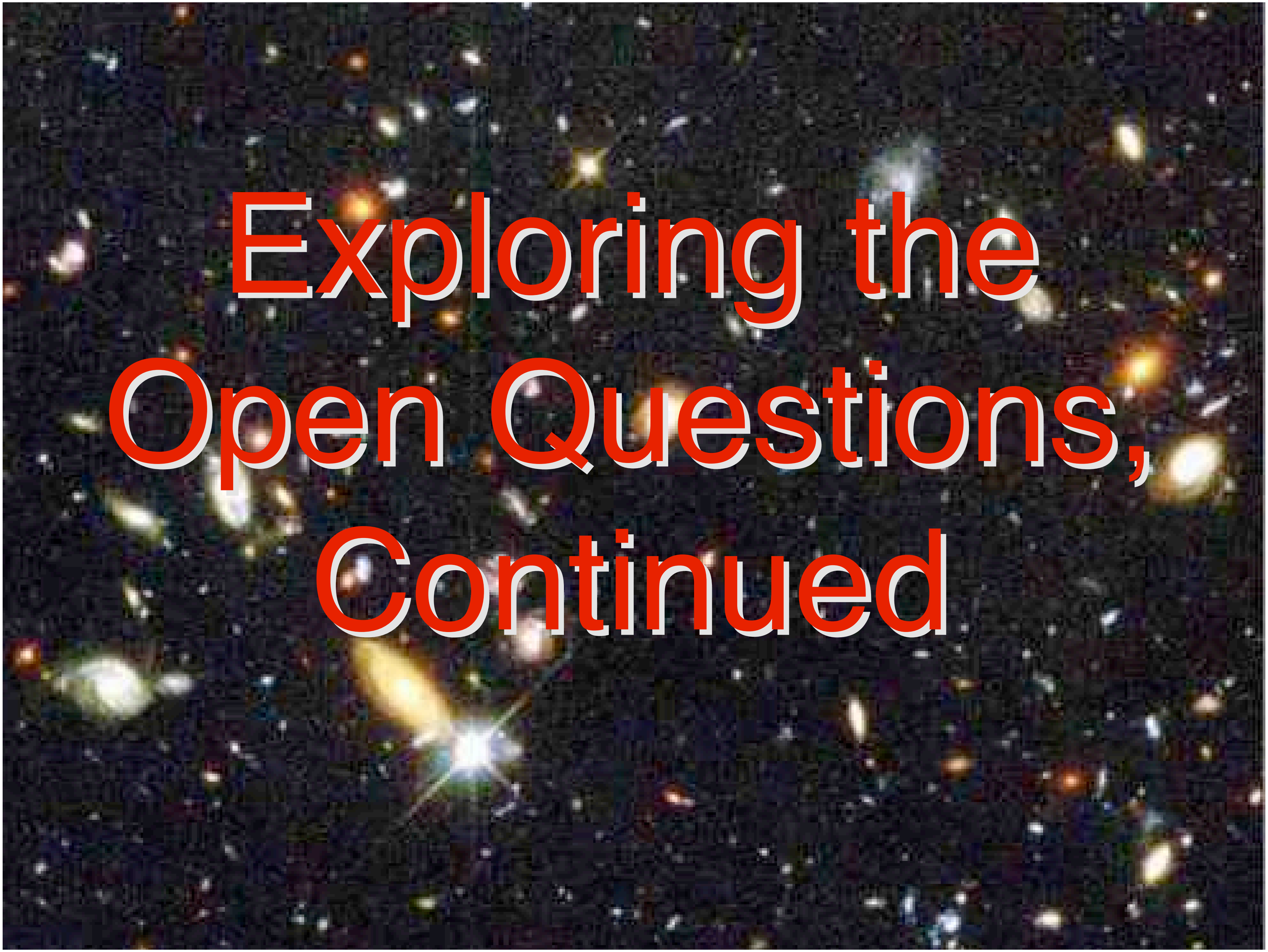
Neutrino Physics: Present and Future

Boris Kayser
CERN
November 30, 2006


Exploring the
Open Questions,
Continued

Are There Sterile Neutrinos?

Rapid neutrino oscillation reported by LSND —

$\sim 1\text{eV}^2$

in contrast to

$\Delta m^2_{atm} = 2.7 \times 10^{-3}\ \text{eV}^2$

$\Delta m^2_{sol} = 8 \times 10^{-5}\ \text{eV}^2$

At least **4** mass eigenstates, hence at least **4** flavors.

Measured $\Gamma(Z \rightarrow \nu\bar{\nu})$ ⇒ only **3** different *active* neutrinos.

At least **1** *sterile* neutrino.

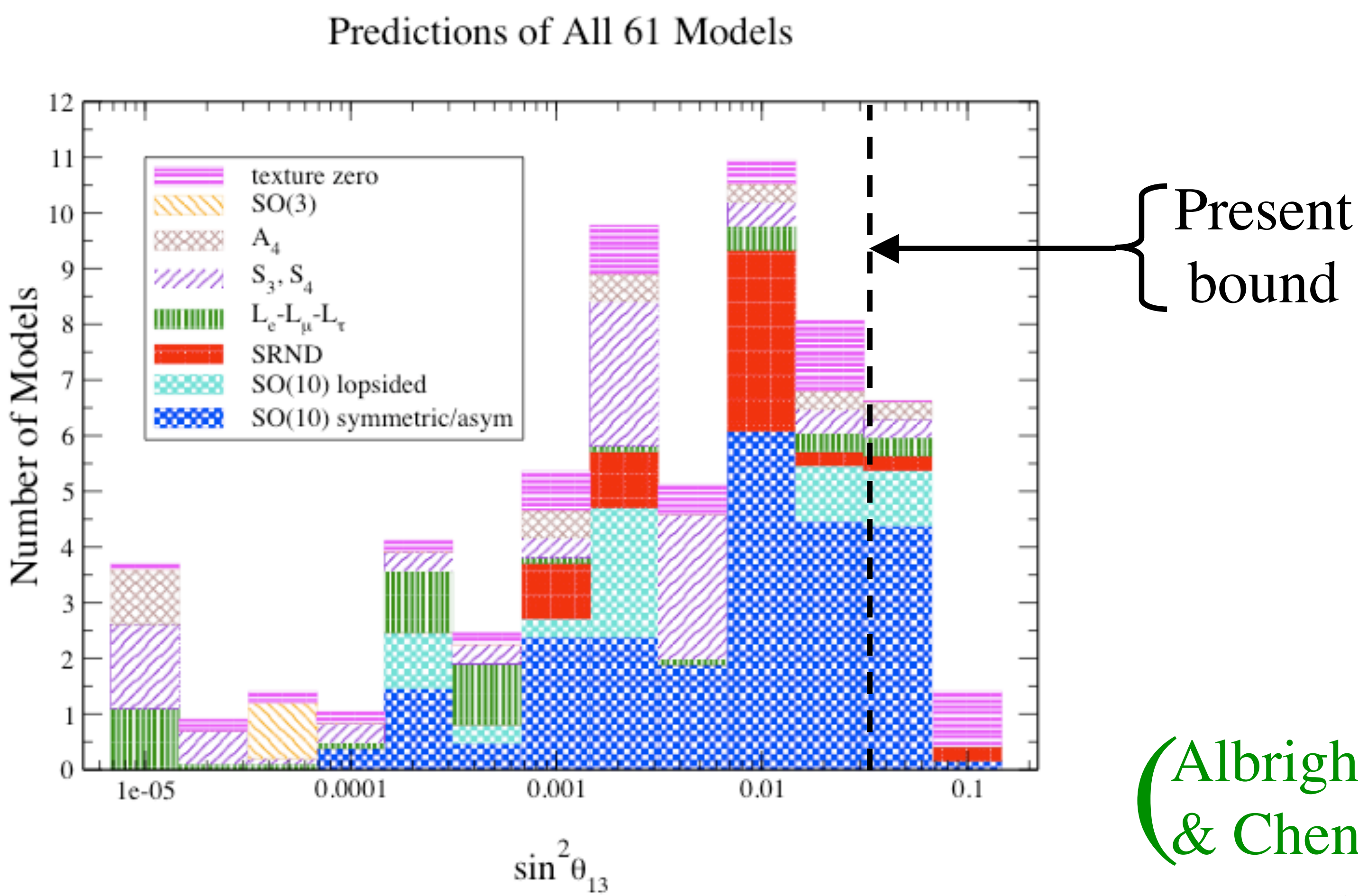
Is the so-far unconfirmed oscillation reported by LSND genuine?

MiniBooNE aims to definitively answer this question.

How Large Is θ_{13}?

We know only that $\sin^2\theta_{13} < 0.032$ (at 2σ).

The theoretical prediction of θ_{13} is not sharp:



(Albright & Chen)

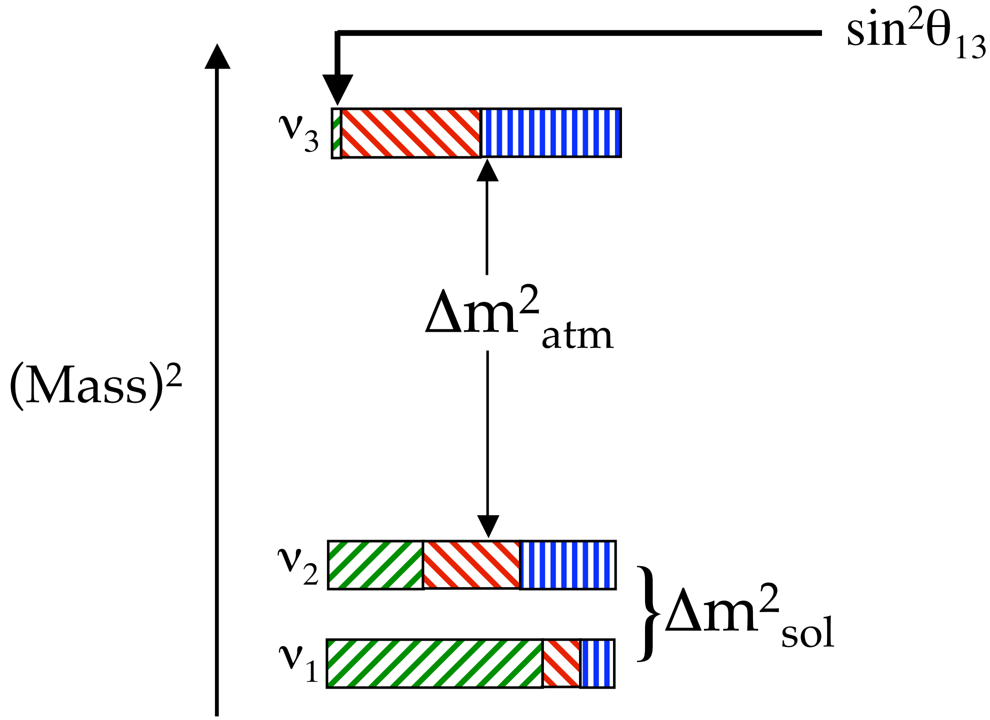
The Central Role of θ_{13}

Both CP violation and our ability to tell whether the spectrum is normal or inverted depend on θ_{13}.

If $\sin^2\theta_{13} > (0.0025 - 0.0050)$, we can study both of these issues with intense but conventional ν and $\bar{\nu}$ beams.

Determining θ_{13} is an important stepping-stone.

How θ_{13} May Be Measured



$\sin^2\theta_{13} = |U_{e3}|^2$ is the small ν_e piece of ν_3.

ν_3 is at one end of Δm^2_{atm}.

$\therefore$ We need an experiment with L/E sensitive to Δm^2_{atm} (L/E ~ 500 km/GeV) , and involving ν_e.

Complementary Approaches

Reactor Experiments

Reactor $\bar{\nu}_e$ disappearance while traveling L ~ 1.5 km. This process depends on θ_{13} alone:

$$P(\bar{\nu}_e \text{ Disappearance}) =$$

$$= \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{atm}(eV^2)L(km)/E(GeV)]$$

Accelerator Experiments

Accelerator $\nu_\mu \rightarrow \nu_e$ while traveling L > Several hundred km. This process depends on θ_{13}, θ_{23}, on whether the spectrum is normal or inverted, and on whether CP is violated through the phase δ.

Neglecting matter effects (to keep the formula from getting too complicated):

The accelerator long-baseline $\overset{(-)}{\nu}_e$ appearance experiment measures —

$$
\begin{aligned}
P[\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e] \cong\ & \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} \\
& + \sin 2\theta_{13} \cos\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\Delta_{31} \sin\Delta_{21} \cos(\Delta_{32} \pm \delta) \\
& + \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}
\end{aligned}
$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E$$

The plus (minus) sign is for neutrinos (antineutrinos).

The Mass Spectrum: or ?

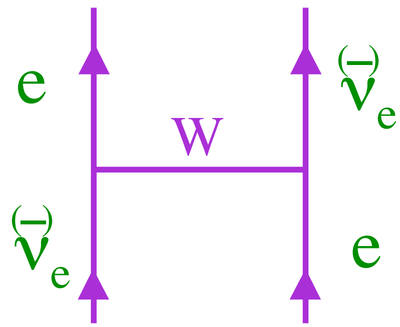
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,



raises the effective mass of ν_e, and lowers that of $\bar{\nu}_e$.

This changes both the spectrum and the mixing angles.
Thus, it changes oscillation probabilities.
In particular, it makes P($\bar{\nu}$ oscillation) $\neq$ P(ν oscillation).

The matter effect grows with energy E.

At E ~ 1 GeV, at oscillation maximum, the matter effect results in —

Sign[m^2(—) - m^2(═)]

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \cong \frac{1+S(E/6\,GeV)}{1-S(E/6\,GeV)}$$

$$\begin{cases} > 1\ ; \\ < 1\ ; \end{cases}$$

Note the $\nu - \bar{\nu}$ asymmetry that is not from CP violation.

When the matter effect may be neglected —

$$P(\nu_\alpha \to \nu_\beta) \propto \sin^2[1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})/E(\mathrm{GeV})]$$

Distance traveled — Energy

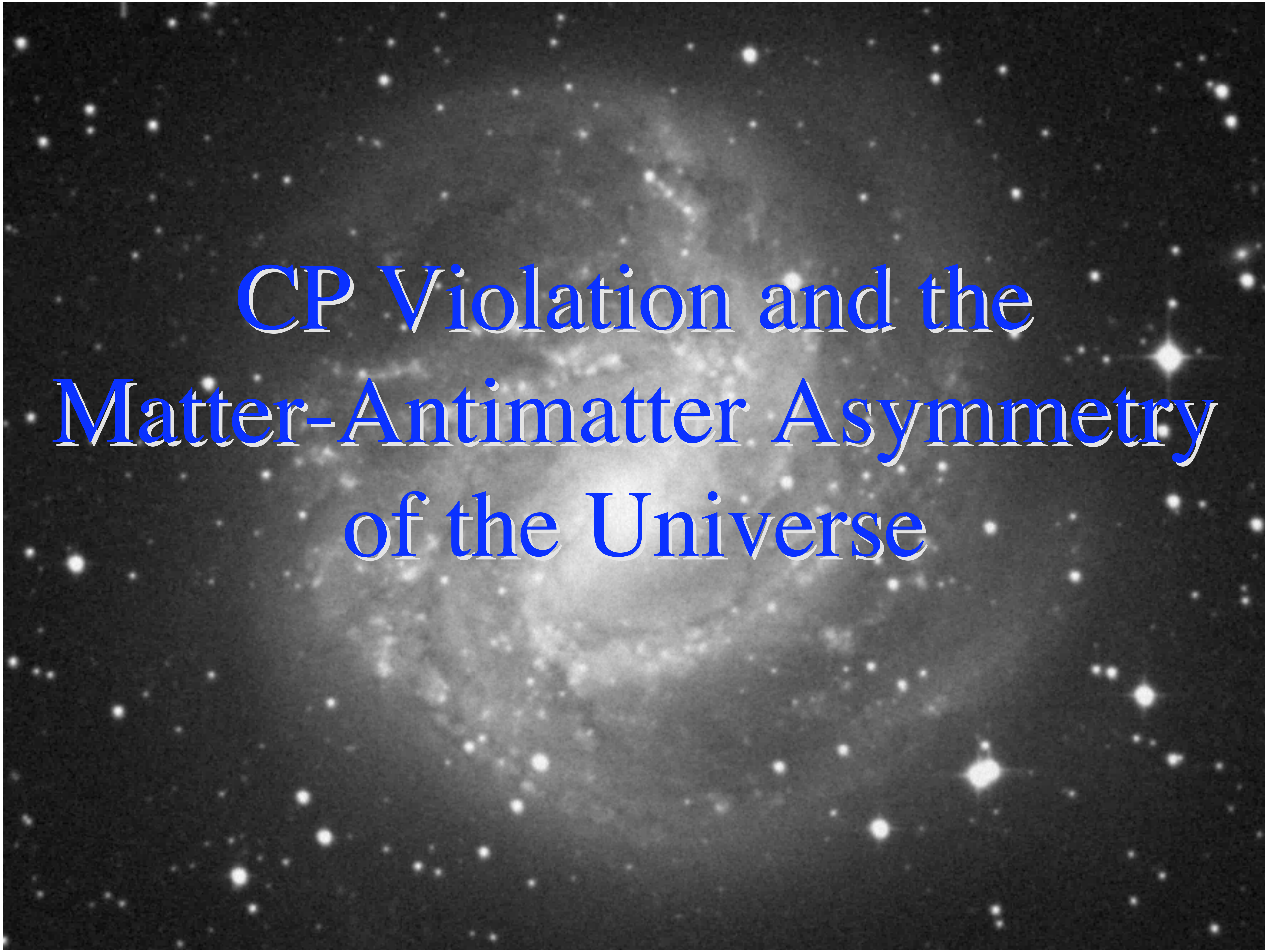
The matter effect grows with energy.

At fixed L/E but two different energies —

$$\frac{P_{\mathrm{Hi\,E}}(\nu_\mu \to \nu_e)}{P_{\mathrm{Lo\,E}}(\nu_\mu \to \nu_e)} \begin{cases} >1 \;; \\ <1 \;; \end{cases}$$

(Mena, Nunokawa, Parke)

CP Violation and the Matter-Antimatter Asymmetry of the Universe



Leptonic CP Violation

- Is there leptonic ~~CP~~, or is ~~CP~~ special to quarks?
- Is leptonic ~~CP~~, through *Leptogenesis*, the origin of the **MATTER**-antimatter asymmetry of the universe?

The universe is presently

MATTER-antimatter asymmetric:

It contains **MATTER** (of which we are made), but essentially no antimatter (which would annihilate us).

Any initial asymmetry would have been washed out by baryon-number (B) and lepton-number (L) violating processes expected from Grand Unified TheorieS.

Therefore, we have to understand how the present **MATTER**-antimatter asymmetry developed from a matter-antimatter-symmetric universe.

This development requires CP violation ($\not{C}\not{P}$).

That is, antimatter must behave differently from matter.

Otherwise, a universe containing **equal** amounts of the two will **continue** to contain **equal** amounts of the two.

Sakharov

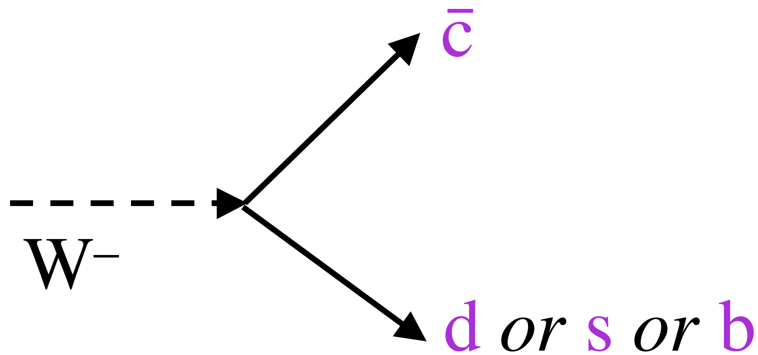
In Standard Model weak processes involving *quarks*, the $\cancel{CP}$ phases are in the quark mixing matrix —

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

$\cancel{CP}$ coming from phases in this matrix is far too small to explain the **MATTER**-antimatter asymmetry of the universe.

One reason: **It was too hot** in the early universe.

In —



the middle row of $V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$ determines the

relative amplitudes for emitting d, s, and b
in combination with $\bar{c}$.

The thinking was that perhaps the matter-antimatter asymmetry was generated by phases in V as the universe cooled through the Electroweak Phase Transiton ($kT \sim m_W$).

But it was **hot** then, compared with the masses of all the quarks except top. The masses of d, s, and b were negligible.

Then one could not tell d from s from b.

The quark mixing matrix did not yet have any meaning.

Hence, it had no consequences.

It could not cause $\cancel{CP}$. {At least, not much.}

Leptogenesis

If the quarks can't generate the observed

MATTER-antimatter asymmetry,

maybe the **leptons** can!