CPT Breaking by Neutrinos

Our experimentally spectacularly successful Standard Model of elementary particle physics is a —

Local, Lorentz-invariant,
quantum field theory .

"Any local, Lorentz-invariant, quantum field theory is CPT invariant."

But is nature CPT invariant??

In considering CPT breaking ($\cancel{CPT}$), one cannot use the usual field theory rules.

Back to the drawing board!

Benefits of considering $\cancel{CPT}$ —

- A severe headache
- A lot of fun
- Testing of a fundamental symmetry

$\text{Mass}(\bar{P}) \neq \text{Mass}(P) \Rightarrow \cancel{CPT}$

$$T\left(\xrightarrow[\vec{p}]{}\right) = T\Big(\underbrace{e^{i\vec{p}\cdot\vec{x}}\, e^{-iEt}}_{\Psi(t)}\Big)$$

$$= \left(\xleftarrow[-\vec{p}]{}\right) = e^{-i\vec{p}\cdot\vec{x}}\, e^{-iEt} = \psi^{*}(-t).$$

Thus, T, hence CPT, is an antiunitary operator:

$$\langle CPT(a) \,|\, CPT(b) \rangle = \langle b \,|\, a \rangle .$$

$$\text{Mass}(\bar{P}) = \langle \bar{P} | \overset{\text{Hamiltonian}}{\overset{\downarrow}{H}} | \bar{P} \rangle = \langle CPT(P) | H | CPT(P) \rangle$$

$$\underset{\text{CPT}}{=} \langle CPT(P) | (CPT) H (CPT)^{-1} | CPT(P) \rangle$$

$$= \langle HP | P \rangle = \langle P | H | P \rangle = \text{Mass}(P)$$

Do Neutrinos Violate Such Rules?

Neutrinos do have masses!

The Discovery of Neutrino Mass

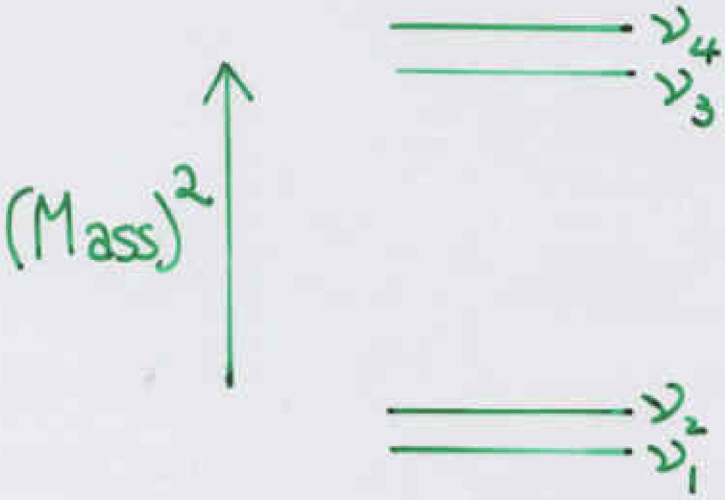
Neutrinos almost certainly change from one flavor to another.

$$\text{Flavor Change} \Longrightarrow \left\{ \begin{matrix} \text{Neutrino Mass} \\ \text{and Mixing} \end{matrix} \right\}$$

∴ Neutrinos almost certainly have masses and mix.

Neutrino Masses and Mixing

There is some spectrum of three or more neutrino mass eigenstates ν_m:



$$\text{Mass}(\nu_m) \equiv M_{\nu_m}$$

When $W^+ \to \ell^+ + \nu_\ell$, where $\ell = e, \mu,$ or τ, the produced neutrino state $|\nu_\ell\rangle$ is

$$|\nu_\ell\rangle = \sum_m U^*_{\ell m} |\nu_m\rangle$$

Neutrino of flavor ℓ

Unitary Leptonic Mixing Matrix

Flavor-ℓ fraction of $\nu_m = |\langle\nu_\ell|\nu_m\rangle|^2 = |U_{\ell m}|^2$.

ν flavor change depends on the $\delta M^2_{mm'} \equiv M^2_{\nu_m} - M^2_{\nu_{m'}}$

Evidence for ν Flavor Change

Solar Neutrinos

The nuclear processes that power the sun make only ν_e.

But the solar neutrino flux arriving at earth includes ν_μ and/or ν_τ.

For the ^8B (high-energy) solar neutrinos, the S(udbury) N(eutrino) O(bservatory) studies —

NC $\nu_\odot d \to \nu n p \Rightarrow \phi_e + \phi_{\mu\tau}$

ES $\nu_\odot e \to \nu e \Rightarrow \phi_e + 0.15\,\phi_{\mu\tau}$

CC $\nu_\odot d \to e p p \Rightarrow \phi_e$

$$\phi_{\mu\tau} = (3.41^{+0.66}_{-0.64}) \times 10^6/\mathrm{cm}^2\,\mathrm{sec}$$

(5.3σ from zero)

Including SK $\nu_\odot e \to \nu e$ data,

$$\phi_{\mu\tau} = (3.45^{+0.65}_{-0.62}) \times 10^6/\mathrm{cm}^2\,\mathrm{sec}$$

(5.5σ from zero)

Neutrinos do change flavor.

SNO : $\phi_{\mathrm{active}}(\mathrm{NC}) = (5.09^{+0.64}_{-0.61}) \times 10^6/\mathrm{cm}^2\mathrm{sec}$

Bahcall : $\phi_{\mathrm{total}}(\mathrm{BP00}) = (5.05^{+1.01}_{-0.81}) \times 10^6/\mathrm{cm}^2\mathrm{sec}$

Evidence for Oscillation

There are 3 pieces of evidence that neutrinos oscillate:

Neutrinos	Evidence of Oscillation	Required δM^2 (eV^2)
$\overset{(-)}{\nu}_\mu$ Atmospheric	Compelling	3×10^{-3}
ν_e Solar	Compelling	4×10^{-10} to 2×10^{-4}
$\overset{(-)}{\nu}_\mu$ LSND **(KRMN)**	Unconfirmed	0.2 to 1, or 7

If all 3 of these oscillations are genuine, then nature must contain —

- At least 4 neutrino masses
- Correspondingly, ν_e, ν_μ, ν_τ, $\nu_{s(\text{terile})}$??

If there are only 3 masses, then we must have

$$\sum \delta M^2 = (M^2_{\nu_3} - M^2_{\nu_2}) + (M^2_{\nu_2} - M^2_{\nu_1}) + (M^2_{\nu_1} - M^2_{\nu_3}) = 0 .$$

Do Neutrino Masses + Mixings Break CPT?

- Does $M_{\bar{\nu}_m} \neq M_{\nu_m}$?

- Does $\underset{\bar{\nu}\text{ mixing matrix} \rightarrow\uparrow}{\bar{U}} \neq \underset{\uparrow\leftarrow\ \nu\text{ mixing matrix}}{U}$?

We know—

- $$\frac{|M_{\bar{K}} - M_K|}{M_K} < 10^{-18}$$

- $$\frac{|M_{\bar{e}} - M_e|}{M_e} < 10^{-8}$$

Why should neutrinos be different?

Gravitons and right-handed neutrinos may be the only particles that travel in extra spatial dimensions.

There, they might see ~~CPT~~ effects from stringy structure. Unlike field theories, string theories could break CPT.

Can there be ~~CPT~~ without ~~Lorentz~~ ?

This question is under study.
(Greenberg; Barenboim & Lykken)

We make no assumption about the answer.

Rather, we ask:

What are the consequences of —

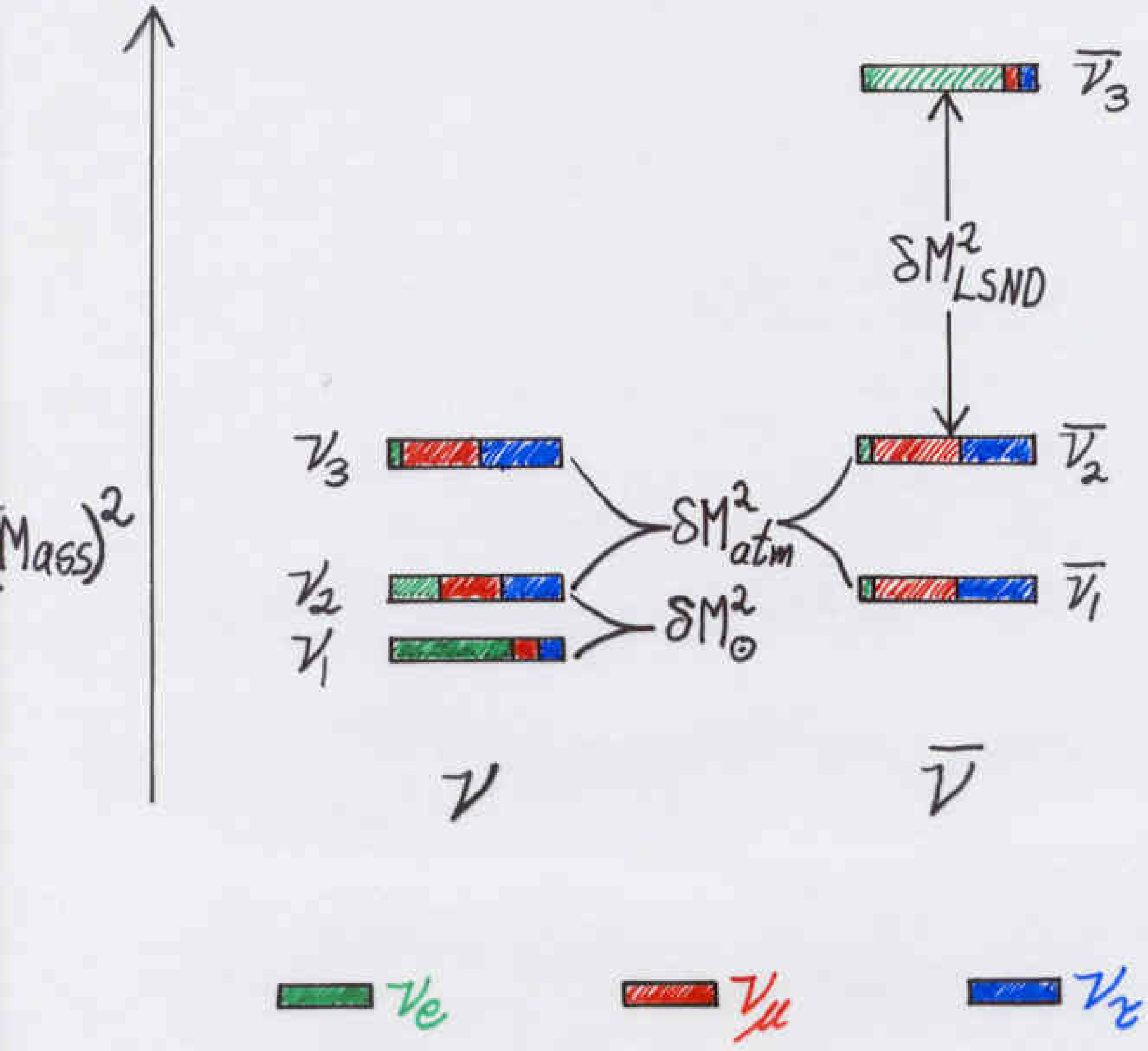
$$M_{\overline{\nu}_m} \neq M_{\nu_m}$$

$$\overline{U} \neq U \qquad ?$$

(Murayama & Yanagida
Barenboim, Borissov, Lykken, Smirnov
Barenboim, Borissov, Lykken
Barger, Pakvasa, Weiler, Whisnant
Barenboim, Beacom, Borissov, BK)

To illustrate, we consider a specific CPT-violating spectrum.

Assume lepton number L is conserved.
No Majorana ($\nu \leftrightarrow \bar{\nu}$) masses.



$\delta M^2_{atm}(\nu)$ need not precisely equal $\delta M^2_{atm}(\bar{\nu})$.

(Barenboim, Borissov, Lykken, Smirnov
Updated)

Consequences

LSND

Reports $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ at $\sim 3\sigma$

" $\nu_\mu \rightarrow \nu_e$ at $\sim 2\sigma$

Both require $\delta M^2 >> \delta M^2_{atm}$.

The ~~CPT~~ spectrum

$\Rightarrow$ Only $(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)_{LSND}$ is genuine.

MiniBooNE (Fermilab) will test this by running with both ν_μ & $\overline{\nu}_\mu$.

Confirmation would $\Rightarrow$ Solar & atmospheric & LSND oscillations can all be understood without sterile neutrinos.

Solar

There are several candidate mechanisms for the observed flavor change.

The L(arge) M(ixing) A(ngle) – M(ikheyev) S(mirnov) W(olfenstein) effect is heavily favored. [Plot]

Future Experiments —

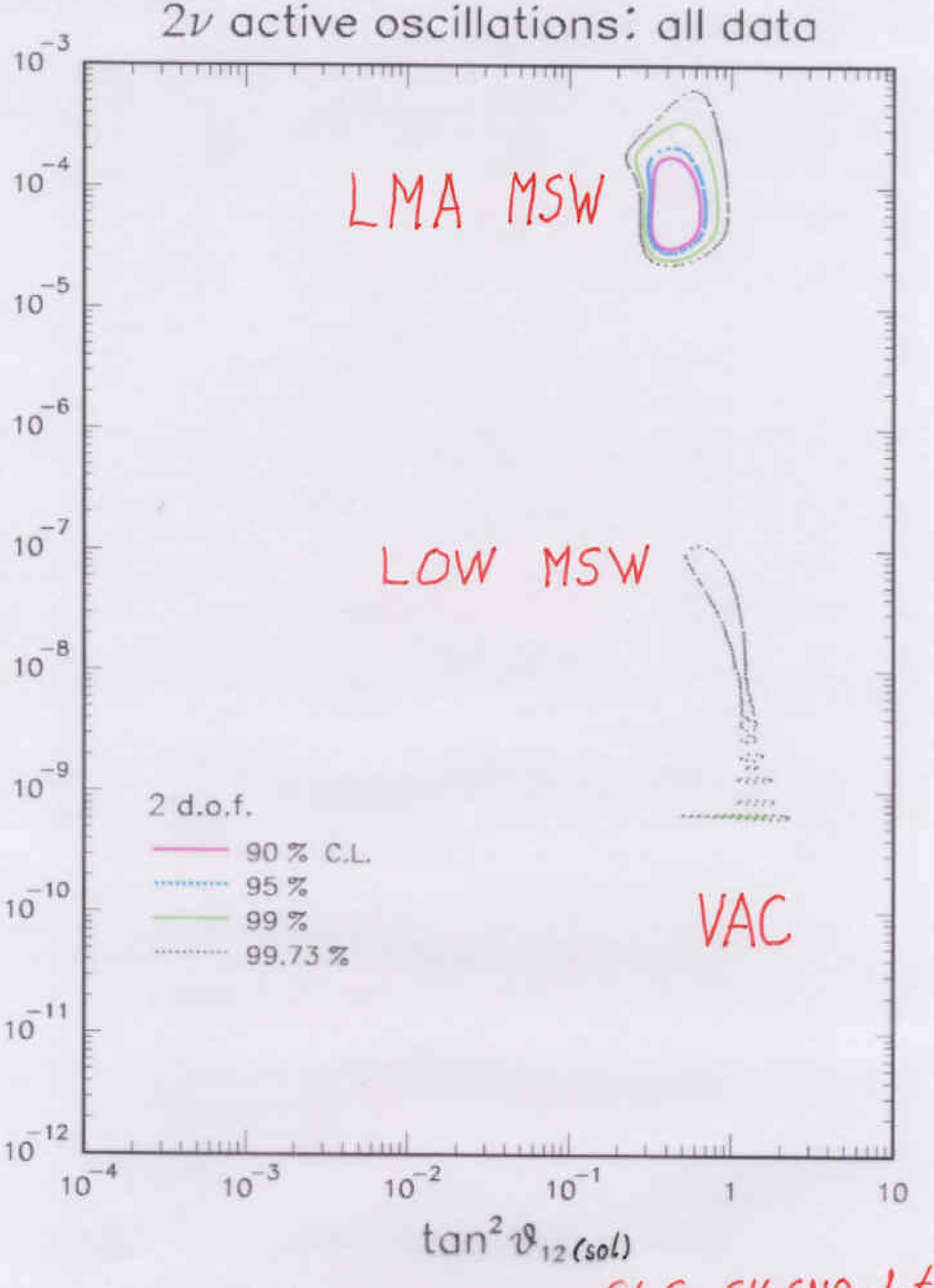
	KamLAND (Reactor $\bar{\nu}$)	Borexino (Solar ν)
~~CPT~~ LMA	✓	✓
LOW	X	Day/Night
VAC	X	Seasonal
Suppose	X	No D/N No Seasonal

⇒ ~~Our big CPT spectrum~~

⇒ ~~CPT~~

(Barenboim, Borissov, Lykken)

Lisi



Global results

Cl, Ga, SK, SNO data

Analysis in terms of pulls

Atmospheric

Our $\not{C}PT$ spectrum predicts no huge effects ($\delta M^2_{atm}(\nu) \approx \delta M^2_{atm}(\bar{\nu})$).

Both $\delta M^2_{atm}(\nu)$ and $\delta M^2_{atm}(\bar{\nu})$ are somewhat constrained by the diameter of the earth.

$$0.20 \lesssim \frac{\delta M^2_{atm}(\bar{\nu})}{\delta M^2_{atm}(\nu)} \lesssim 2.5 \quad @\, 90\%\ CL$$

(Super Kamiokande, assuming max. mixing)

Future Long Base Line accelerator neutrino experiments, running separately on ν and $\bar{\nu}$, will be more incisive.

Tritium β Decay

KATRIN will look for an absolute $\bar{\nu}$ mass (not splitting!) in —

$$\sum_{m} \left({}^{3}H \rightarrow {}^{3}He + e^{-} + \bar{\nu}_{m} \right)$$

In our ~~CPT~~ spectrum,

$$M_{\bar{\nu}_3} \geq \sqrt{\delta M^2_{LSND}} \gtrsim 0.4\,eV.$$

${}^{3}H$ has a big B.R. to decay to $\bar{\nu}_3$, because $\bar{\nu}_3$ is largely $\bar{\nu}_e$.

Maybe KATRIN can see $M_{\bar{\nu}_3}$.

$\cancel{CP}$

The search for $\cancel{CP}$ in neutrino oscillation will seek asymmetries—

$$\Delta(\ell\ell') \equiv P(\nu_\ell \to \nu_{\ell'}) - P(\bar{\nu}_\ell \to \bar{\nu}_{\ell'}).$$

When CPT invariance holds,

$$\Delta(\ell\ell') \neq 0 \Longrightarrow \cancel{CP}.$$

When CPT invariance holds,

- $\bar{\nu}$ and ν masses agree
- $\bar{\nu}$ and ν mixing angles agree
- "$\bar{U}$" $= U^*$

$\Delta(\ell\ell')$ comes from phases in U.

When CPT invariance does not hold,

$$\Delta(\ell\ell') \neq 0 \not\Rightarrow \cancel{CP}.$$

When CPT invariance does not hold, the $\bar{\nu}$'s and ν's differ in every way.

Then $\bar{\nu}$ and ν oscillation patterns can be completely different even if there is no $\cancel{CP}$.

Make sure an observed $\Delta(\ell\ell')$ is $\cancel{CP}$, not $\cancel{CPT}$.

One check:

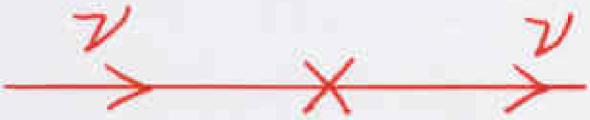
$$CPT \Longrightarrow P(\nu_\ell \rightarrow \nu_{\ell'}) = P(\bar{\nu}_{\ell'} \rightarrow \bar{\nu}_\ell)$$

$$\text{So test if: } P(\nu_\ell \rightarrow \nu_\ell) = P(\bar{\nu}_\ell \rightarrow \bar{\nu}_\ell)$$

Majorana Masses

Nature may contain —

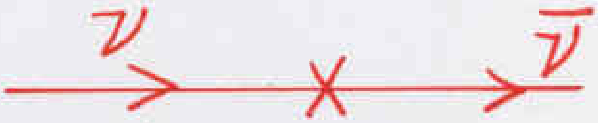
Dirac mass terms:



Conserves L

and / or

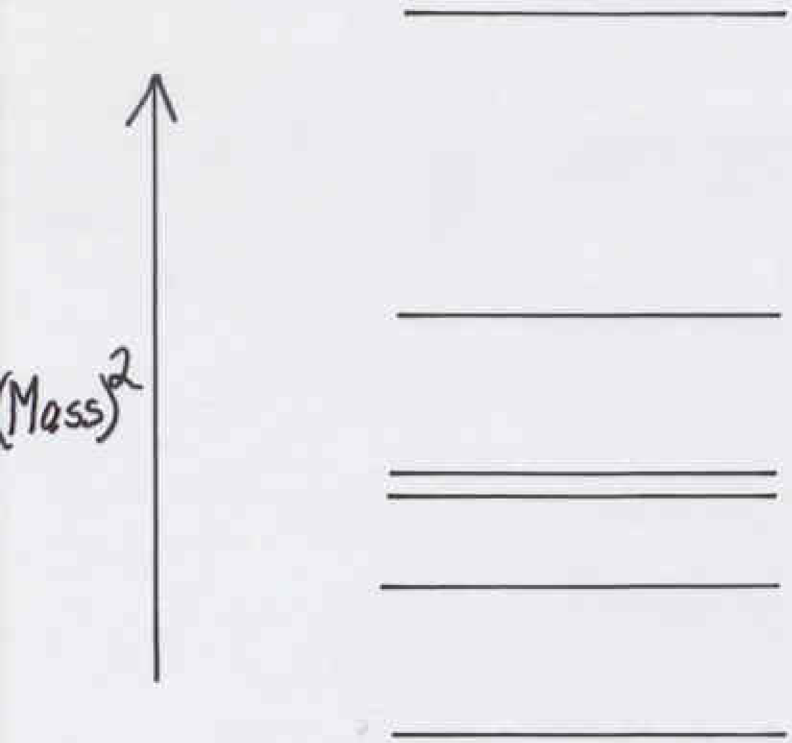
Majorana mass terms:



Violates L

Our illustrative ~~CPT~~ spectrum assumed there are no Majorana mass terms.

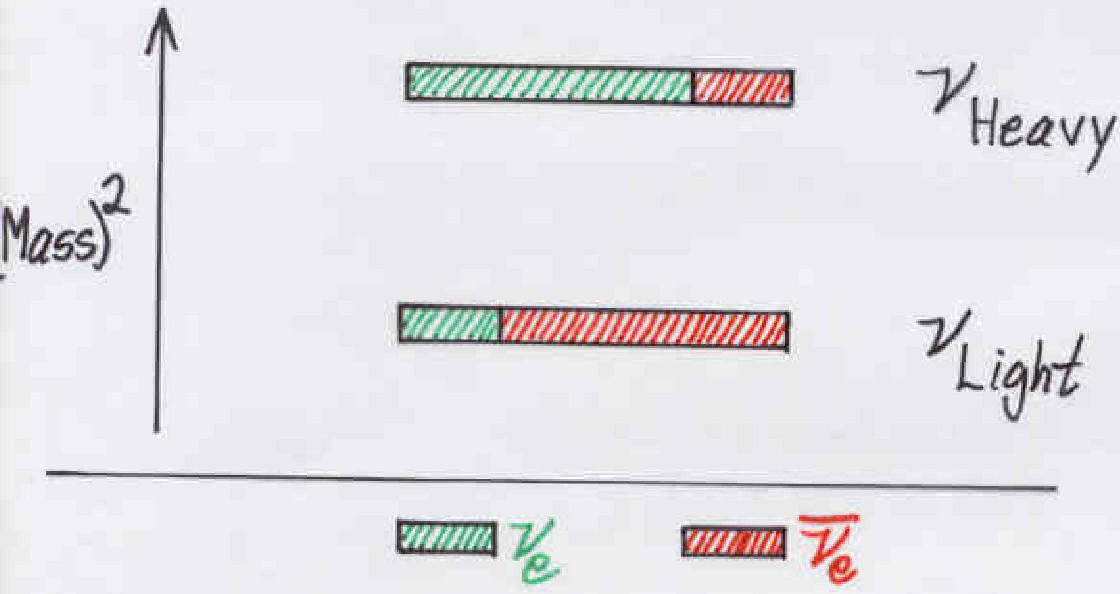
When both Dirac and Majorana mass terms are present —



Each eigenstate has both ν and $\overline{\nu}$ content!

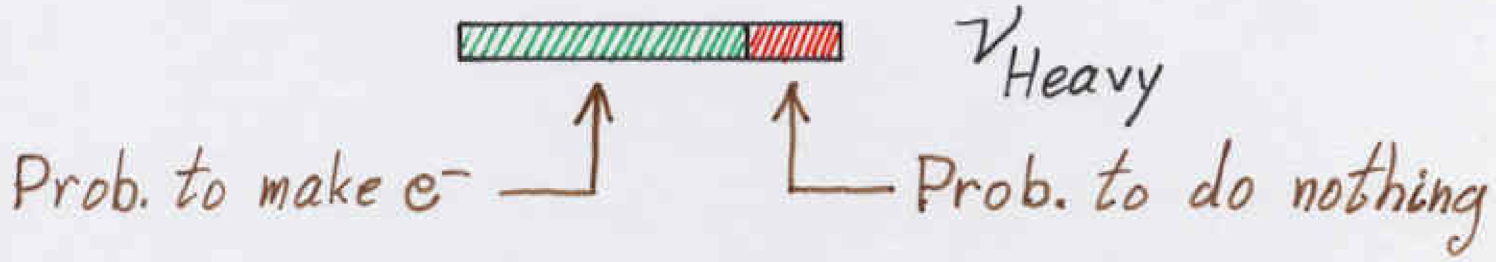
Just one spectrum

To illustrate, suppose there is just one flavor (e).

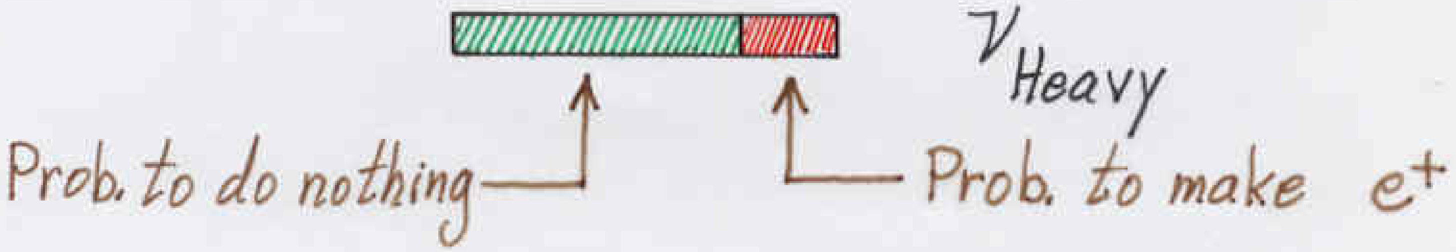


The interactions of ν_{Heavy} —

When Left-Handed:



When Right-Handed:



CPT $\Rightarrow$ { Green and Red regions are of equal size. }

Then we have a Majorana (CPT-self-conjugate) neutrino.

~~CPT~~ $\Rightarrow \left\{ \begin{matrix} \text{Neutrinos are not} \\ \text{Majorana particles} \end{matrix} \right\}$

When CPT holds,

$\beta\beta_{0\nu}$ [Nucl $\rightarrow$ Nucl$'$ + $2e^-$]

$\Rightarrow$ Neutrinos are Majorana particles.

When CPT does not hold,

$\beta\beta_{0\nu} \Rightarrow$ Majorana ($\nu \leftrightarrow \bar{\nu}$) masses,
but not Majorana ($\bar{\nu} = \nu$) neutrinos.

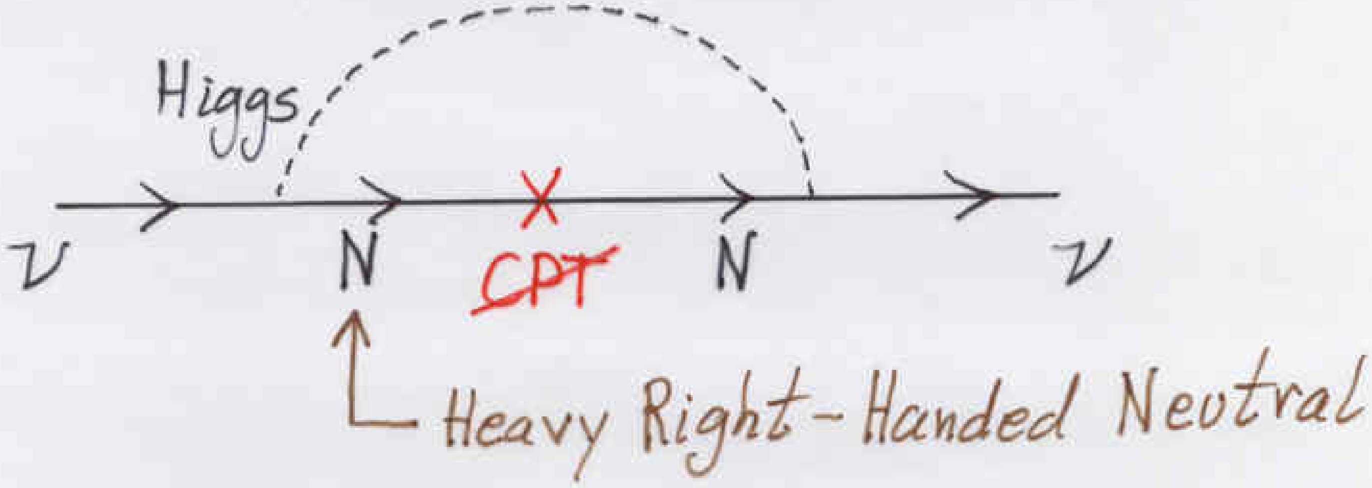
(Barenboim, Beacom, Borissov, BK)

~~CPT~~ Leakage

Does ~~CPT~~ among neutrinos **leak out** to other particles?

Do constraints on ~~CPT~~ by other particles bound ~~CPT~~ by neutrinos?

In a simple scheme where neutrino ~~CPT~~ comes from —



~~CPT~~ leakage is very efficient.

CPT constraints on $e^{\pm}$

(Adelberger, Heckel, et al.)

$$\Longrightarrow \quad |M_{\nu} - M_{\bar{\nu}}| < 10^{-13}\,\mathrm{eV}.$$

(Mocioiu + Pospelov)

How general is this??

Conclusion

Nature could surprise us by violating CPT.

Neutrinos could prove to be the messengers of this violation.

The consequences of CPT breaking by neutrinos would be interesting indeed.