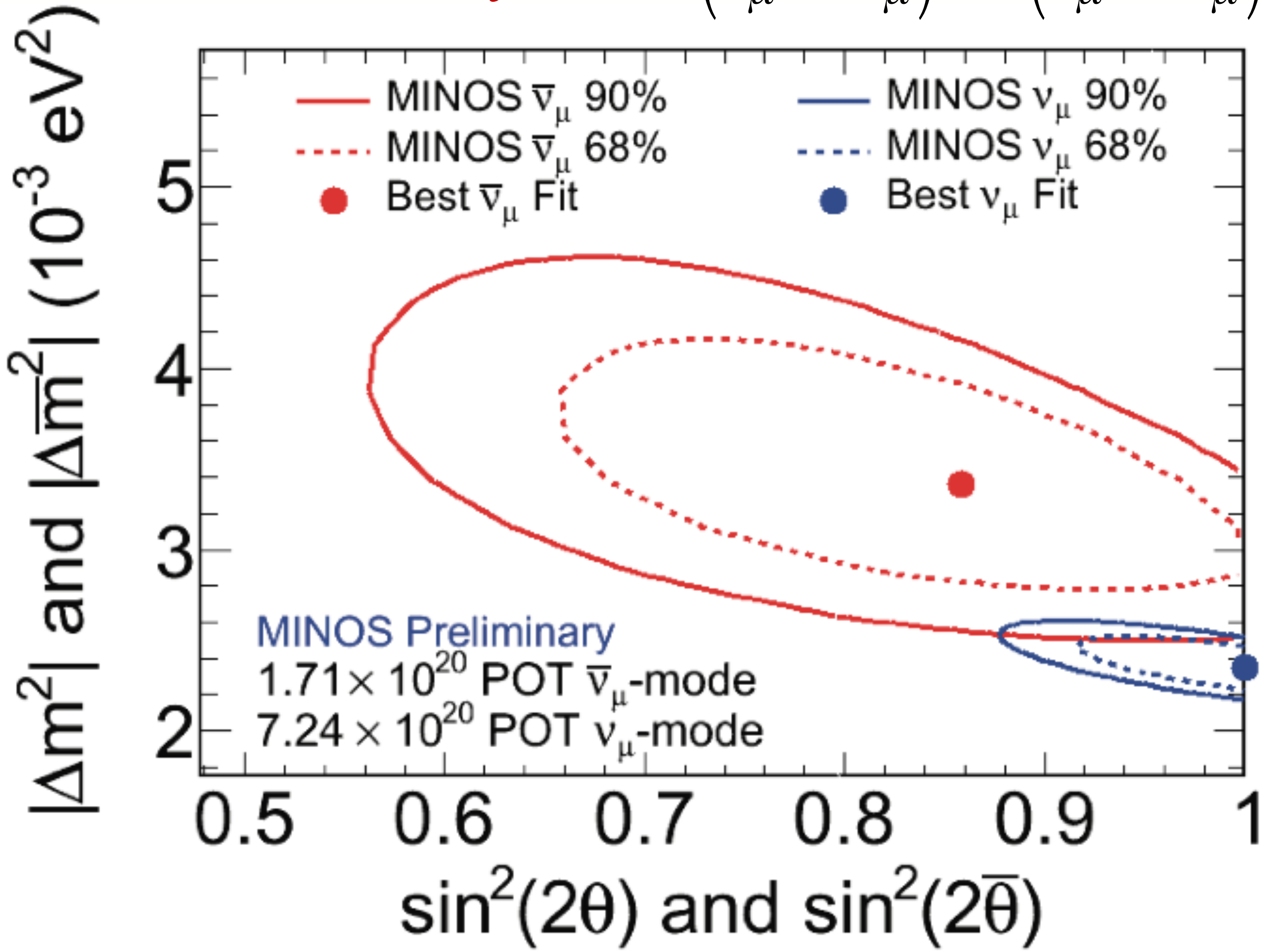
MINOS: ***Maybe*** $P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \neq P(\nu_\mu \to \nu_\mu)$



P. Vahle, Neutrino 2010

Non-SM neutrino interactions?? (Kopp, Machado, Parke)

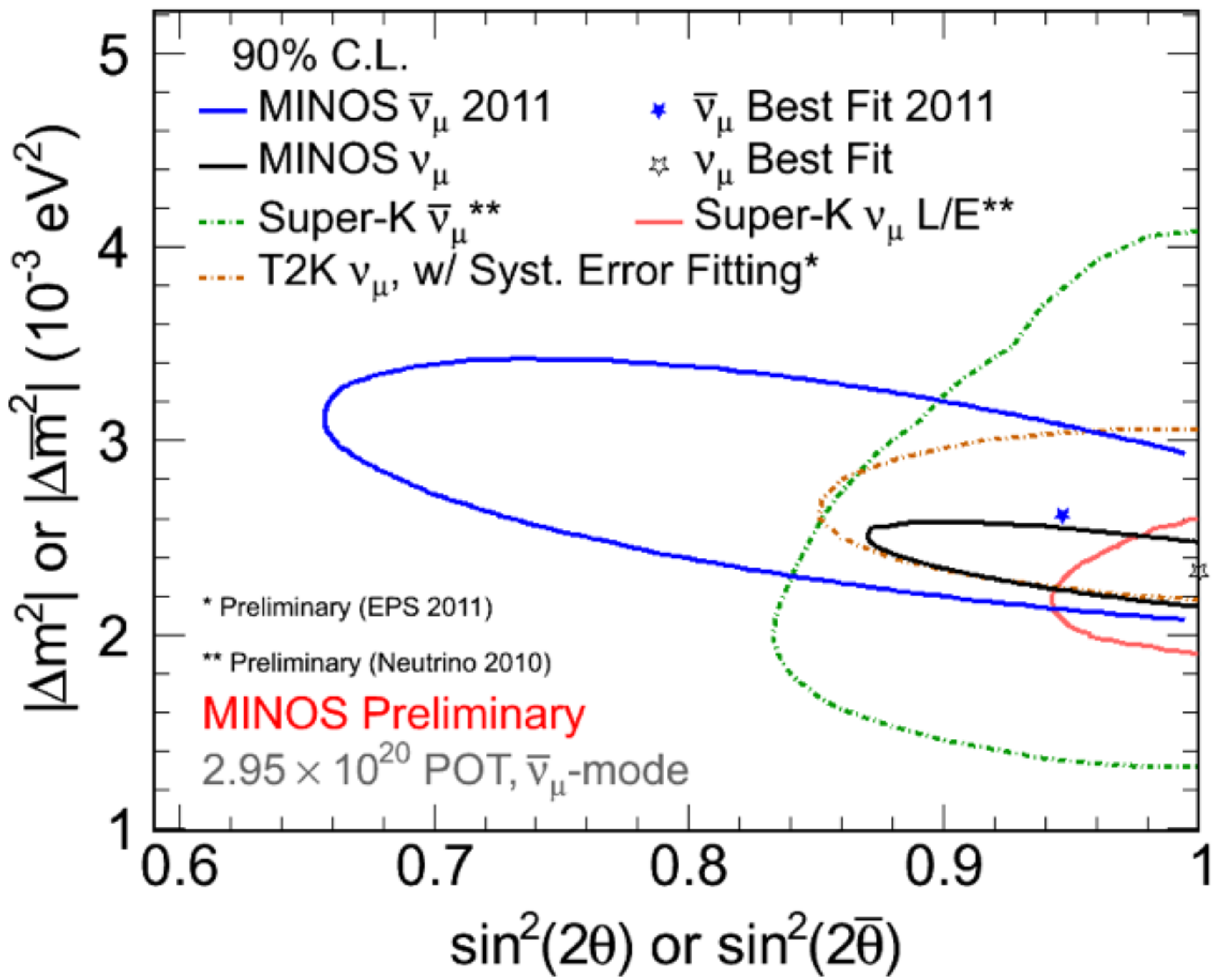
MINOS *may* find $P\left(\bar{\nu}_\mu \to \bar{\nu}_\mu\right) \neq P\left(\nu_\mu \to \nu_\mu\right)$



P. Vahle, Neutrino 2010

NSI at the detector $\nu_\tau + N \to X + \mu$ (Kopp, Machado, Parke)

MINOS: *With 70% More $\bar{\nu}$ Data*



The Model and the Moral

A measurement of "$P(\nu_\mu \to \nu_\mu)$" is really a measurement of the μ^- production rate in a far detector.

Similarly for "$P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$" and the μ^+ production rate.

Kopp et al. included not only the possibility of ν_μ survival, but also the possibility of $\nu_\mu \xrightarrow[\text{Osc.}]{} \nu_\tau + N \to X + \mu^-$.

Interference between the amplitudes for these two processes led to a CP-violating difference between the μ^- and the μ^+ production rates. There was no CPT violation!

The moral: A difference between the μ^- production rate in an initially ν_μ beam, and the corresponding μ^+ production rate in an initially $\bar{\nu}_\mu$ beam, is not necessarily a violation of CPT.

Such a difference may be a striking effect of NSI.

NSI Parametrization

Possible neutrino NSI are parametrized by an effective 4-fermion interaction —

$$\mathcal{L}_{eff}\,(\mathrm{NSI}) = -2\sqrt{2}G_F \sum_{\substack{\alpha,\beta=e,\mu,\tau \\ f=e,u,d}} \left[\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right]\left[\bar{f}\gamma^\mu\left(\varepsilon_{\alpha\beta}^{fL} P_L + \varepsilon_{\alpha\beta}^{fR} P_R\right) f\,\right],$$

where $P_{L,R} \equiv \frac{1}{2}\left(1 \mp \gamma_5\right)$.

We expect that $\varepsilon \sim (M_W/M_{NSI})^2$.

$\boldsymbol{M_{NSI} = ???}$

Allowed Ranges of NSI Couplings

90% CL. From ν scattering experiments, etc.

$\alpha\beta$	$\varepsilon_{\alpha\beta}^{eL}$	$\varepsilon_{\alpha\beta}^{eR}$
ee	$(-0.03, 0.08)$	0.004
$\mu\mu$	0.03	0.03
$\tau\tau$	$(-0.46, 0.24)$	$(-0.25, 0.43)$
$e\tau$	0.33	0.18
$\mu\tau$	0.1	0.1

Single-number entries are bounds on $|\varepsilon|$.

$\alpha\beta$	$\varepsilon^{uL}_{\alpha\beta}$	$\varepsilon^{uR}_{\alpha\beta}$	$\varepsilon^{dL}_{\alpha\beta}$	$\varepsilon^{dR}_{\alpha\beta}$
ee	$(-1.0, 0.3)$	$(-0.4, 0.7)$	$(-0.3, 0.3)$	$(-0.6, 0.5)$
$\mu\mu$	0.003	$(-0.008, 0.003)$	0.003	$(-0.008, 0.015)$
$e\tau$	0.5	0.5	0.5	0.5
$\mu\tau$	0.05	0.05	0.05	0.05

(From “The Physics of Neutrinos”, by Barger, Marfatia, and Whisnant)

Violation of CPT Invariance

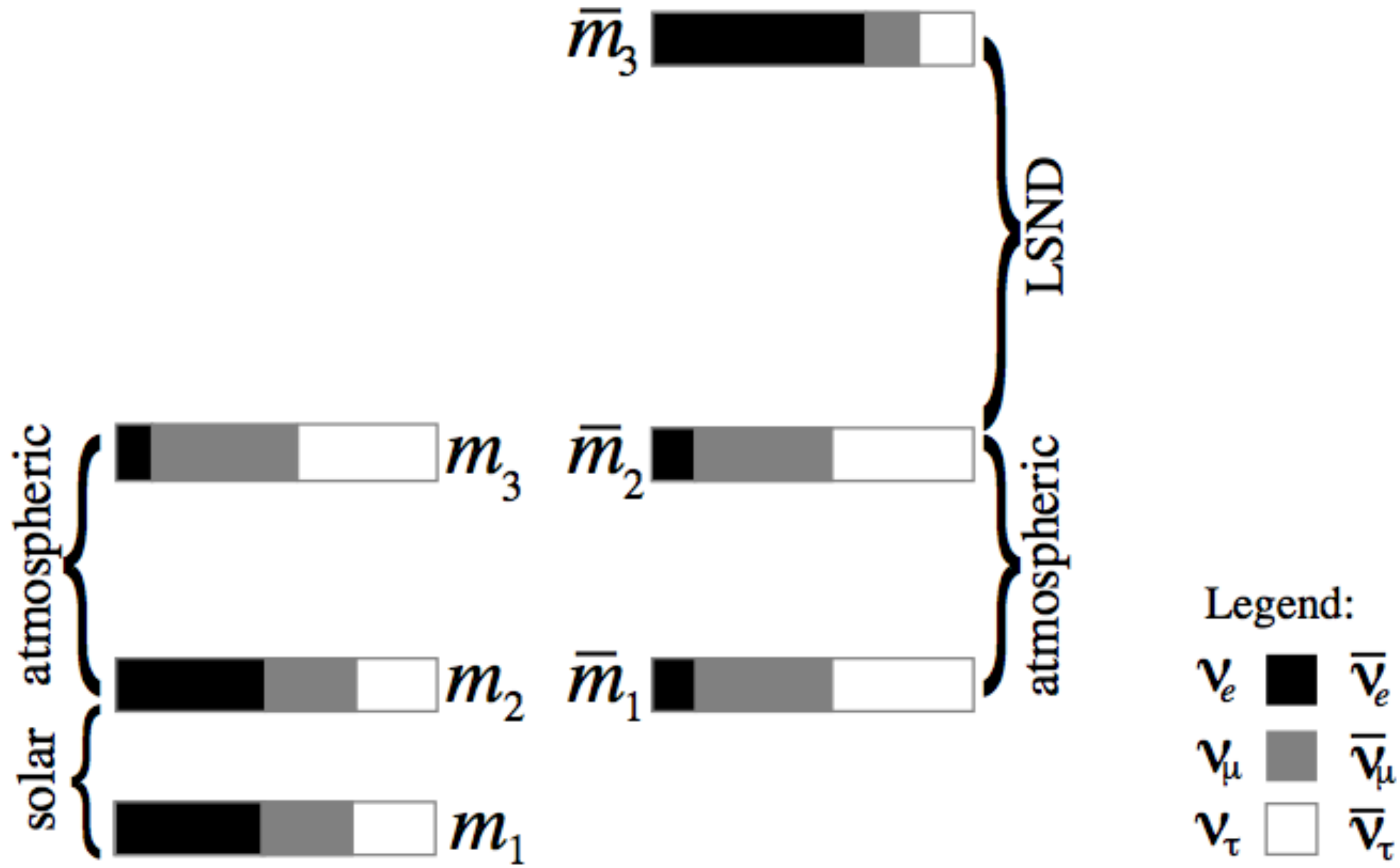
A Lorentz-invariant local quantum field theory with Hermitean interactions and with the usual spin-statistics relation will be CPT invariant.

Thus, discovery of CPT violation ($\cancel{\text{CPT}}$) would be revolutionary!

We have already noted that $\cancel{\text{CPT}}$ would be signalled by a difference, for a given flavor, between ν and $\bar{\nu}$ disappearance probabilities (if you can measure them).

The Lorentz-violating model we mentioned also violates CPT.

A CPT - violating neutrino world



(Barenboim, Borissov, Lykken)

With —

$$\boxed{\mathrm{Mass}(\overline{\nu}_i) \neq \mathrm{Mass}(\nu_i)}$$

and

$$\boxed{\text{Mixing matrix (Antileptons)} \neq \text{Mixing matrix (Leptons)}} \; ,$$

oscillation can be greatly affected, with different oscillation frequencies for neutrinos than for antineutrinos, and with different amounts of oscillation for the two.

One often hears that **"The observation of neutrinoless double beta decay (0νββ) would prove that neutrinos are their own antiparticles."**

This is true only if there is no ~~CPT~~!

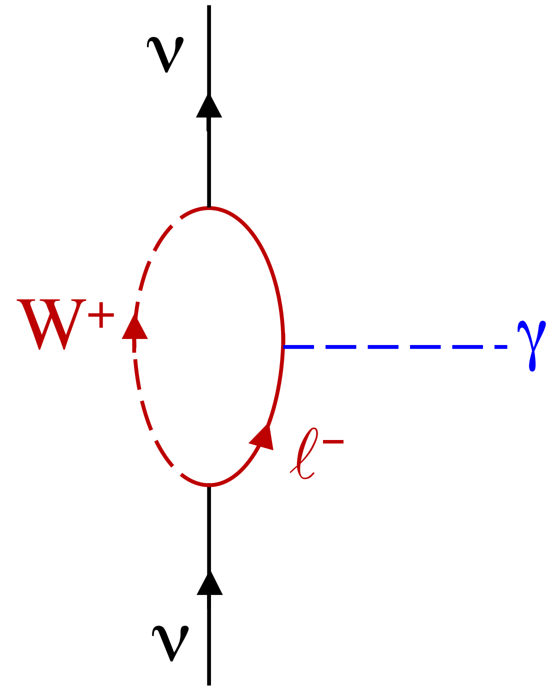
When there is ~~CPT~~, observation of **0νββ** proves only that the lepton number $L \equiv$ #(leptons) – #(antileptons) is not conserved, and that neutrinos have Majorana ($\nu - \bar{\nu}$ mixing) masses.

That is still a lot (!), but the neutrino mass eigenstates are not their own antiparticles (CPT self-conjugate).

(Barenboim, Beacom, Borissov, BK)

Anomalous Neutrino Dipole Moments

In the Standard Model,
loop diagrams like



produce, for a *Dirac* neutrino of mass m_ν,
a magnetic dipole moment —

$$\mu_\nu = 3 \text{ x } 10^{-19} \, (m_\nu/1\text{eV}) \, \mu_B$$

(Marciano, Sanda; Lee, Shrock; Fujikawa, Shrock)

Assuming CPT, a *Majorana* neutrino cannot have a magnetic or electric dipole moment:

$$\vec{\mu}\left[\ \uparrow_{e^+}\ \right] \underset{\text{CPT}}{=} -\,\vec{\mu}\left[\ \uparrow_{e^-}\ \right]$$

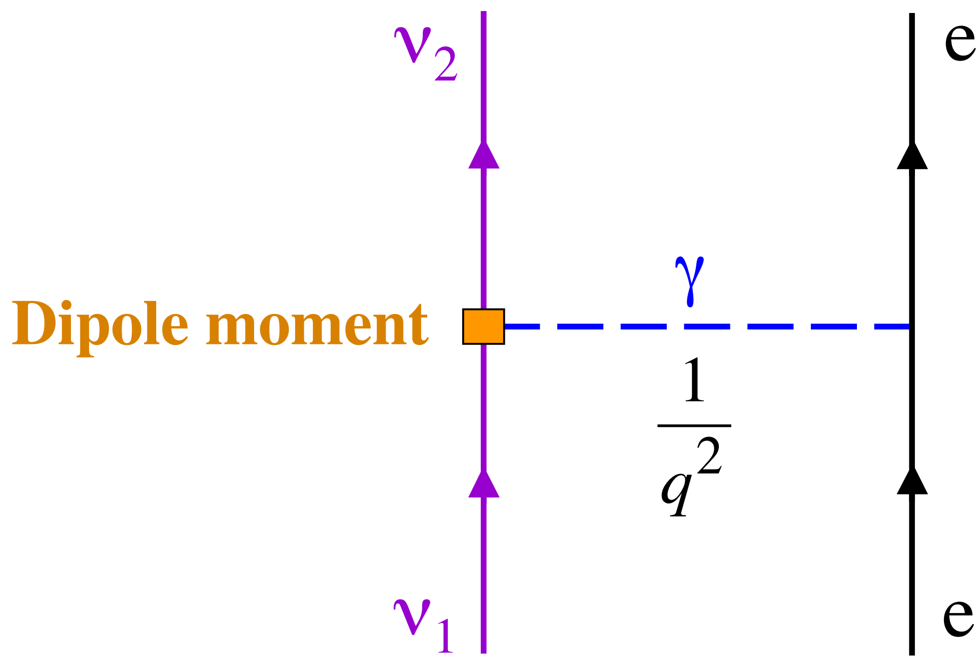
But for a Majorana neutrino,

$$\overline{\nu_i} = \nu_i$$

Therefore,

$$\vec{\mu}\,[\overline{\nu_i}] = \vec{\mu}\,[\nu_i] = 0$$

Both *Dirac* and *Majorana* neutrinos can have ***transition*** dipole moments, leading to —



One can look for the dipole moments this way.

To be visible, they would have to ***vastly*** exceed Standard Model predictions.

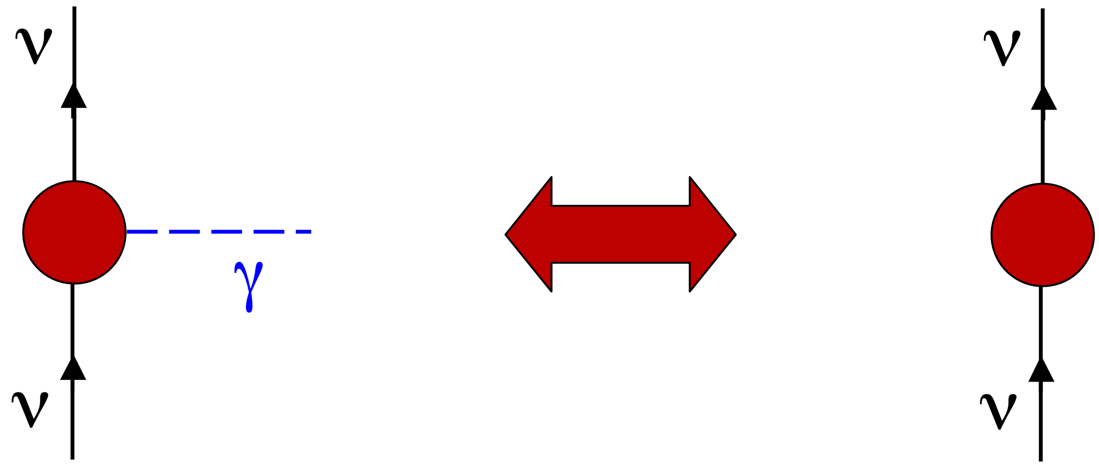
Present Bounds On Dipole Moments

$$\text{Upper bound} = \begin{cases} 7 \times 10^{-11}\,\mu_B & ;\ \text{Wong et al. (Reactor)} \\ 5.4 \times 10^{-11}\,\mu_B & ;\ \text{Borexino (Solar)} \\ 3 \times 10^{-12}\,\mu_B & ;\ \text{Raffelt (Stellar E loss)} \end{cases}$$

New Physics can produce larger dipole moments than the $\sim 10^{-20}\mu_B$ SM ones.

But the dipole moments cannot be arbitrarily large.

The Dipole Moment – Mass Connection



Dipole Moment | Mass Term

$$\mu_\nu \sim \frac{eX}{\Lambda} \qquad m_\nu \sim X\Lambda$$

Scale of New Physics

$$\Rightarrow \quad m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

(Bell *et al.*)

Any dipole moment leads to a contribution to the neutrino mass that grows with the scale Λ of the new physics behind the dipole moment.

The dipole moment must not be so large as to lead to a violation of the upper bound on neutrino masses.

The constraint —

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \left(\frac{\mu_\nu}{10^{-18}\mu_B}\right)\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

can be evaded by some new physics.

But the evasion can only go so far.

In the *Majorana* case, a *symmetry* suppresses the contribution of the dipole moment to the neutrino mass. So a bigger dipole moment is permissible. One finds —

For *Dirac* neutrinos, $\mu < 10^{-15}\,\mu_B$ for $\Lambda > 1$ TeV

For *Majorana* neutrinos, $\mu <$ ***Present Bound***

(Bell, Cirigliano, Davidson, Gorbahn, Gorchtein, Ramsey-Musolf, Santamaria, Vogel, Wise, Wang)

An observed μ below the present bound but well above $10^{-15}\ \mu_B$ would imply that neutrinos are Majorana particles.

A dipole moment that large requires L-violating new physics $\lesssim$ 1000 TeV.

Neutrinoless double beta decay at the planned level of sensitivity only requires this new physics at ~ 10^{15} GeV, near the Grand Unification scale.

Searching for $0\nu\beta\beta$ is the more conservative way to probe whether $\bar{\nu} = \nu$.

A Word About Neutrino Decay

$$\nu_\mu = U^*_{\mu 1}\nu_1 + U^*_{\mu 2}\nu_2 + U^*_{\mu 3}\underbrace{\nu_3}_{\text{Decay}}$$

obviously will affect oscillation.

A component of the beam will die away exponentially.

There is little evidence that this is happening,
but it should be kept in mind.

(Gonzalez-Garcia & Maltoni; 0802.3699)

Summary

Neutrino behavior could point to physics outside the realm of today's core principles and the Standard Model.

Let's be ever alert to what the neutrinos are trying to tell us!