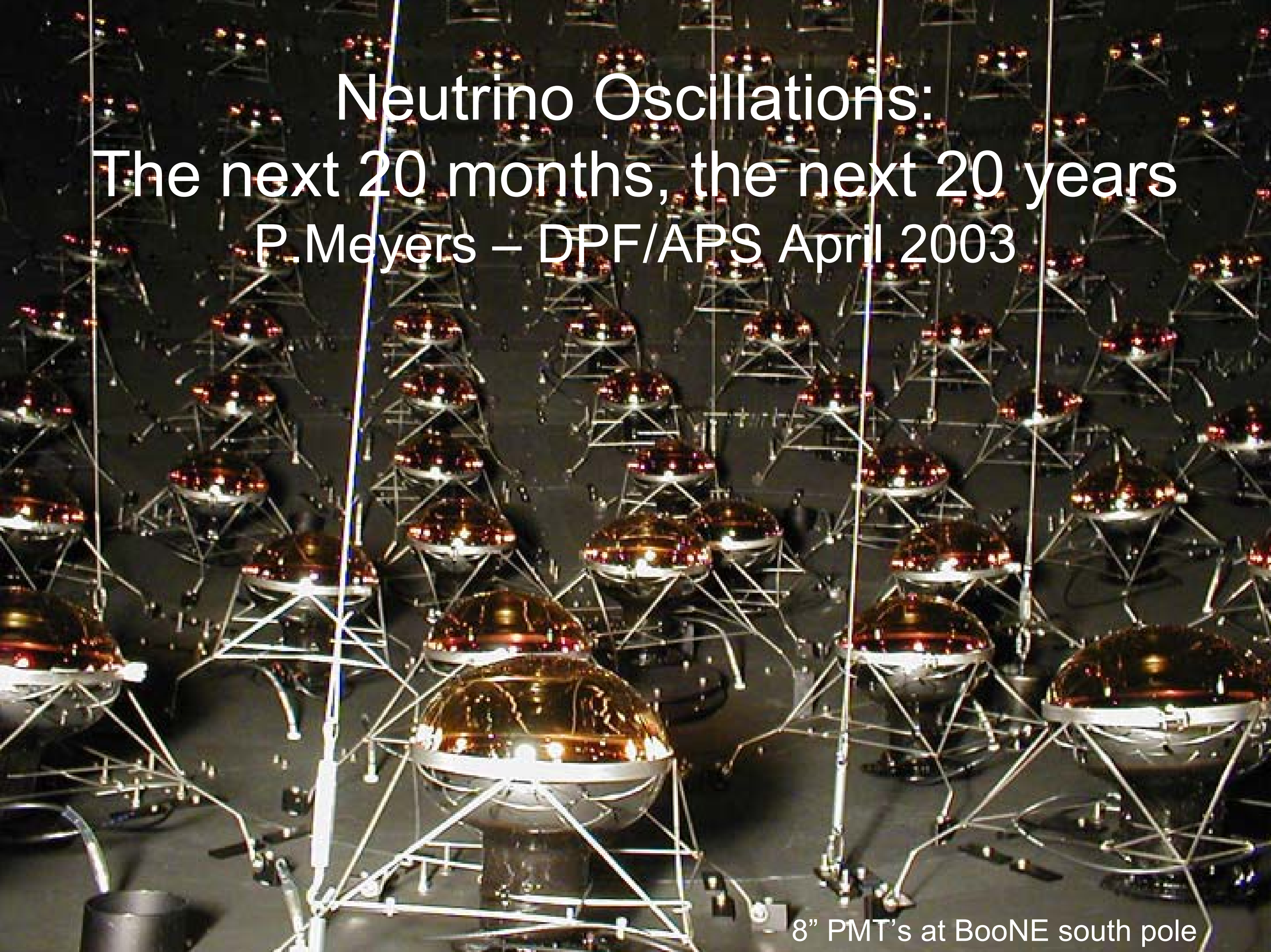
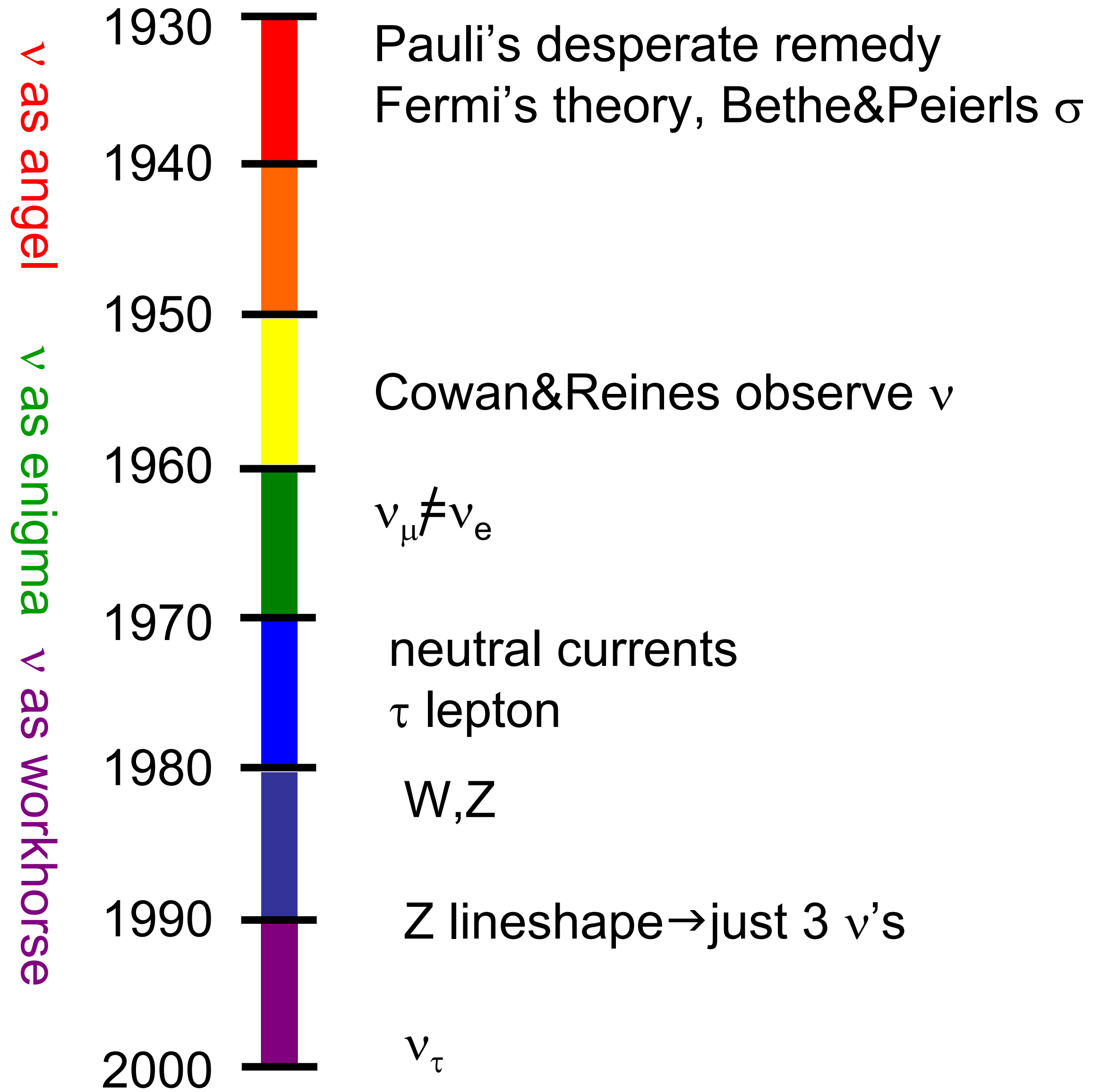
Neutrino Oscillations:
The next 20 months, the next 20 years

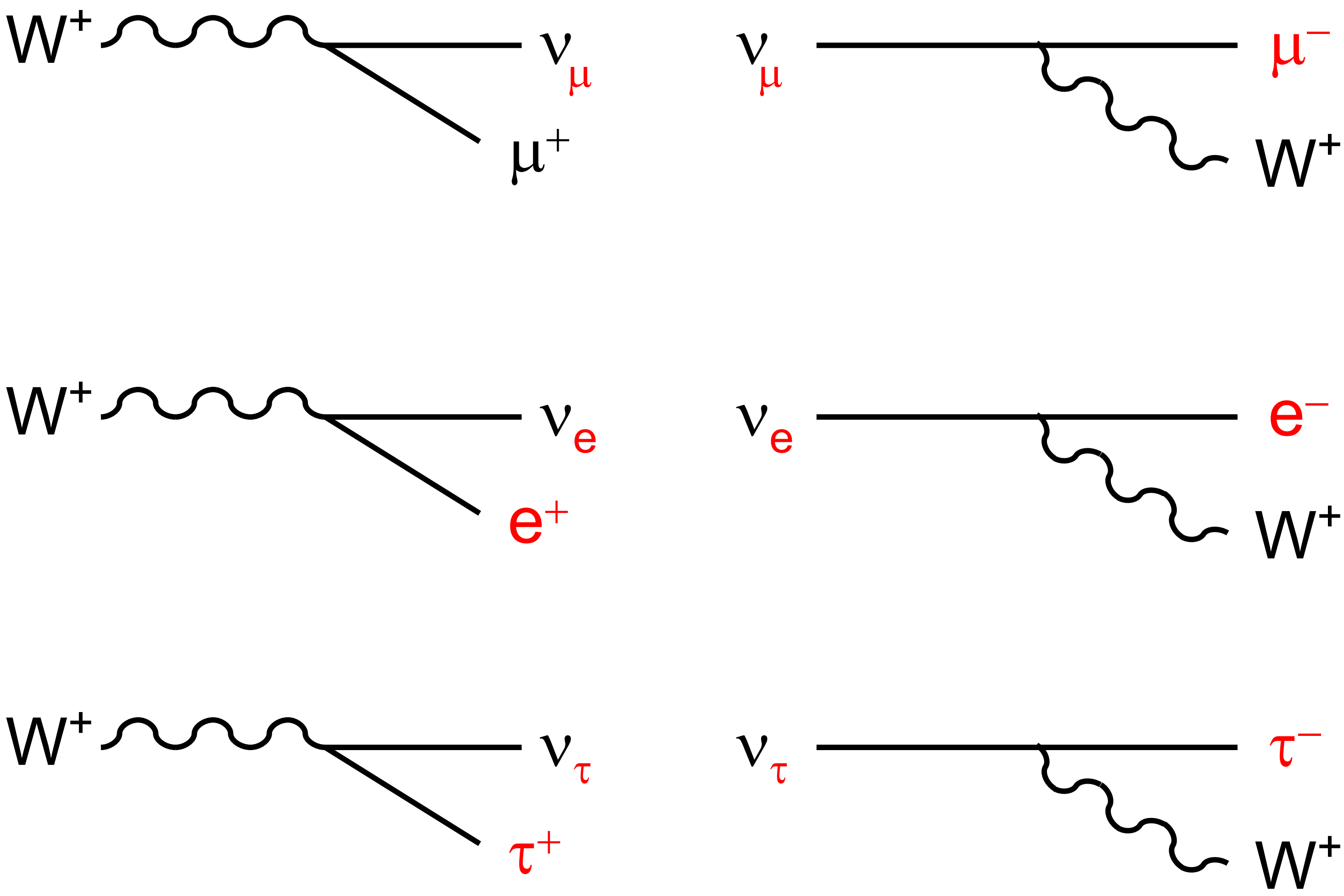
P.Meyers – DPF/APS April 2003



8” PMT’s at BooNE south pole


ν as angel
ν as enigma
ν as workhorse
1930
1940
1950
1960
1970
1980
1990
2000
Pauli's desperate remedy
Fermi's theory, Bethe&Peierls σ
Cowan&Reines observe ν
$\nu_\mu \neq \nu_e$
neutral currents
τ lepton
W,Z
Z lineshape→just 3 ν's
ν_τ

Weak Interactions: conserve lepton "flavor"



ν as angel ν as enigma ν as workhorse

1930

Pauli's desperate remedy

Fermi's theory, Bethe&Peierls σ

1940

1950

Cowan&Reines observe ν

Pontecorvo $\nu \leftrightarrow \bar{\nu}$

1960

$\nu_\mu \neq \nu_e$

Solar ν problem

1970

neutral currents

τ lepton

1980

W,Z

Atmospheric anomaly

1990

Z lineshape $\rightarrow$ just 3 ν's

ν_τ

2000

If weak (flavor) ≠ mass (energy) eigenstates…
(2-neutrino case for simplicity)

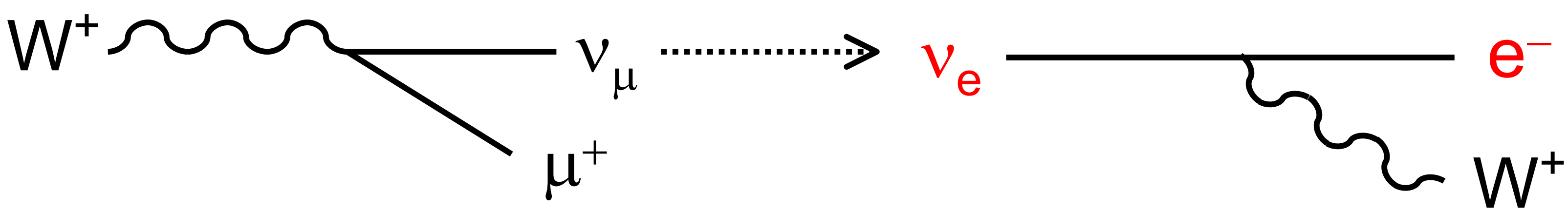
$$\left|\nu(t=0)\right\rangle = \left|\nu_\mu\right\rangle = \cos\theta\left|\nu_1\right\rangle + \sin\theta\left|\nu_2\right\rangle$$

$$\left|\nu(t)\right\rangle = \cos\theta\left|\nu_1\right\rangle e^{-iE_1 t} + \sin\theta\left|\nu_2\right\rangle e^{-iE_2 t} \neq \left|\nu_\mu\right\rangle \text{ if } m_1 \neq m_2$$

$$P(\nu_\mu \to \nu_e) = \left|\left\langle \nu_e \middle| \nu(t)\right\rangle\right|^2$$

$$= \sin^2 2\theta \sin^2\left[1.27\underline{\Delta m^2}(\mathrm{eV}^2)\underline{L}(\mathrm{m}) / \underline{E}(\mathrm{MeV})\right]$$

$$\text{with } \Delta m^2 \equiv m_2^2 - m_1^2$$



With *n* flavors α,β,… and masses *i*,*j*,…

$$\left|\nu(t=0)\right\rangle = \left|\nu_\alpha\right\rangle = \sum_i U^*_{\alpha i}\left|\nu_i\right\rangle$$

Matrix *U* like quark CKM

$$\left|\nu(t)\right\rangle = \sum_i U^*_{\alpha i}\left|\nu_i\right\rangle e^{-iE_i t} \neq \left|\nu_\alpha\right\rangle \text{ if } m_i\text{'s not all the same}$$

$$P(\nu_\alpha \to \nu_\beta) = \left|\left\langle \nu_\beta \middle| \nu(t)\right\rangle\right|^2 = \delta_{\alpha\beta}$$

$$-4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta i})\sin^2\left[1.27\Delta m_{ij}{}^2(\mathrm{eV}^2)L(\mathrm{m})/E(\mathrm{MeV})\right]$$

$$+2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta i})\sin^2\left[2.54\Delta m_{ij}{}^2(\mathrm{eV}^2)L(\mathrm{m})/E(\mathrm{MeV})\right]$$

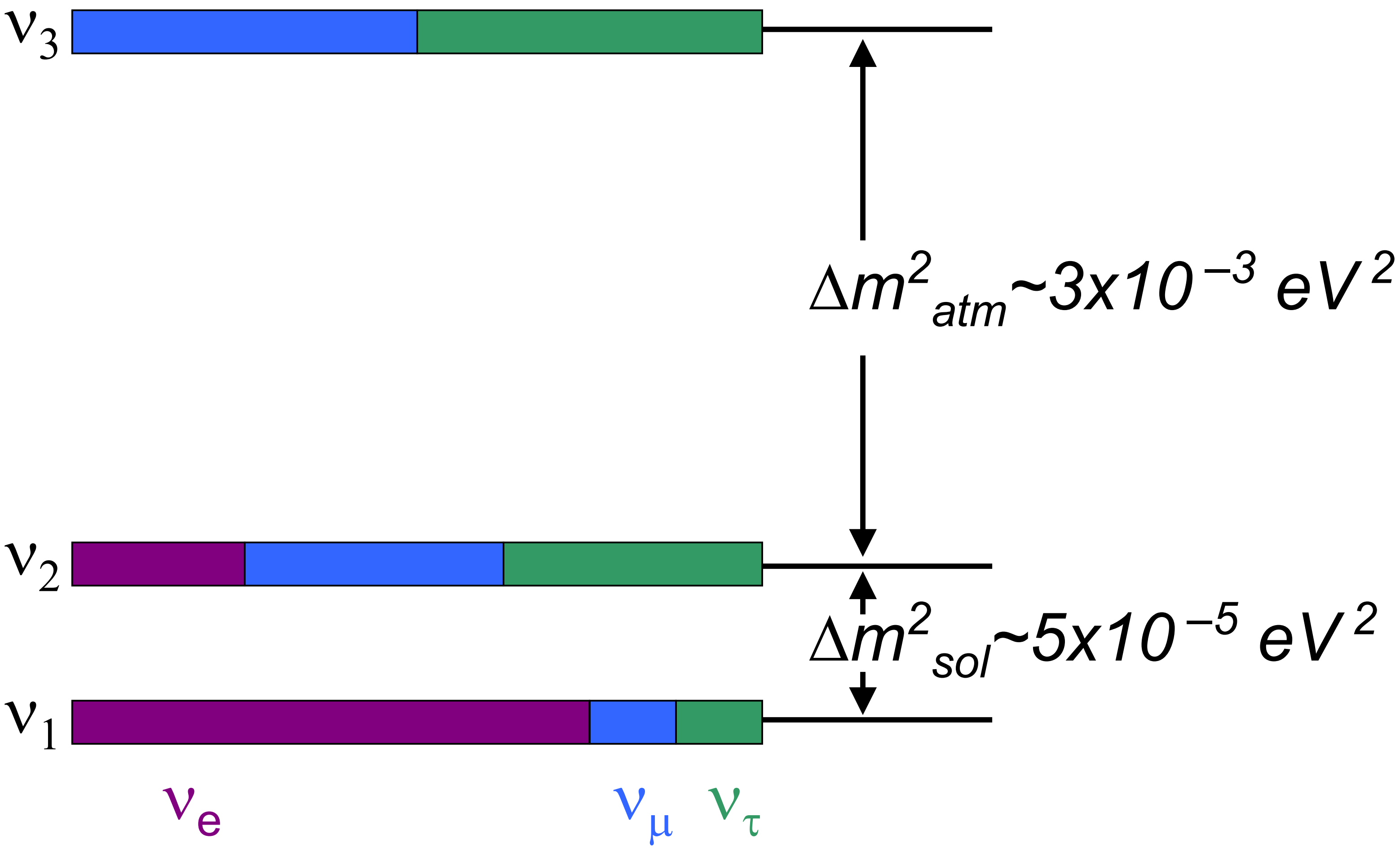
$$\text{with } \Delta m_{ij}{}^2 \equiv m_i^2 - m_j^2$$

As with quark mixing, >2 flavors ⇨ a CP-violating phase

Oscillation Evidence

Evidence	Effect real?	Is it osc?	Δm^2 (eV^2)	Flavor
Solar: Homestake missing ν_e	Gallex,SAGE, K, Super-K SNO, (KamLAND)	SNO	5×10^{-5} (MSW)	$\nu_e \rightarrow \nu_\mu, \nu_\tau$ <13% ν_s ($\bar{\nu}_e \rightarrow$?)
Atmospheric: Kamiokande missing ν_μ	Super-K, (K2K)	(Super-K)	3×10^{-3}	$\nu_\mu \rightarrow \nu_\tau$ <20% ν_e <25% ν_s
LSND: accelerator $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$		appear-ance	0.3-1	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Solar + atmospheric ⇨ a consistent picture



LSND and the curse of arithmetic

$\Delta m^2_{LSND} \sim 1$ $\Delta m^2_{sol} \sim 5x10^{-5}$ $\Delta m^2_{atm} \sim 3x10^{-3}$

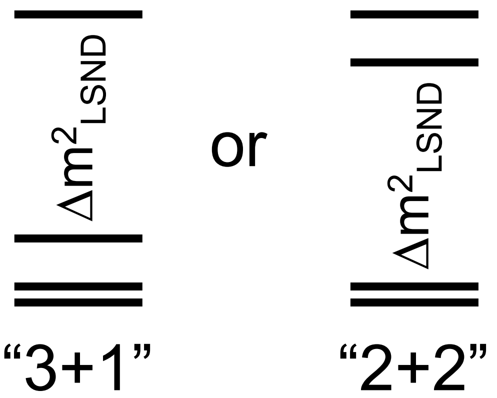
but $\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$

and Z lineshape ⇨ $N_\nu = 2.994 \pm 0.012$

Conclusion:

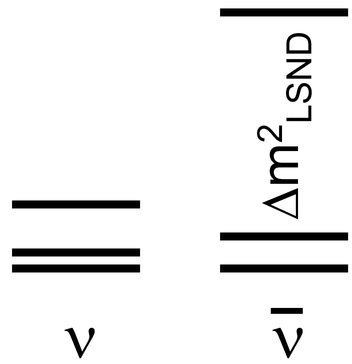
If LSND is correct, it requires something drastic

3 active + 1 sterile



- hard to make work
- limits on ν_s in solar and atm
- short-baseline exclusion
- on to "3+2"?

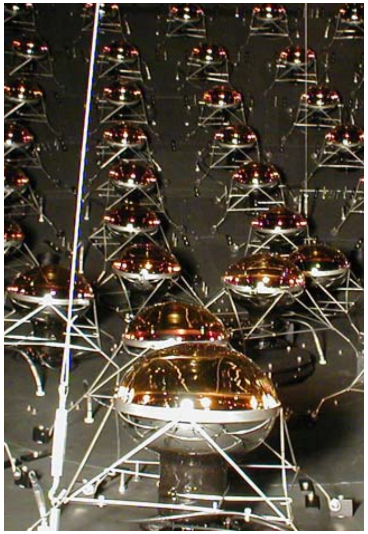
CPT violation



- level of ~~CPT~~ required is < K^0-$\bar{K}^0$ mass limit
- on the other hand, it *is* a theorem…

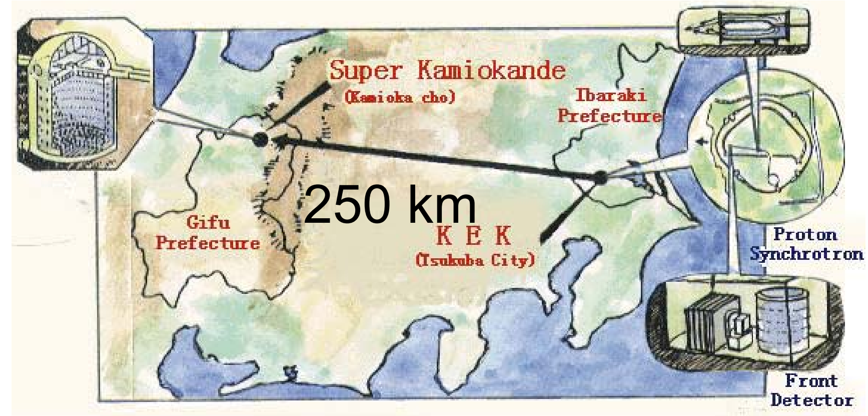
Coming Attractions

Running Experiments



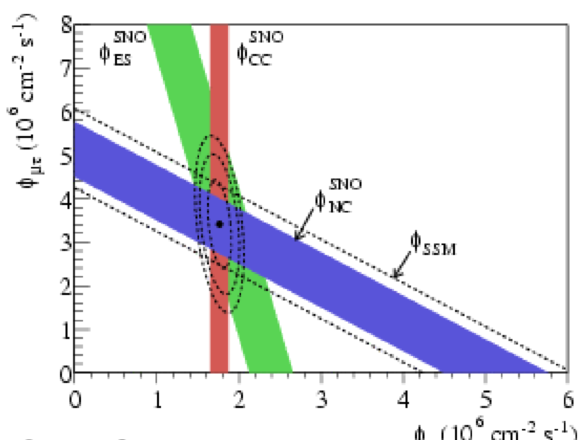
MiniBooNE

- $\nu_\mu \rightarrow \nu_e$ appearance with ν beam
- Check LSND
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, but slower



K2K

- Atmospheric anomaly with accelerator ν beam

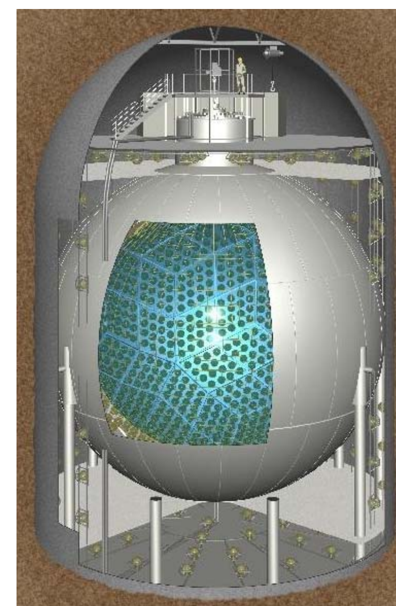


SNO

- Solar neutrinos with flavor selection
- Phase 3 with new neutron counters

KamLAND

- Reactor expt at solar Δm^2



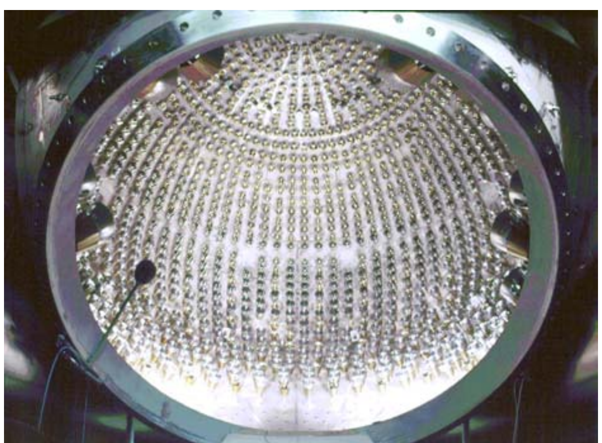
Under construction

MINOS

- Fermilab ν beam to Soudan, L=730 km
- Measure atmospheric oscillation
- Search for $\nu_\mu \rightarrow \nu_e$

CERN ν to Gran Sasso

- L=730 km (!)
- Focus on $\nu_\mu \rightarrow \nu_\tau$ appearance
- OPERA: emulsion
- ICANOE: LAr TPC



Borexino

- Solar neutrinos
- Real-time, very low threshold
- Measure ^{7}Be line

From the current round:

LSND: yes or no

- New physics!
- Short baseline stays interesting
- Plus all this (with different meaning)

- Δm^2_{atm}, Δm^2_{sol} well measured
- θ_{12}, θ_{23} pretty well known
- Know if $\theta_{13} \lesssim 0.1$
- Now: $\theta_{12} \sim \pi/6$, $\theta_{23} \sim \pi/4$, $\theta_{13} < 0.2$

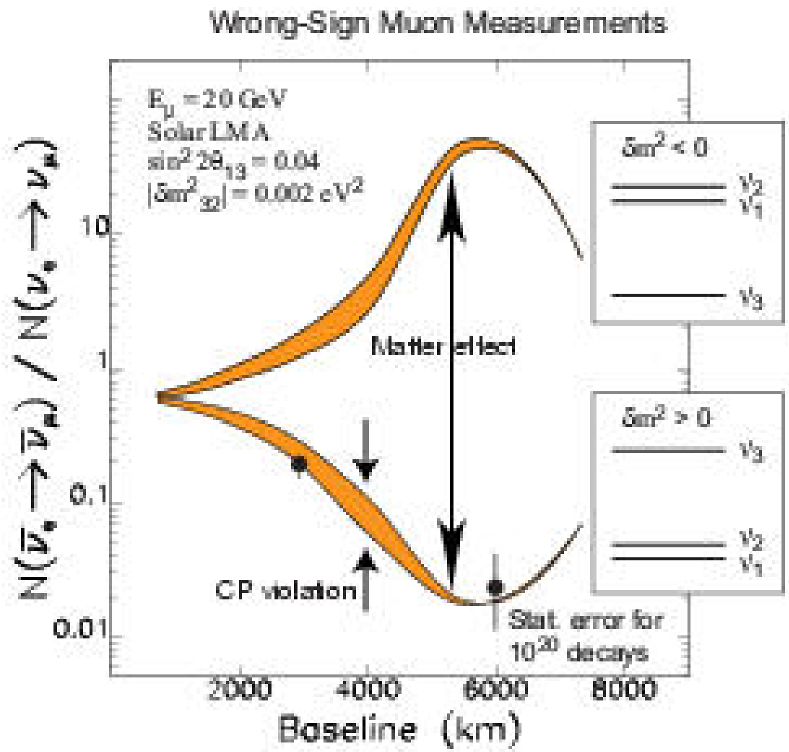
$$U = \begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \end{array}$$

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

The next goals:

- Further confirming the picture (cf. CKM)
- Ordering the mass hierarchy
- CP violation
- θ_{13} is the gatekeeper

Thanks to several Fermilab studies…



Barger *et al.*, hep-ph/0003184

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) = 16 s_{12} c_{12} \underline{s_{13}} c_{13}^2 s_{23} c_{23} \times$$

$$\underline{\sin\delta} \sin\underline{\left(\frac{\Delta m_{12}^2 L}{4E}\right)} \sin\left(\frac{\Delta m_{13}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{23}^2 L}{4E}\right)$$

The velvet rope: is $\theta_{13} \gtrsim 0.05$?

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right)$$

⇨Look for $\nu_\mu \leftrightarrow \nu_e$ at *atmospheric* L/E – needs:

- bigger detectors (~20 kt)

  and/or
- better detectors (calorimeter for e^-?, LAr?)

  and/or
- higher intensity neutrino beams (x2-10)

$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(1.27\Delta m^2_{atm}\frac{L}{E}\right)$$

⇨ν_e disappearance at *atmospheric* L/E – needs:

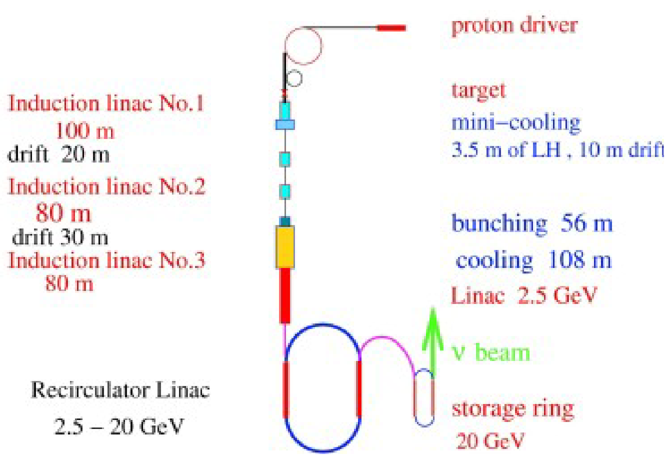
- Very high precision reactor experiment

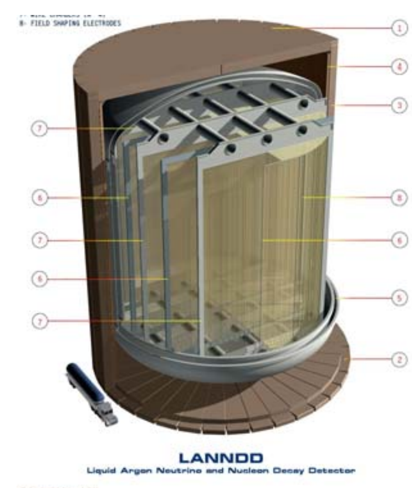
“Phase I” proposals:

- Fermilab-Minn/Canada
- Brookhaven-Homestake/WIPP
- Japan Hadron Facility-Kamioka

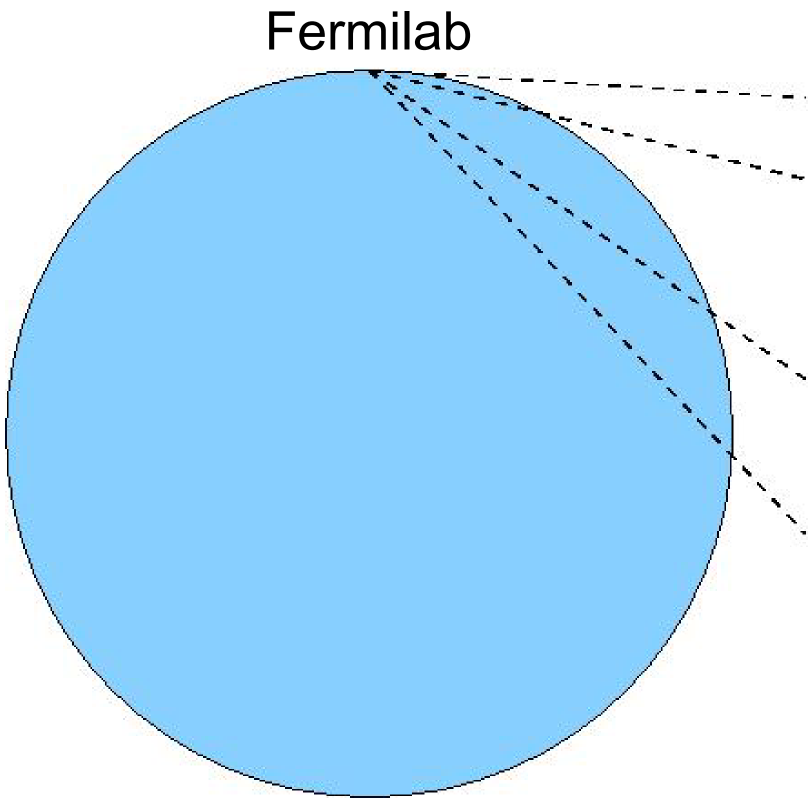
If $\theta_{13} \gtrsim 0.05$, the next steps are just wildly difficult

- Multi-1000-km baselines optimal
- Conventional “superbeams” *may* get sign(Δm^2_{atm})
- CP violation needs new technology beam:
  muon storage ring “neutrino factory”





Think big: the ~~sky's~~ ground's the limit…



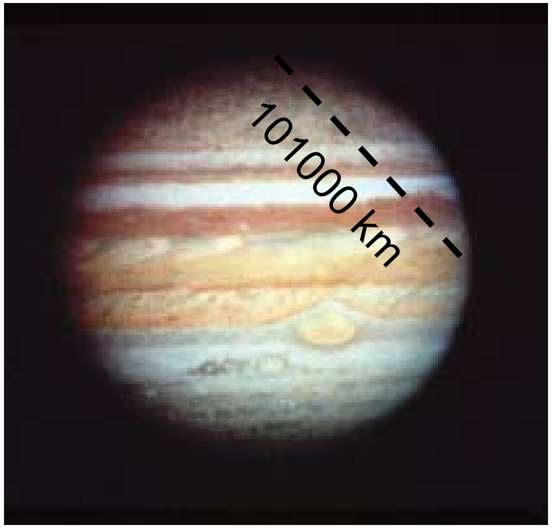
	dist (km)	angle
Soudan	730	3.3^o
California	3000	13.6^o
Gran Sasso	7300	34.9^o
Japan	9300	46.6^o

(Pike's Peak cog railway: 9.1^o)

Bigger! Slower!! More expensive!!!
…the anti-Golden Age? (with apologies to NASA)

Synergism with other physics?
- proton decay, astrophysics?

See-saw relation for new facilities?
- new detectors in existing beams
- new beams to existing detectors
- Super-K/K2K/JHF example



Remember: we're high energy physicists—
this is what happens when we're *wildly successful!*