Charge 2: If the LSND result is confirmed by the results from MiniBooNE, neutrinos do not fit the standard picture of three neutrino flavors with full weak coupling. How might the neutrino program evolve as results appear from MiniBooNE?

• Louis Description of MiniBooNE Complex & Capabilities
• Louis Scenario 1: MiniBooNE Sees a Signal in Neutrino Mode
• Conrad Scenario 2: MiniBooNE Sees No Signal In Neutrino Mode, but Does See a Signal in Antineutrino Mode
• Conrad Scenario 3: MiniBooNE Sees No Signal in Neutrino Mode & Is Turned Off
MiniBooNE Complex & Capabilities

The Booster Beamline is the World's Best SBL Neutrino Beam!

The Booster Beamline is now providing $> 8 \times 10^{18}$ POT/week!

The Booster Beamline Can Continue to Operate in the NuMI Era!
MiniBooNE Site Layout
MiniBooNE - A Definitive Test of the LSND Evidence for $\nu$ Oscillations

- **Booster** - 8 GeV proton beam ($5 \times 10^{20}$ POT/y)
- **Target** - 71 cm Be
- **Horn** - 5 Hz, 170 kA, 143 $\mu$s, 2.5 kV, $10^8$ pulses/y
- **Decay Pipe** - 50 m (adjustable to 25 m)
- **Neutrino Distance** - $\sim 0.5$ km
- $<E_{\nu}> \sim 1$ GeV
- $(\nu_e / \nu_\mu) \sim 5 \times 10^{-3}$
- **Detector** - 40' diameter spherical tank
- **Mass** - 800 (450) tons of mineral oil
- **PMTs** - 1280 detector + 240 veto, 8" diameter
Expected MiniBooNE Sensitivity
Measurement of Oscillation Parameters

With 5E20 POT, we cannot distinguish $\Delta m^2$!
Current State of Neutrino Oscillation Evidence

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Type</th>
<th>$\Delta m^2$ (eV$^2$) $\sin^2 2\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>$\sim 1$ $\sim 3 \times 10^{-3}$</td>
</tr>
<tr>
<td>Atm.</td>
<td>$\nu_\mu \rightarrow \nu_\tau$</td>
<td>$\sim 2 \times 10^{-3}$ $\sim 1$</td>
</tr>
<tr>
<td>Solar</td>
<td>$\nu_e \rightarrow \nu_{\mu,\tau}$</td>
<td>$\sim 7 \times 10^{-5}$ $\sim 0.8$</td>
</tr>
</tbody>
</table>
Scenario 1: MiniBooNE Sees a Signal in Neutrino Mode

If MiniBooNE sees a signal in neutrino mode, then, together with solar and atmospheric data, it will imply
Physics Far Beyond the Standard Model!

For example, theories with large neutrino-mode signal:

3+2 Sterile Neutrinos

Sorel, Conrad, & Shaevitz  hep-ph/0305255
2 $\Delta m^2$ with roughly same magnitude.
Goodness of fit 30%

R-Process in Supernovae?

MaVaNs

mass varying neutrinos

Fardon, Nelson, & Weiner  astro-ph/0309800
Kaplan, Nelson, & Weiner  hep-ph/0401099
Explain Dark Energy?
Physics Goals to Pursue

- An exciting short baseline physics program with room for many experiments at many facilities!

- Measure $\nu_\mu \rightarrow \nu_e$ parameters more precisely

- Search for $\nu_\mu$ disappearance, large in 3+N models

- Search for $\nu_\tau$ appearance

- Check if neutrino and antineutrino oscillation parameters are the same (CP or CPT violation? see scenario 2)

- Search for more than one $\Delta m^2$
BooNE Physics Program

- Build 1 or more BooNE detectors at different distances (e.g. a FINeSSE detector (~$5M) at 100 m and a far detector (~$8M) at 1000 m)
- Run with both neutrino and antineutrino beams
- Search for $\nu_\mu$ disappearance via NC and CC to test for active neutrino and sterile neutrino mixing.
MiniBooNE + small near detector

~$5M (fully loaded including civil)

T2K Near Detector Complex can probably do similarly well.

An additional large detector (~$8M) reduces errors by $\times 2$
A Stopped Beam Program at SNS
(or possibly at an FNAL proton driver)

- Build a MiniBooNE-like detector (~$12M) at the SNS (1.4 MW!)
- Monoenergetic $\nu_\mu$ from $\pi^+$ decay & $\bar{\nu}_\mu$, $\nu_e$ from $\mu^+$ decay
- Measure $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- Search for $\nu_\mu$ disappearance with the $\nu C \rightarrow \nu C^*(15.11$ MeV) NC reaction to test for sterile neutrino oscillations
- High oscillation signal & very low backgrounds (S/B ~ 10)
- Flux shapes are known perfectly and cross sections are known very well (< few%): $\nu C \rightarrow \nu C^*(15.11$ MeV), $\nu e \rightarrow \nu e$, $\bar{\nu}_e p \rightarrow e^+ n$, $\nu_e C \rightarrow e^- N_{gs}$
SNS Time & Energy Spectra

![Graphs showing time and energy spectra with labels for $\nu_\mu$, $\bar{\nu}_\mu$, and $\nu_e$.]
Other Short Baseline Possibilities

I. Reactors

Two or more near detectors at different distances
- One close to the reactor @ ~30 m (cf. Bugey)
- excellent if large mixing, small $\Delta m^2$ is LSND solution

Measure $\overline{\nu}_e$ disappearance

II. BNL

Can vary proton energy from 3 to 20 GeV
Room for two or more detectors at different distances
Tom Kirk has requested a proposal in autumn for near detector
Long Baseline Physics Program

- Minos, Nova, Reactor Experiments, CNGS, T2K, & BNL
- **Good News:** The MiniBooNE signal entails additional oscillation physics to explore!
  - May be exciting sterile & active \( \nu \) studies for Minos & T2K!
- **Bad News:** MiniBooNE signal will be a background for \( \theta_{13} \) measurements (to be discussed in Scenario 2)
- **A Proton Driver will be needed to disentangle all of the oscillation signals!**
  - High statistics
  - Ability to run multiple distance-scale studies
The 8-&-120 GeV Proton Driver Option

from talk by D. Michael, BNL Superbeams working group meeting:
can provide
short, long and very long baseline beams, with tunable energy

The VLBL program would be at least as good as the BNL proposal
Scenario 2

MiniBooNE sees no signal in Neutrino Mode

but sees a signal in Antineutrino Mode.
Sorel and Whisnant,
preliminary

\[ P_{\text{osc}}(\nu_\alpha \rightarrow \nu_\beta) \neq P_{\text{osc}}(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \]
Potential effect on Nova

Black: Nova sensitivity for no LSND signal
Red: Sensitivity for LSND CP conserving signal
Blue: Sensitivity for a CP violating signal with $P_{\text{osc}}^{\text{LSND}} = 0.02$

(this is worst case)
CPT Violation

Mass Spectrum Model:
hep-ph/0210411  Barenboim, Lykken

disfavored unless steriles are also invoked

Lorentz Invariance Violation:
Kostelecky and Mewes, hep-ph/0308300

Fits to neutrino data can, in principle, accommodate an LSND signal

Quantum Gravity Decoherence Model:
Additional mixing induced by singular space-time configurations
(wormholes, microscopic black holes, geons = "space time foam")

fit to data: $\chi^2/\text{DOF} = 60.7/56$    hep-ph/0404014, 0406035 Barenboim, Mavromatos
Followups to Scenario 2

Essentially the same followup program as for scenario 1

• Install near detector at FNAL
• Build BooNE at FNAL
• Run the stopped muon beam detector
• Upgrade FINeSSE@ BNL and run in v-bar mode
• Run T2K with antineutrinos and use the near detectors

Capability of Minos to address the sterile neutrino mixing matrix content needs to be studied ... may be exciting!
Scenario 3

MiniBooNE sees no signal in Neutrino Mode and Fermilab Directorate "sunsets" the experiment.
This would be a mistake.

You may miss an opportunity for a major discovery.

You will hobble your proposed program because you will have to assume LSND as a systematic error.
As a result, a conclusion of the APS Neutrino Study is that MinibooNE antineutrino running is crucial to the field.

Antineutrino running will be noted as a priority in the final APS Study Report.
Final Thoughts
Nu-signal Map

Fermilab

2005
MiniBooNE nbar run
Design BooNE
If you had FINeSSE at this point, you could modestly address steriles
Build BooNE

2010
BooNE starts
BooNE does precise L/E measurements.
A near detector would allow for $\nu_\mu$ disappearance

2015
an 8-\&-120 GeV program would nail the question

World-wide
Short-baseline reactor experiment
FINeSSE @ BNL upgraded with second detector.
Can do E scan from 3 to 20 GeV pot

Combo of 200m and 2 km T2K near detectors provide another L/E and disapp measure

SNS far detector precision L/E \& disapp @ high $\Delta m^2$

Run precision $\nu_s$ \& $\nu_\tau$ experiment???
MiniBooNE nbar run  

MiniBooNE nbar results  
Design BooNE while MiniBooNE runs for even more statistics  
Build BooNE  
BooNE starts using proton driver  

Red = mass question,  
Blue = sterile question  

Start building SNS  
Combo of 200m and 2 km T2K near detectors checks result running in nbar (means a shift of schedule for nbar run?)  
SNS far detector precision L/E & disapp @ high $\Delta m^2$  

FINeSSE @ BNL upgraded with second detector. Can do E scan from 3 to 20 GeV pot
We Need A Proton Driver Somewhere!

In the end, if MiniBooNE sees a signal, a proton driver will be necessary to obtain the statistics to sort it out.

There are a lot of other good reasons to build a Proton driver.

Many sites would like to host a Proton Driver in the U.S.

In order to be a viable candidate for the Proton Driver:

> a site must build the confidence of the neutrino community that they can deliver a competitive physics program.
A Great Scenario for FNAL

now-2015: Run MiniBooNE and BooNE
       Run Minos
       Run a lively program of other small experiments
           wanting to use these beams

Post-2015 (Proton Driver):
       Build the 8-and-120 GeV option
           Which allows short, medium and long baseline expts.

This scenario will be successful **whether or not MiniBooNE** sees a signal.

This scenario propels Fermilab to the forefront of Neutrino Physics
    at the end of the 2010's
It isn't the lab which confirms the anomaly that will get all of the accolades. It's the one that figures out the physics.

Carpe Diem!
Backup slides
SNS Signal & Backgrounds

- **Signal:** \( \bar{\nu}_e \ p \rightarrow e^+ \ n, \ n \ p \rightarrow d \ \gamma \ (2.2 \ \text{MeV}) \)
  
  For LSND parameters, expect \(~350\) oscillation events per year! (x2 more \(\nu\) & x5 more mass)

- **Background:** \( \bar{\nu}_e \ p \rightarrow e^+ \ n, \ n \ p \rightarrow d \ \gamma \ (2.2 \ \text{MeV}) \)
  
  Expect \(~10\) \(\nu\) background events per year! (background reduced by \(r^{-2} = 1/10\))
  
  Expect \(< 20\) beam-off background events per year (DF lower by 100)
  
  Total background \(< 30\)

  \[
  \text{S/B} > 10 \ (\text{for } \Delta m^2 \sim 0.3 \ \text{eV}^2) \]
SNS Schematic

- Front-End Systems (Lawrence Berkeley)
- Accumulator Ring (Brookhaven)
- Target (Oak Ridge)
- Linac (Los Alamos and Jefferson)
- Instrument Systems (Argonne and Oak Ridge)
How the Nova sensitivity was calculated:

Code: a package written by Mike Shaevitz for APS Nu Study. (includes osc. prob. code from S.Parke)

Purpose: Study relative contributions of Reactor, T2K, Nova to atmospheric \( \Delta m^2 \) studies individually, in groups, as fn of time.

Agreement between Groups:
A meeting between representatives of the SuperBeams and Reactor APS Study Groups (SW, JC, DM, BM/MD, GB, EB, MS, GF) led to agreement on this code, statistical methods & presentation layout.

How the code works, in general:

1) Generate data (osc. probs) for a given point in \( \delta \) and \( \sin^2 \theta_{13} \) space.
2) Find the minimum \( \chi^2 \) demanding \( \delta=0 \) but allowing \( \theta_{13} \) and \( \theta_{23} \) to vary
3) The 2\( \sigma \) limit curve is where the \( \chi^2=4 \)
For a MiniBooNE CP Conserving signal:

1) Generate data (osc. probs) for a given point in $\delta$ and $\sin^2\theta_{13}$ space.
2) Add an additional oscillation signal w/ P=0.02 to both neutrino and antineutrino data
3) Find the minimum $\chi^2$ demanding $\delta=0$ but allowing $\theta_{13}$ and $\theta_{23}$ to vary also, acknowledge the additional signal of unknown size by allowing an extra systematic term, $k_{MB}$, to vary
   (contrained to a minimum of zero LSND signal)
   with a $\chi^2$ penalty of $(k_{MB}/0.02)^2$
   $k_{MB}$ is the same for neutrinos and antineutrinos
4) The $2\sigma$ limit curve is where the $\chi^2=4$

For a CP Violating signal (known or unknown):

Same as above except that $k_{MB}$ term is only applied to antineutrinos
Theoretical Justification for 3+2 .... examples from the last 6 months

THE STERILE NEUTRINO: FIRST HINT OF 4TH GENERATION FERMIONS?

LARGE MIXING FROM SMALL: PSEUDODIRAC NEUTRINOS AND THE SINGULAR SEESAW.
By G.J. Stephenson,Jr. (New Mexico U.), T. Goldman (Los Alamos), B.H.J. McKellar, M. Garbutt (Melbourne U.),.

TWO LIGHT STERILE NEUTRINOS THAT MIX MAXIMALLY WITH EACH OTHER AND MODERATELY WITH THREE ACTIVE NEUTRINOS.
e-Print Archive: hep-ph/0402183

(3+2) NEUTRINO SCHEME FROM A SINGULAR DOUBLE SEESAW MECHANISM.
e-Print Archive: hep-ph/0401241

SIMPLE MODEL FOR (3+2) NEUTRINO OSCILLATIONS.
e-Print Archive: hep-ph/0312285
Doesn't Cosmology Rule Out 3+2 Models?

Nope.

Many proposals have been made to evade the cosmological limits. For recent relevant articles (last 6 months) see...

Beacom, Bell & Dodelson, astro-ph/0404585
Hannestad, hep-ph/0404239
Gelmini, Palomares-Ruiz, & Pascoli. astro-ph/0403323
Olive, Skillman, astro-ph/0405588

And for a very nice review see
Abazajian, astro-ph/0205238