DAEδALUS

A Novel Approach to CP violation in the ν sector

Jose Alonso

MIT/Sanford Lab

Sanford

Underground Laboratory @ Homestake

Adventures at the Forefront of Neutrino Physics

Sanford
Underground Laboratory @ Homestake

… for the DAEδALUS Collaboration

- Special thanks to :
  - – Janet Conrad (MIT), Mike Shaevitz (Columbia)

- References
  - – DAEδALUS Expression of Interest (EOI):

    arXiv.org > physics > arXiv:1006.0260
  - – Boris Kayser: lectures posted Fermilab website
  - – Los Alamos Science # 25 (1997)

DAEδALUS

Decay

At rest

Experiments for

δ_{CP}

At the

Laboratory for

Underground

Science

MIT / Sanford Laboratory

“Executive Summary”

$\pi - \mu - e$ decay at rest produces neutrino components of great use for oscillation and CP-violation studies

“Executive Summary”

$\pi - \mu - e$ decay at rest produces neutrino components of great use for oscillation and CP-violation studies

Producing sufficient quantities of pions requires megawatt-class, > 600 MeV proton beams

“Executive Summary”

$\pi - \mu - e$ decay at rest produces neutrino components of great use for oscillation and CP-violation studies

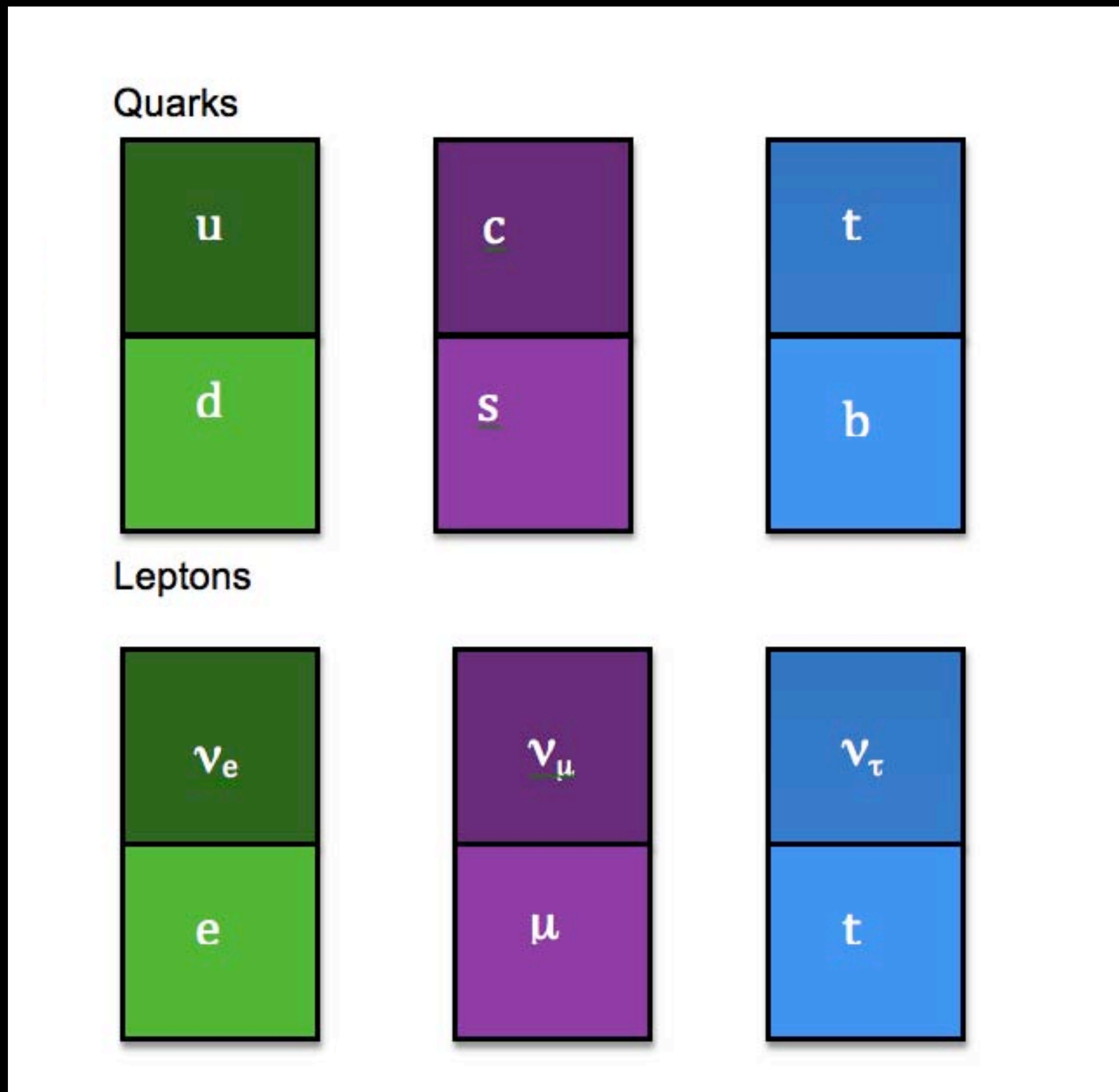
Producing sufficient quantities of pions requires megawatt-class, > 600 MeV proton beams

DAEδALUS experiment needs three production sites close to the 300 kton water-Cerenkov detector planned for DUSEL

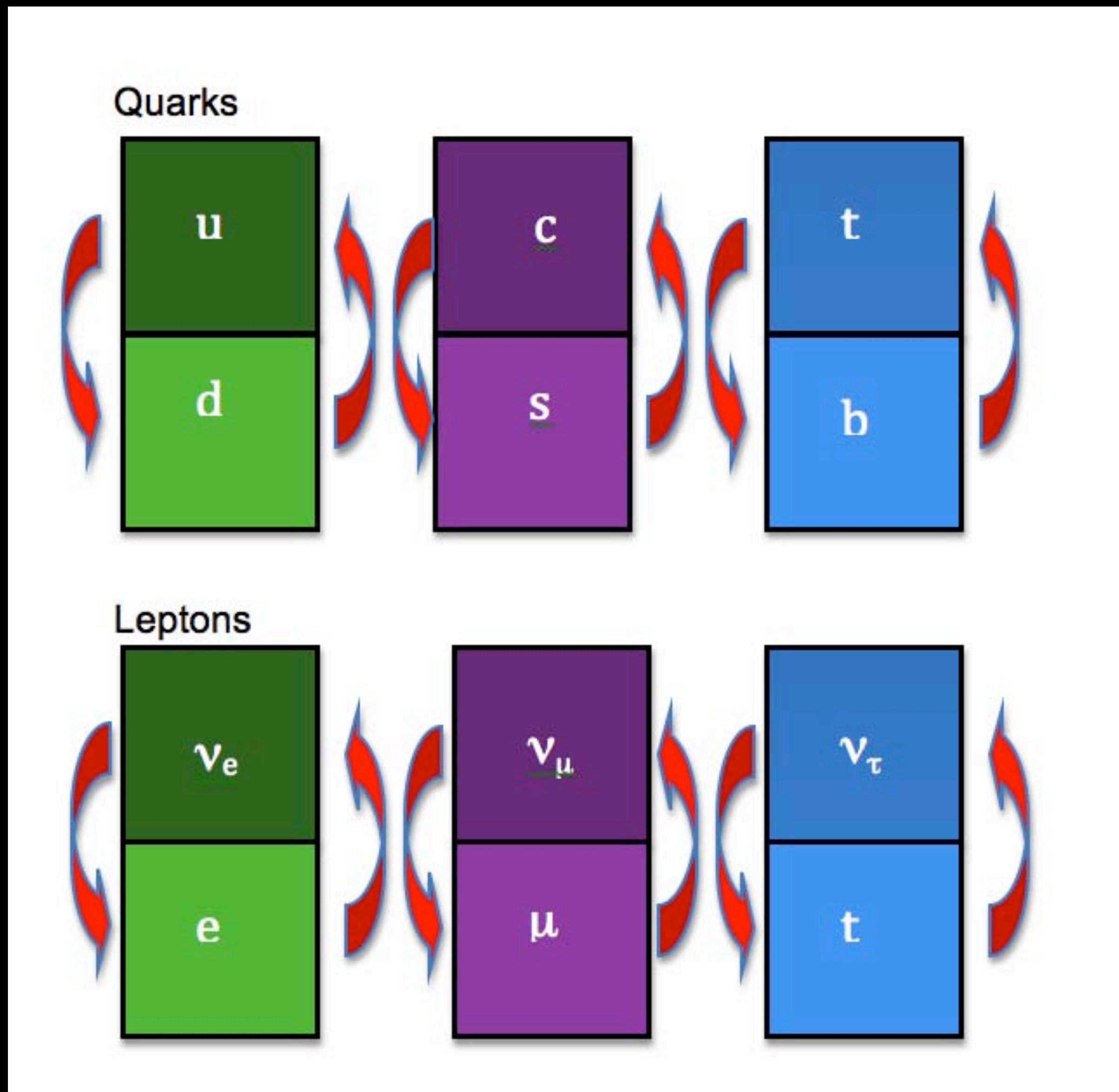
What’s all the excitement about Neutrinos?

Sanford Underground Laboratory @ Homestake

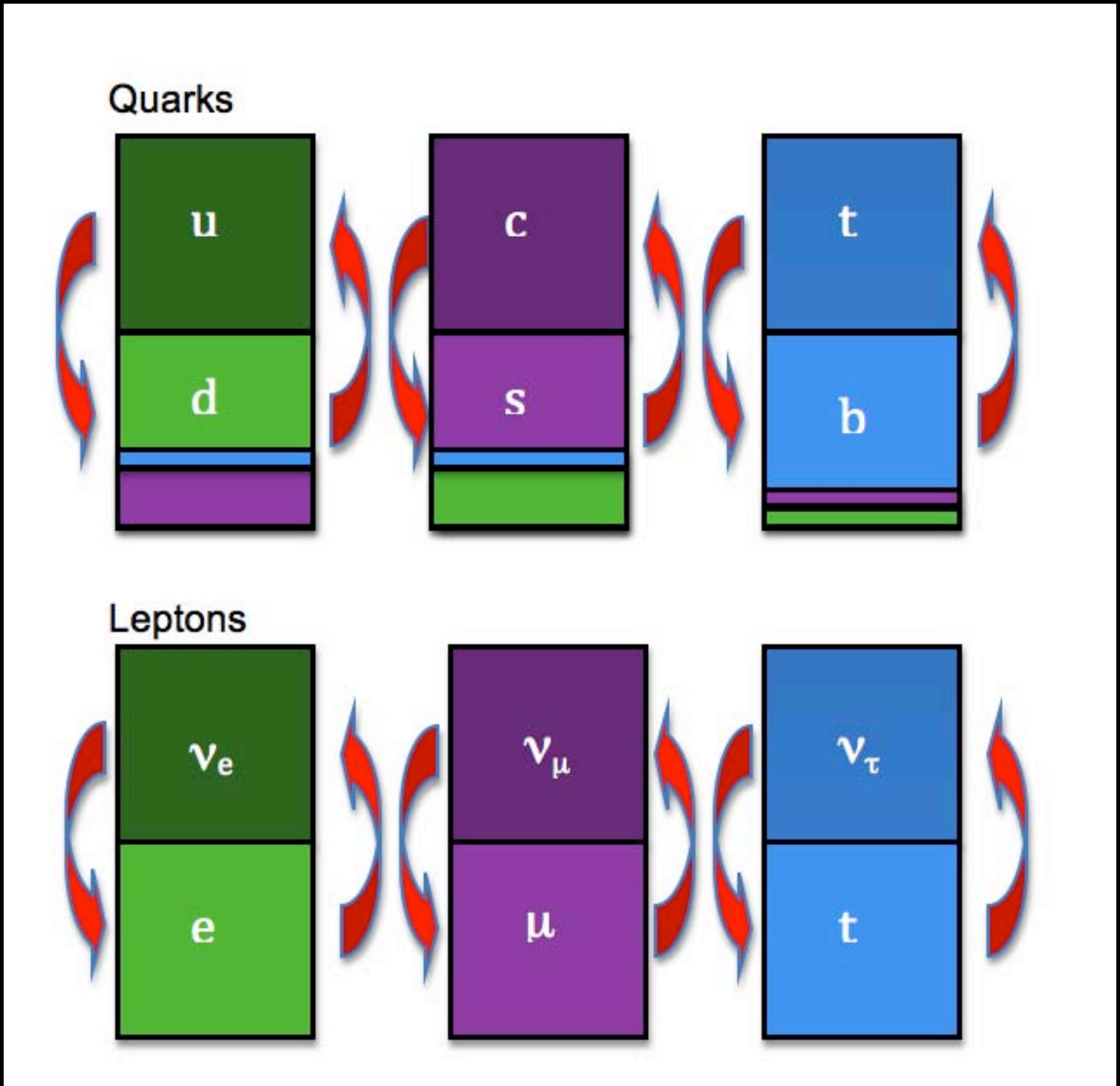
Brief look at Standard Model



Transitions within Families

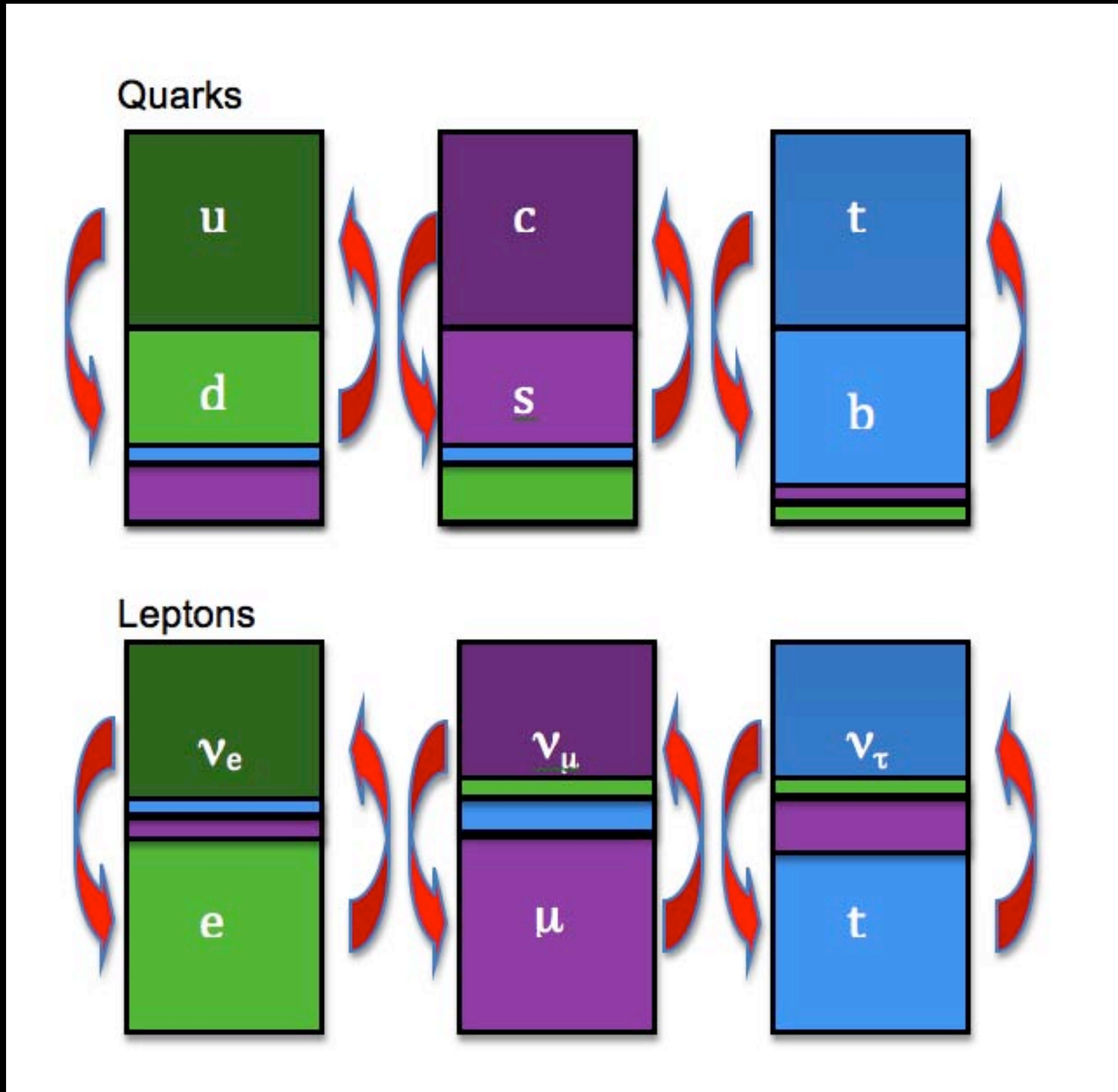


Mixing within Quark Families



Required to explain Weak Decays of Hadrons

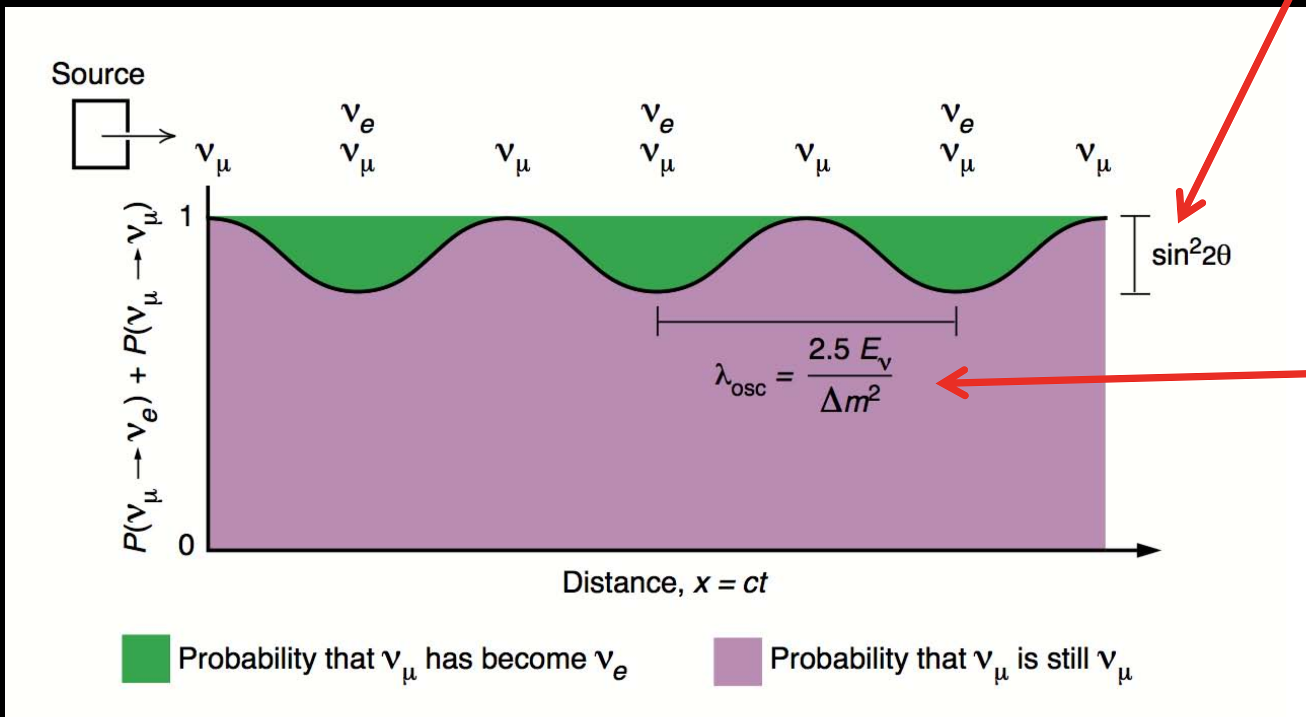
Mixing within Lepton Families?



Oscillations!

Oscillations of Neutrinos

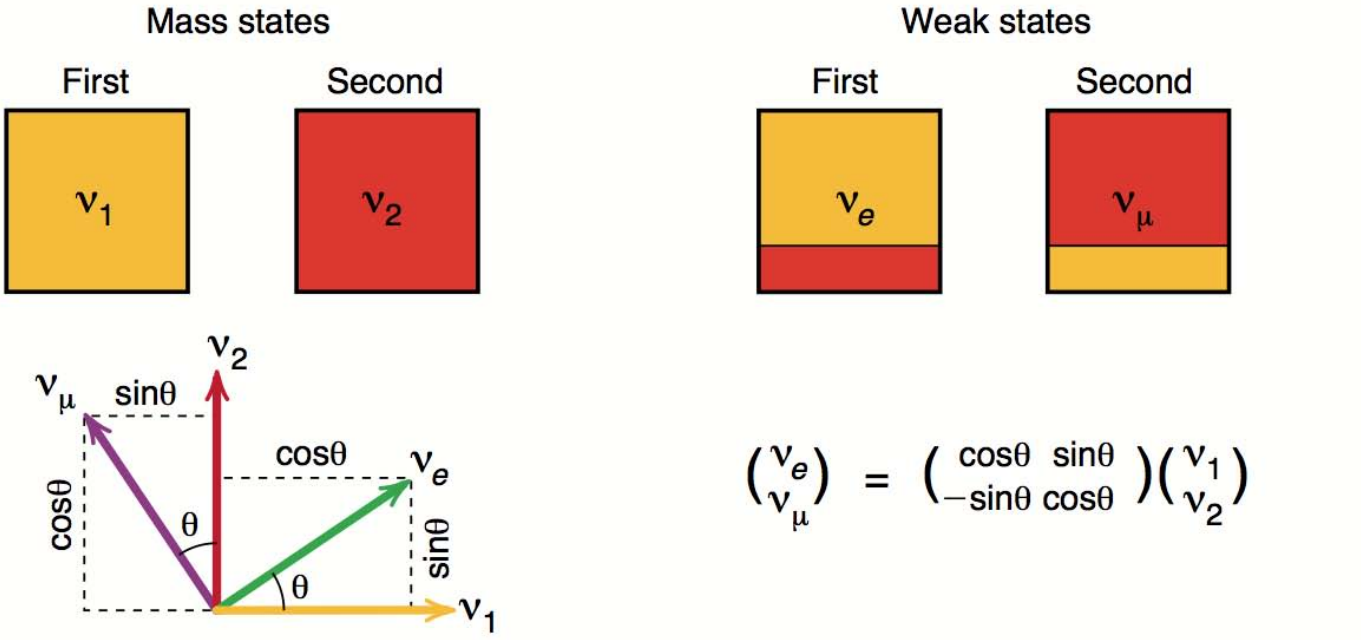
θ = mixing angle



λ = oscillation frequency

NOTE: $\lambda/E \sim 1/\Delta m^2$

Mixing



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Neutrino Mixing

- Have 3 families

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Mixing - *complicated*

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

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Neutrino Mixing - *complicated*

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

The CP Violation Parameter

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

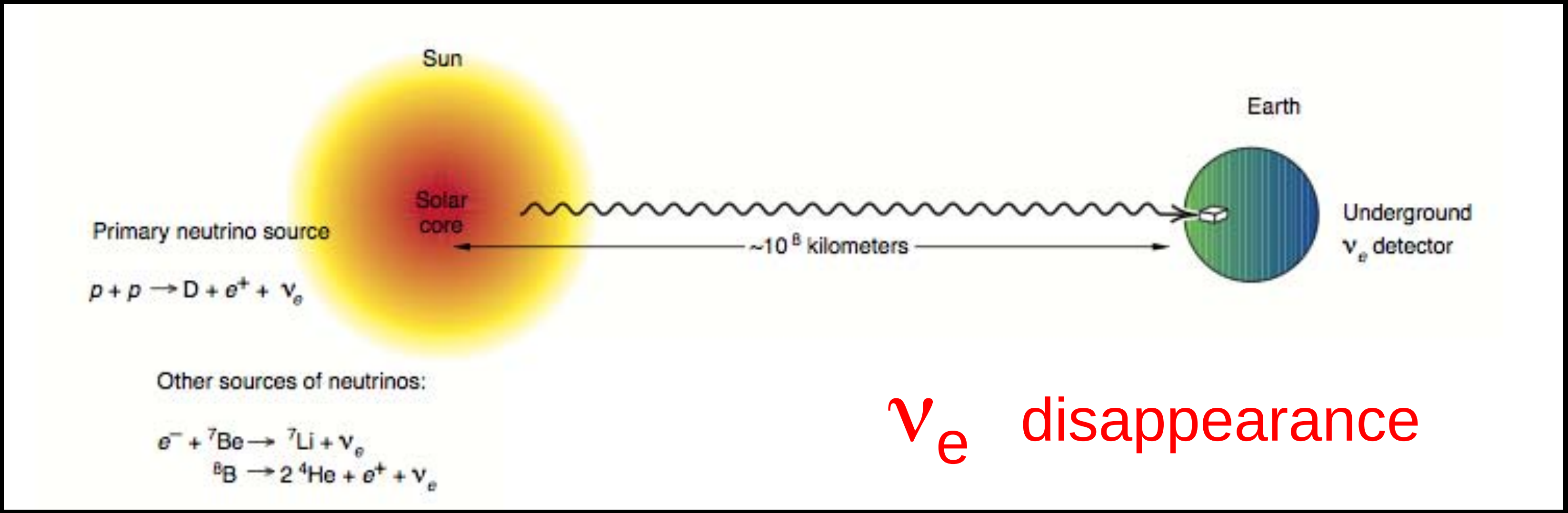
From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

θ_{12} Solar Neutrinos

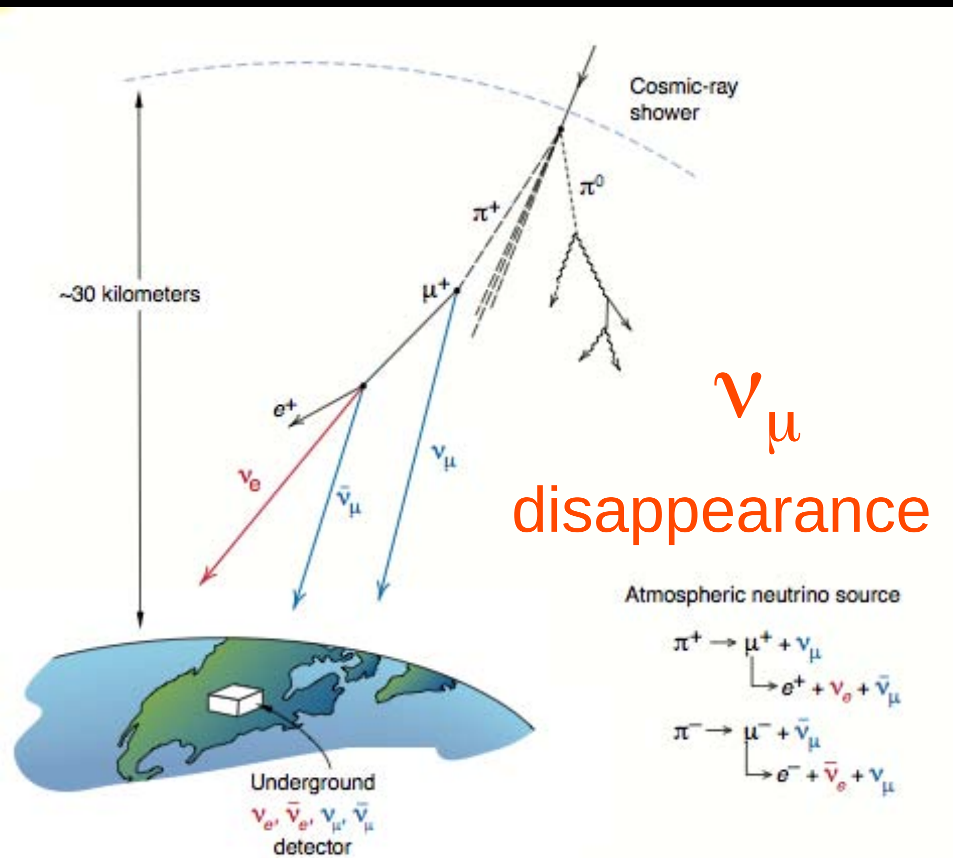


$$\sin^2 2\theta_{12} = 0.846 \pm .033$$

$$\Delta m_{12}^2 = (7.65 \pm 0.23)\ 10^{-5}\ eV^2$$

MIT / Sanford Laboratory

θ_{23} Atmospheric Neutrinos

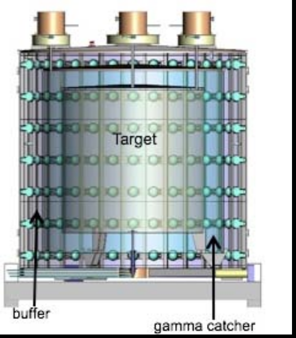


$$\sin^2 2\theta_{23} = 1.00 \pm 0.02$$

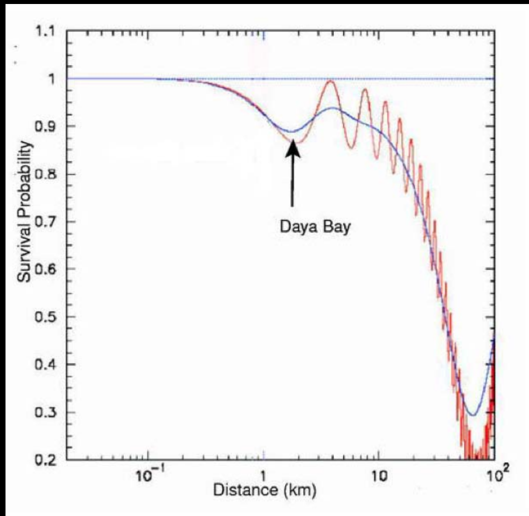
$$\Delta m_{13}^2 \sim \Delta m_{23}^2 \sim (2.40 \pm 0.12)\ 10^{-3}\ \mathrm{eV}^2$$

θ_{13} ~ Reactor Neutrinos

Daya Bay



$\bar{\nu}_e$ disappearance



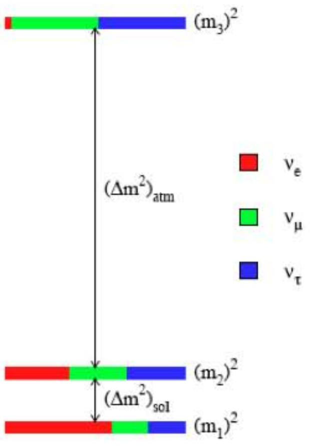
$\mathrm{Sin}^2 2\theta_{13} = ?$ (0.06±0.04)

Expect answer in 5 years

MIT / Sanford Laboratory

Focusing on CP term…

The oscillation of muon-flavor to electron-flavor
at the atmospheric Δm^2
may show CP-violation dependence!



in a vacuum…

$$
\begin{aligned}
P = \quad & (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31}) \\
& \mp \underline{\sin\delta}\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \underline{\cos\delta}\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}).
\end{aligned}
$$

We want to see if δ is nonzero

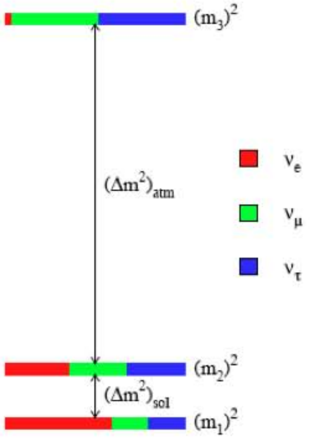
terms depending on mixing angles

terms depending on mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

Focusing on CP term…

The oscillation of muon-flavor to electron-flavor
at the atmospheric Δm^2
may show CP-violation dependence!



Our equation flips sign between
$\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

LBNE

in a vacuum…

$$\begin{aligned} P = \;& (\sin^2\theta_{23}\sin^2 2\theta_{13})\,(\sin^2\Delta_{31}) \\ & \mp \sin\delta\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin^2\Delta_{31}\sin\Delta_{21}) \\ & + \cos\delta\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\ & + (\cos^2\theta_{23}\sin^2 2\theta_{12})\,(\sin^2\Delta_{21}). \end{aligned}$$

We want to see if δ is nonzero

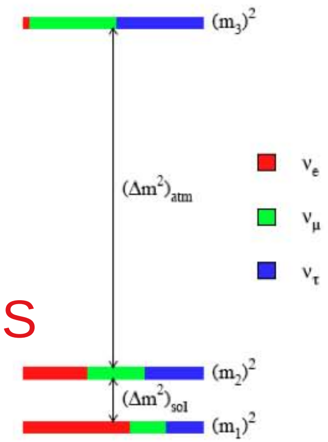
terms depending on mixing angles

terms depending on mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

Focusing on CP term…

The oscillation of muon-flavor to electron-flavor at the atmospheric Δm^2 may show CP-violation dependence!



in a vacuum…

δ also available by varying L

DAEδALUS

$$
\begin{aligned}
P = \quad & (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31}) \\
& \mp \sin\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \cos\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}).
\end{aligned}
$$

We want to see if δ is nonzero

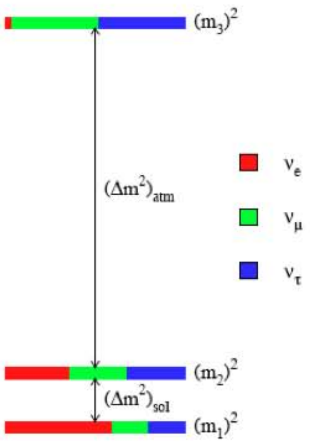
terms depending on mixing angles

terms depending on mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

Focusing on CP term…

The oscillation of muon-flavor to electron-flavor
at the atmospheric Δm^2
may show CP-violation dependence!



in a vacuum…

"Variables"

$$
\begin{aligned}
P = & \quad (\sin^2\theta_{23}\sin^2 2\theta_{13})\,(\sin^2\Delta_{31}) \\
& \mp \sin\delta\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \cos\delta\,(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\,(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& + (\cos^2\theta_{23}\sin^2 2\theta_{12})\,(\sin^2\Delta_{21}).
\end{aligned}
$$

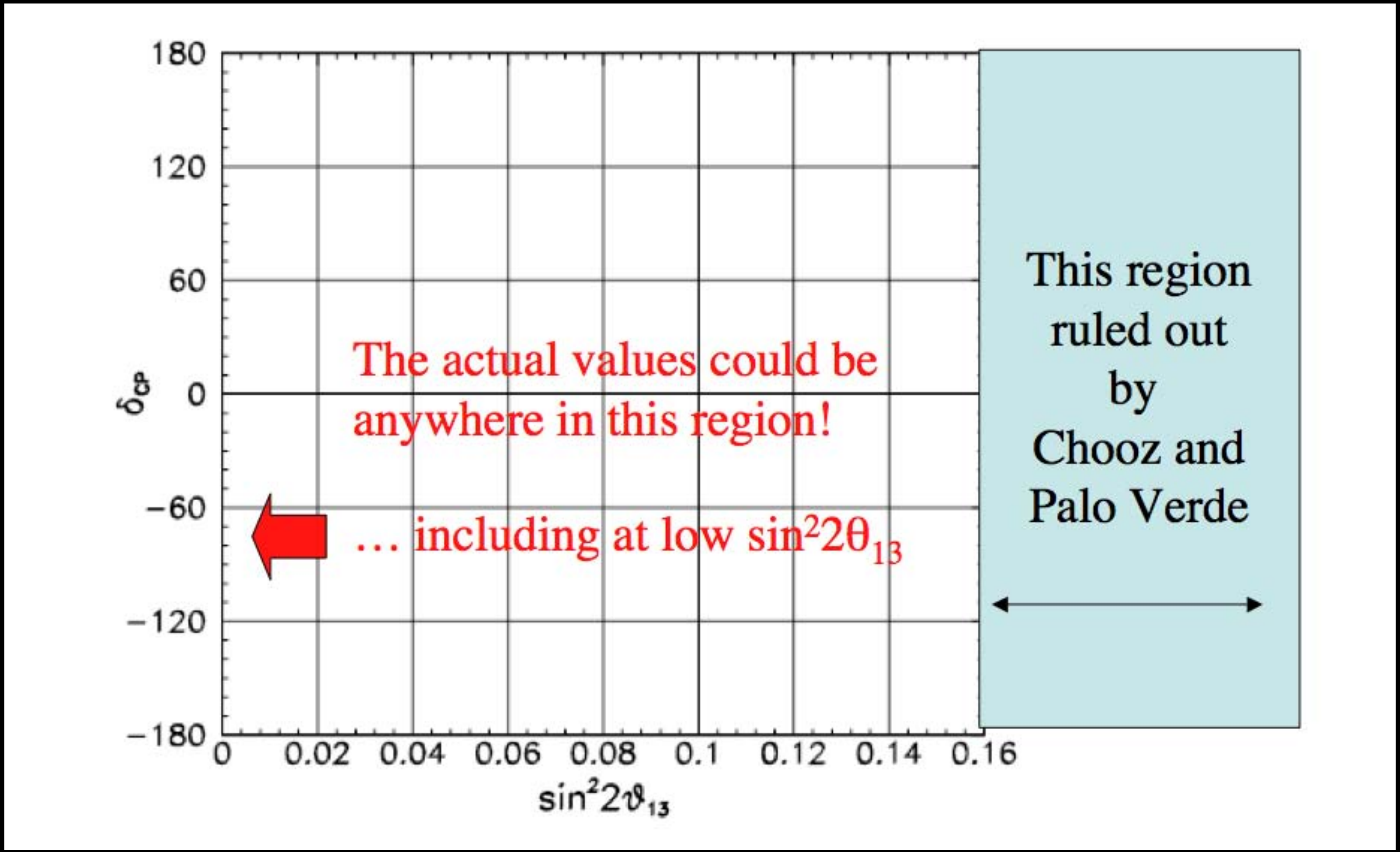
We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

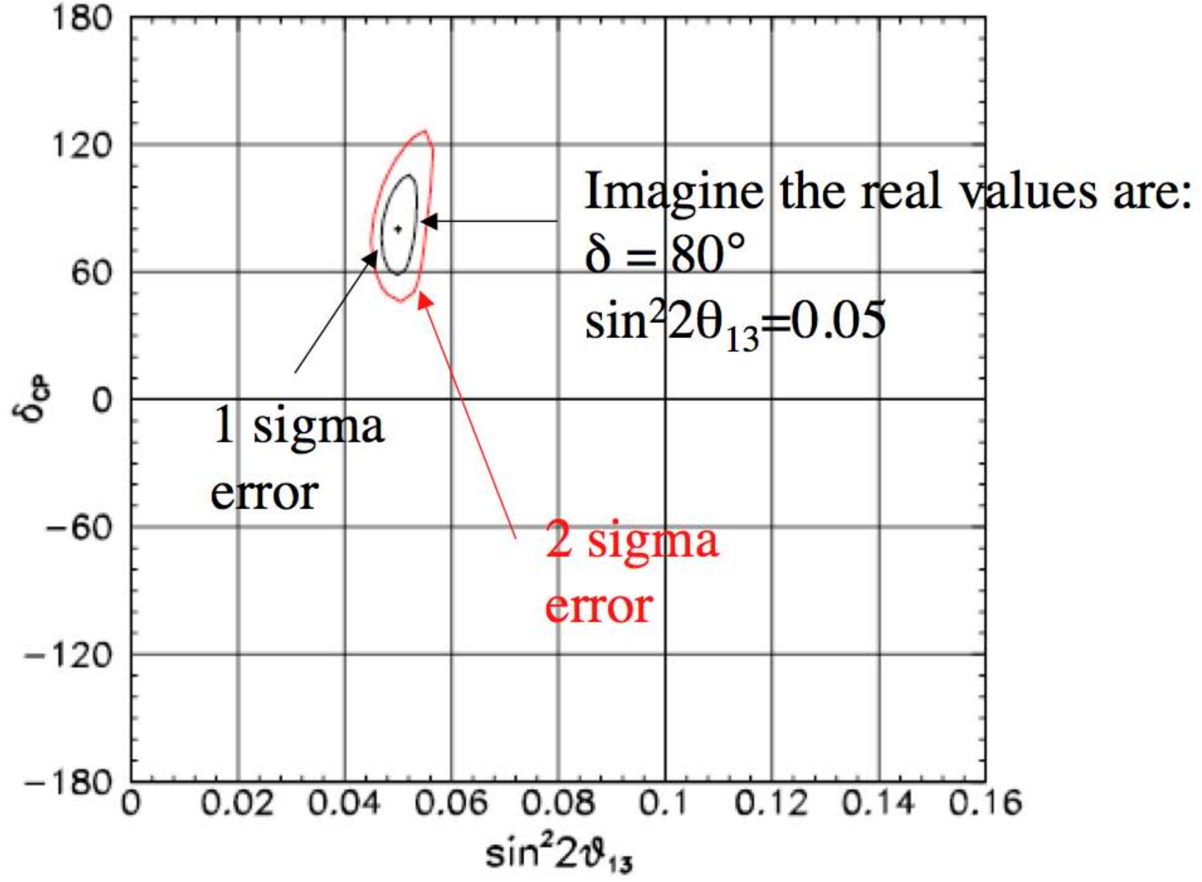
Measure of CP Violation



MIT / Sanford Laboratory

“Jelly Bean” Plots

The experimental goal is to minimize the “Jelly Bean” across this plane



Neutrino Experiments & Detectors

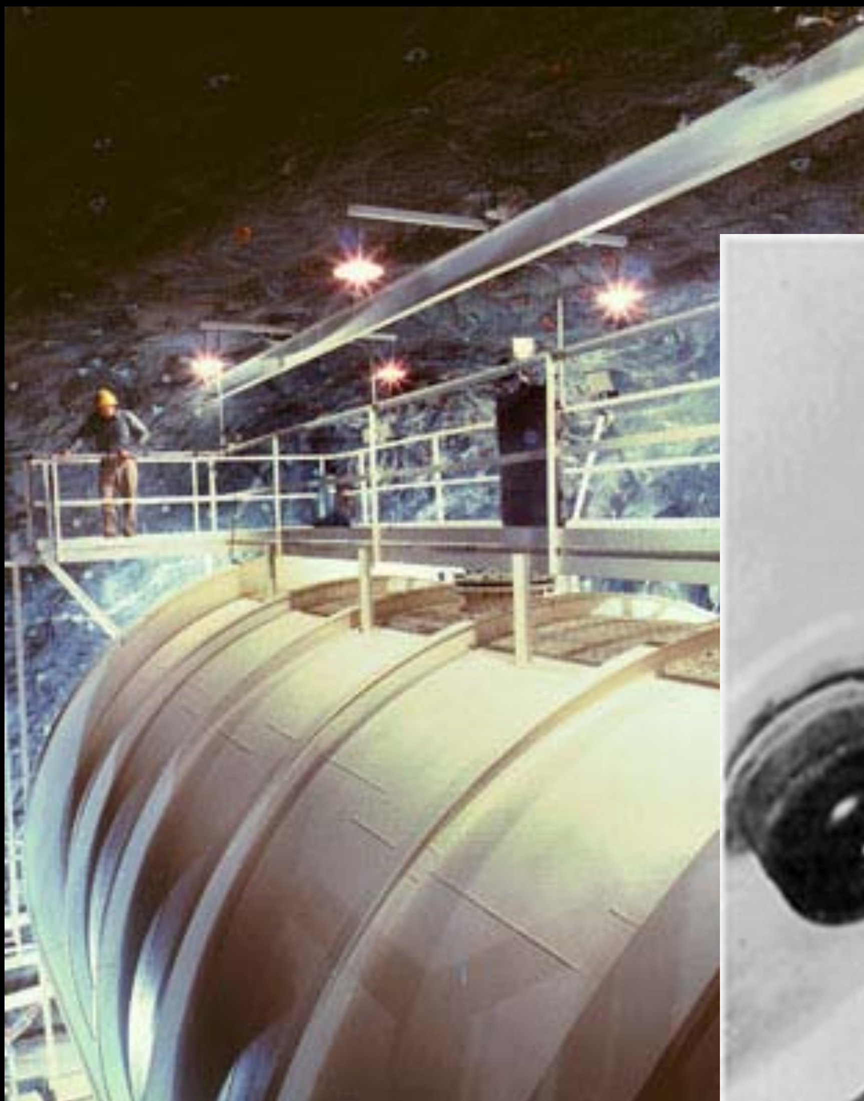
Sanford
Underground Laboratory @ Homestake

Solar Neutrinos at Homestake

1965

100 K gal Perchloroethylene

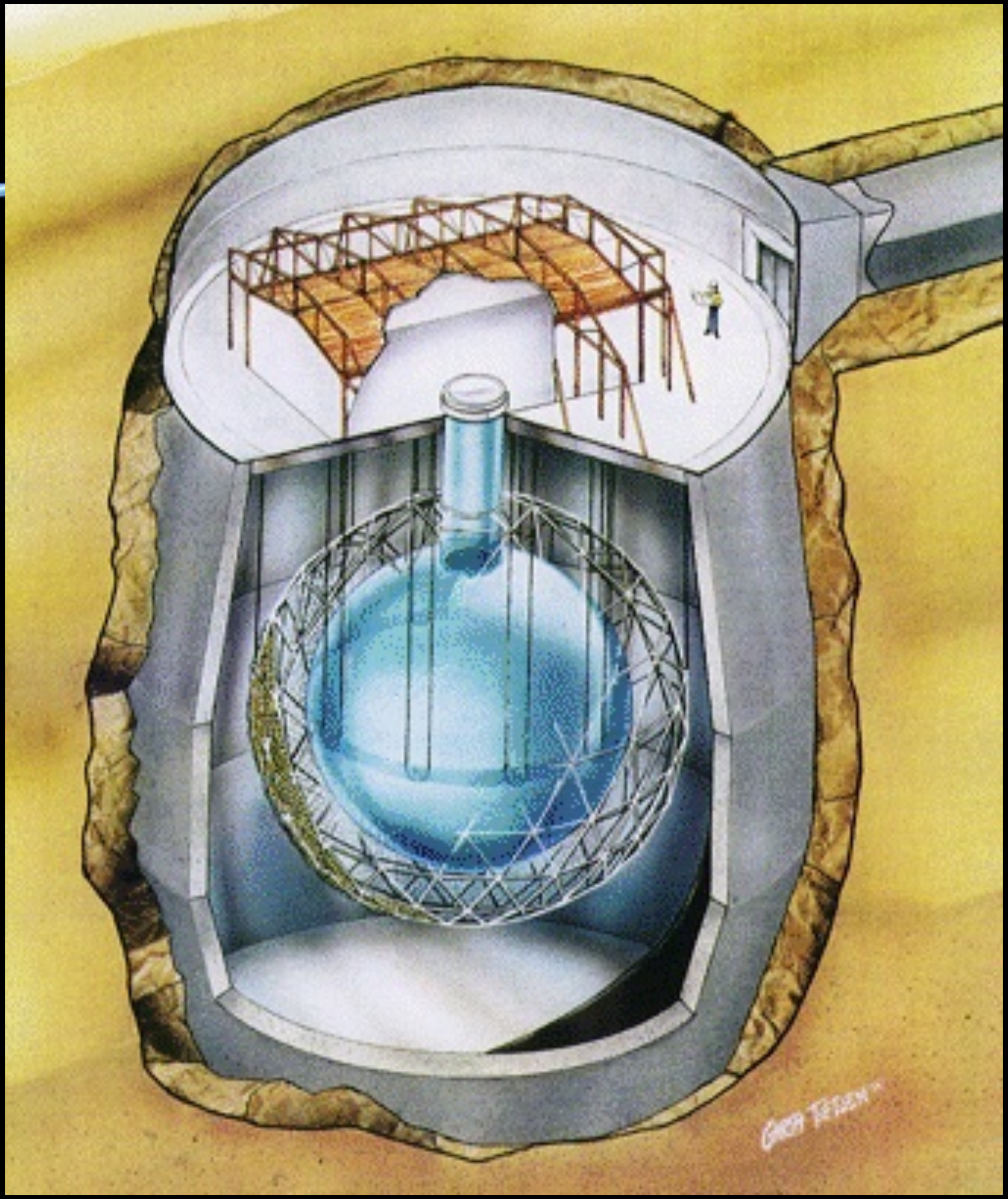
Missing ν_e



Ray Davis John Bahcall

SNO

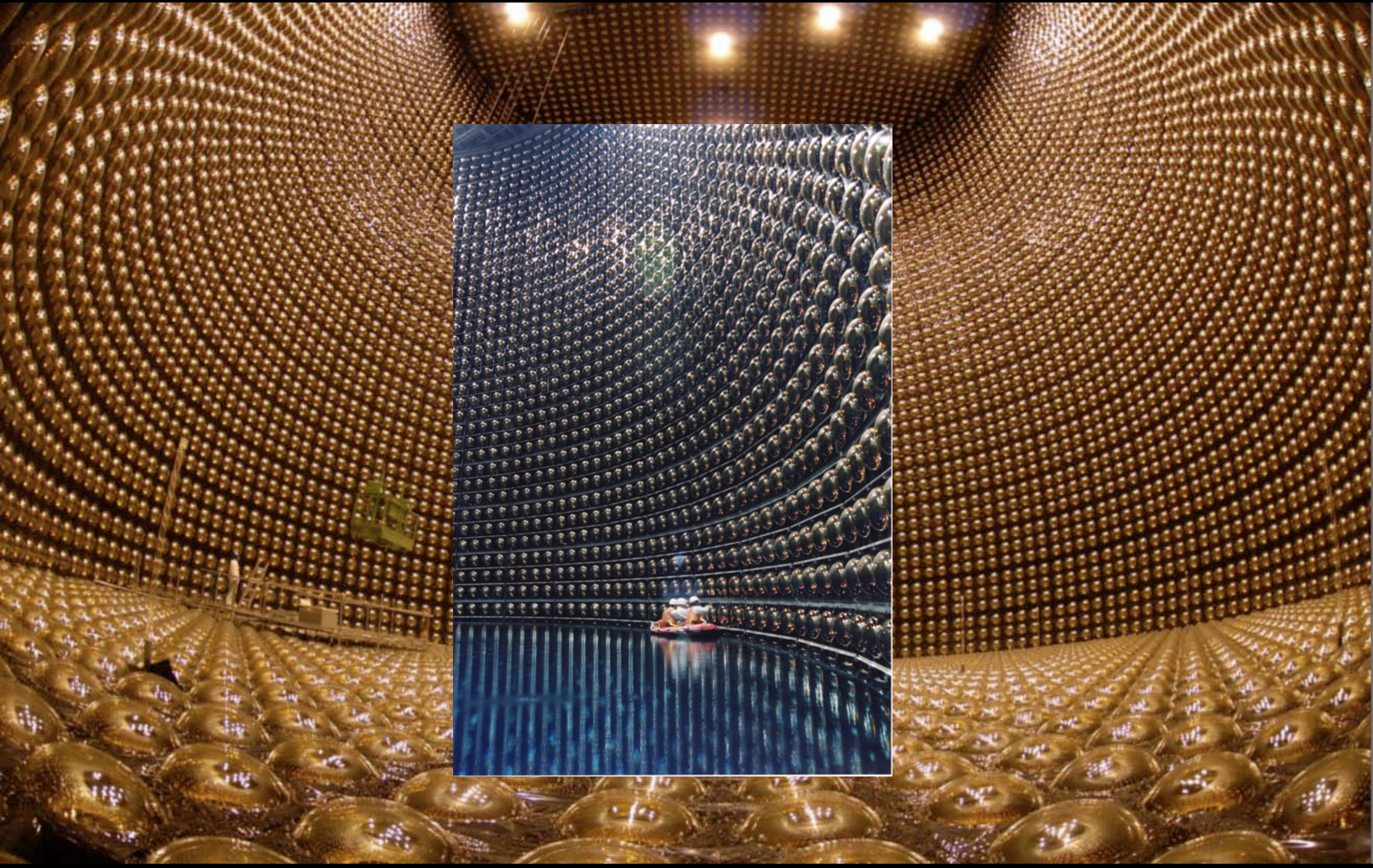
2000
- 1 kT D_2O
- Confirmed oscillation



MIT / Sanford Laboratory

Super-Kamiokande --- Japan

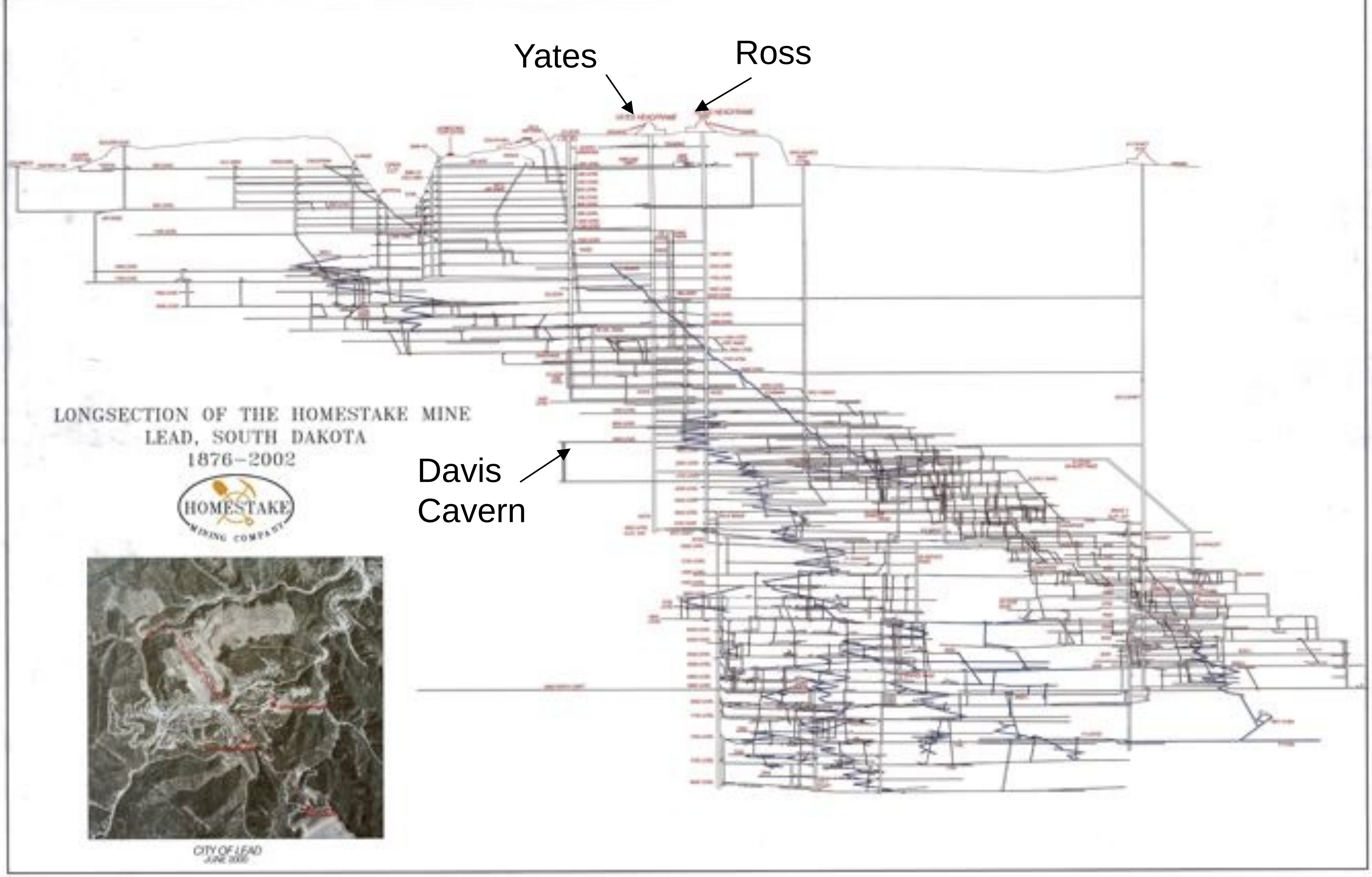
50,000 tons water-Cerenkov



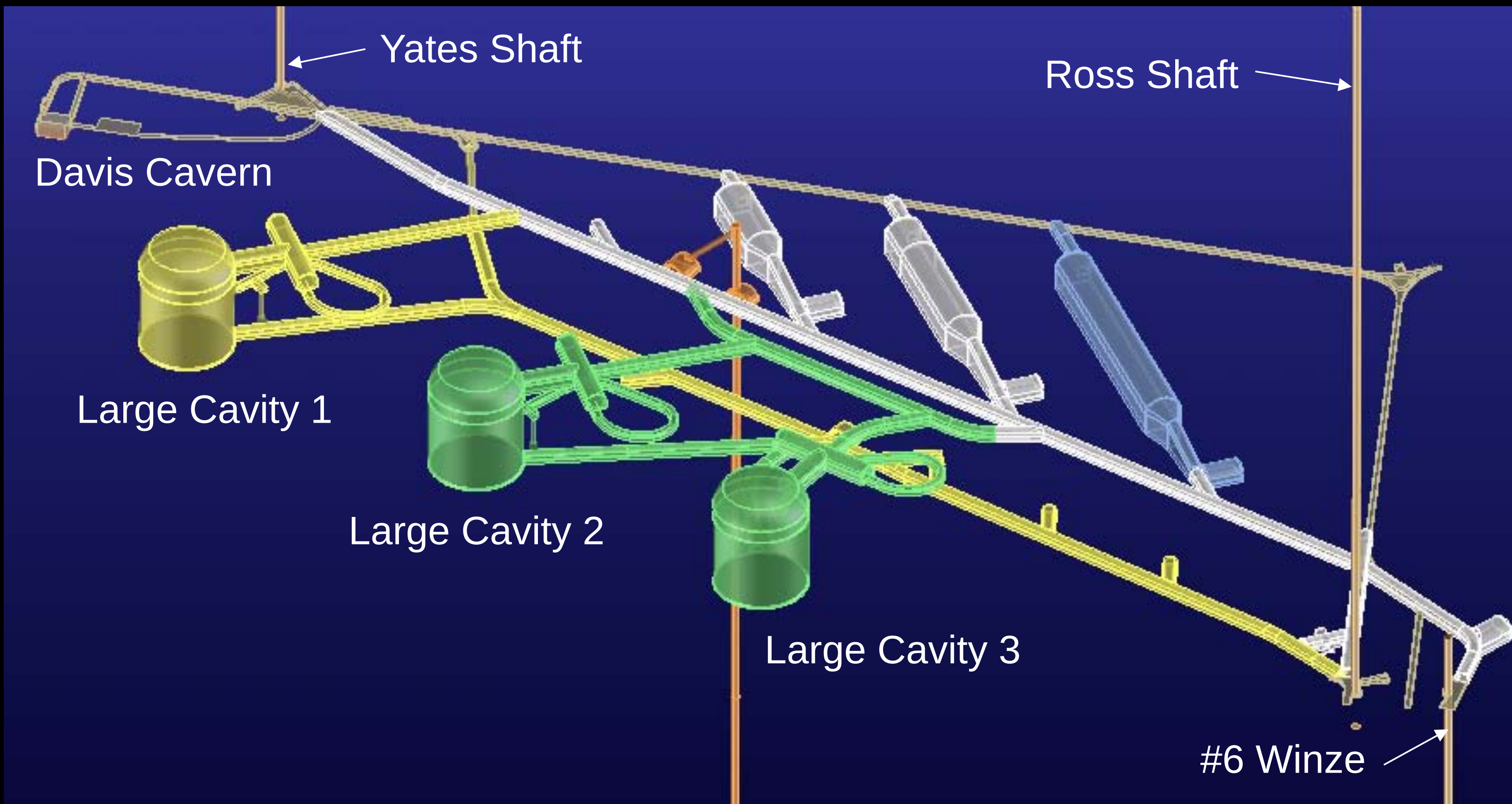
Homestake Mine –

Site of Sanford Lab: Lead, South Dakota

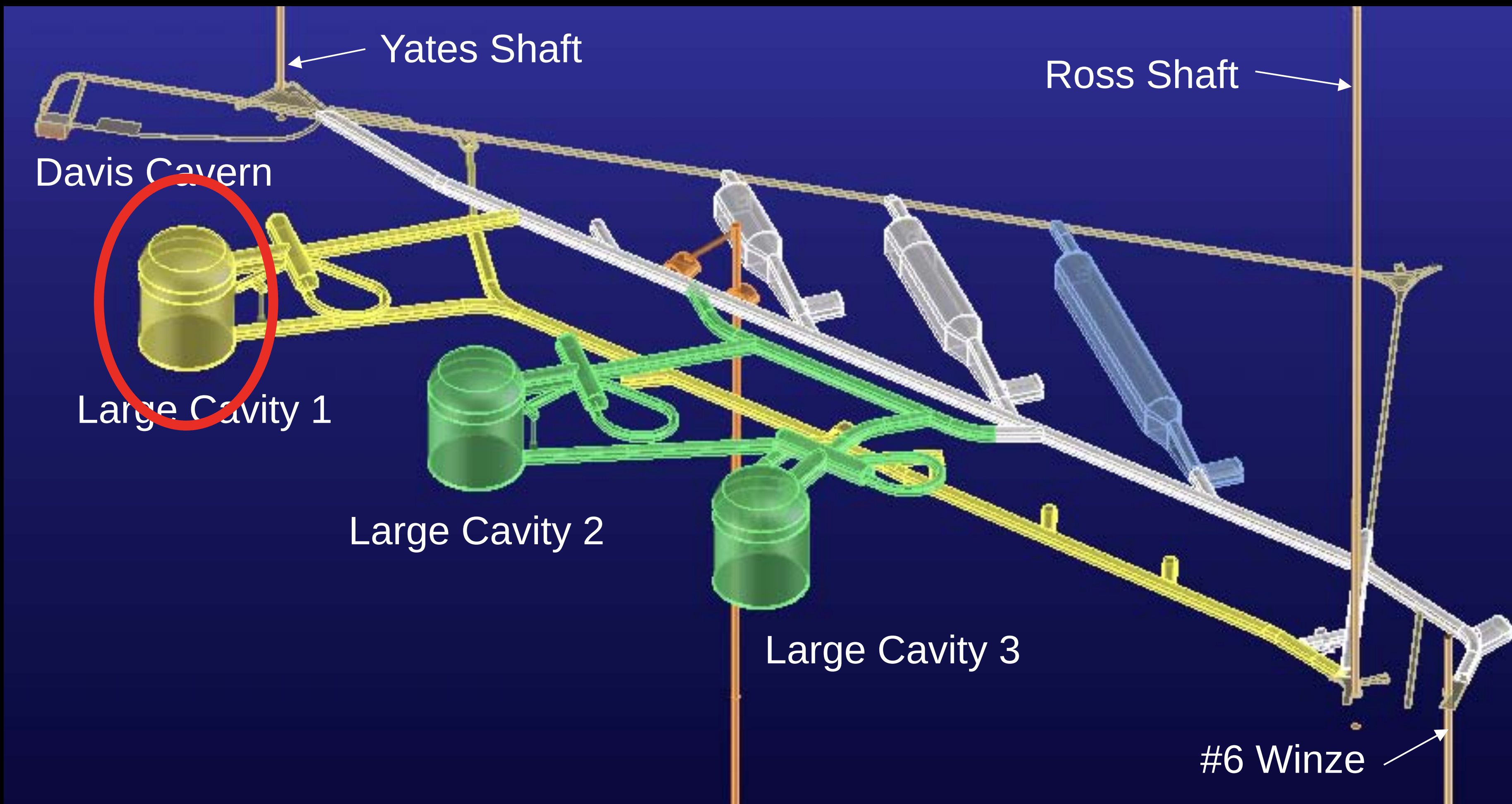
Section View of Homestake Mine

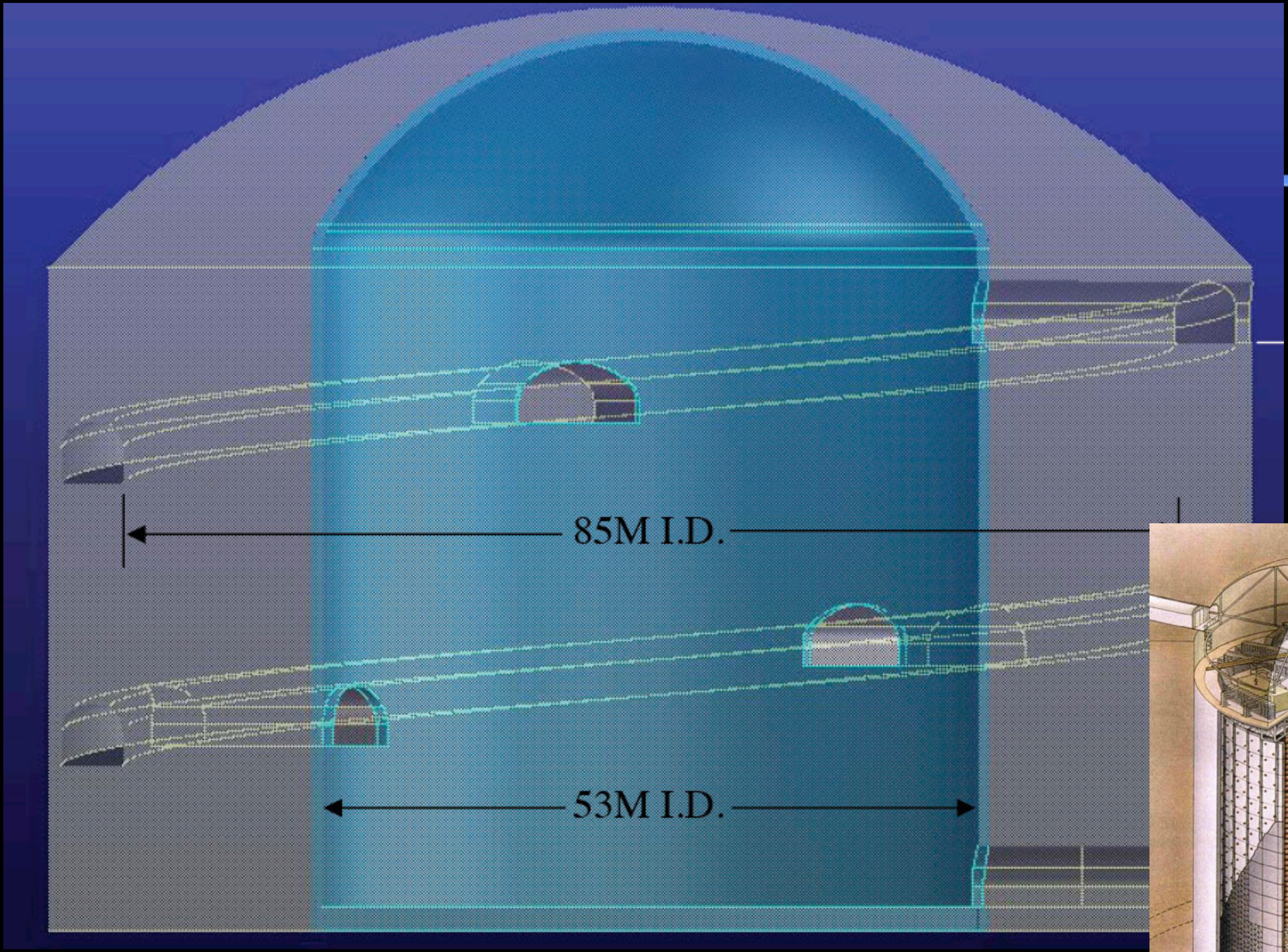


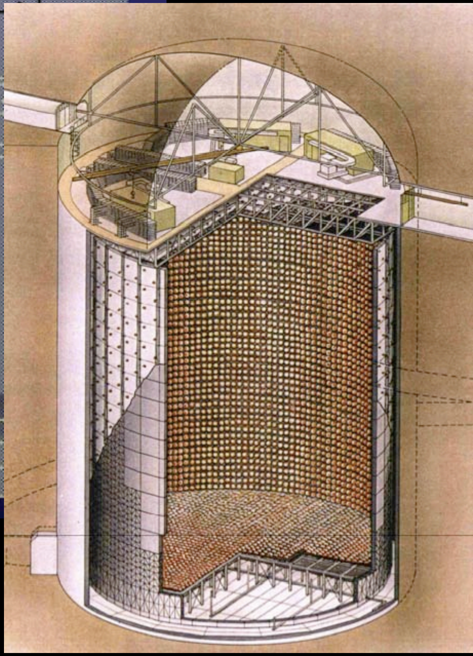
4850 Level of Sanford Lab



4850 Level of Sanford Lab







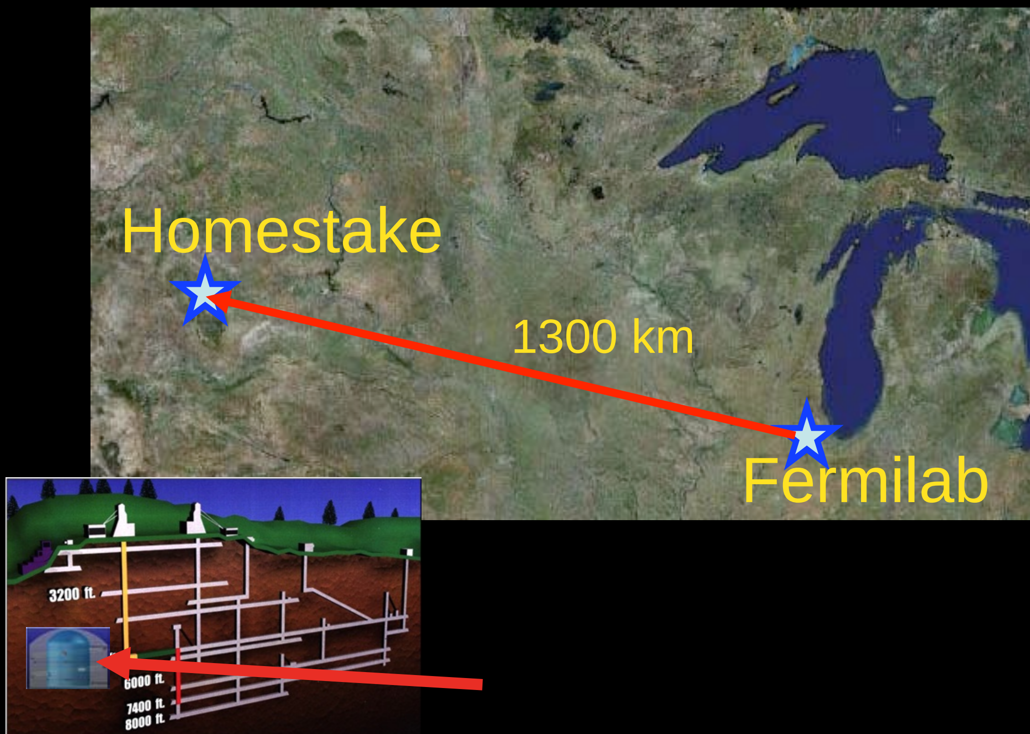
300,000 tons!

MIT / Sanford Laboratory

Rock Volume in Perspective

MIT / Sanford Laboratory

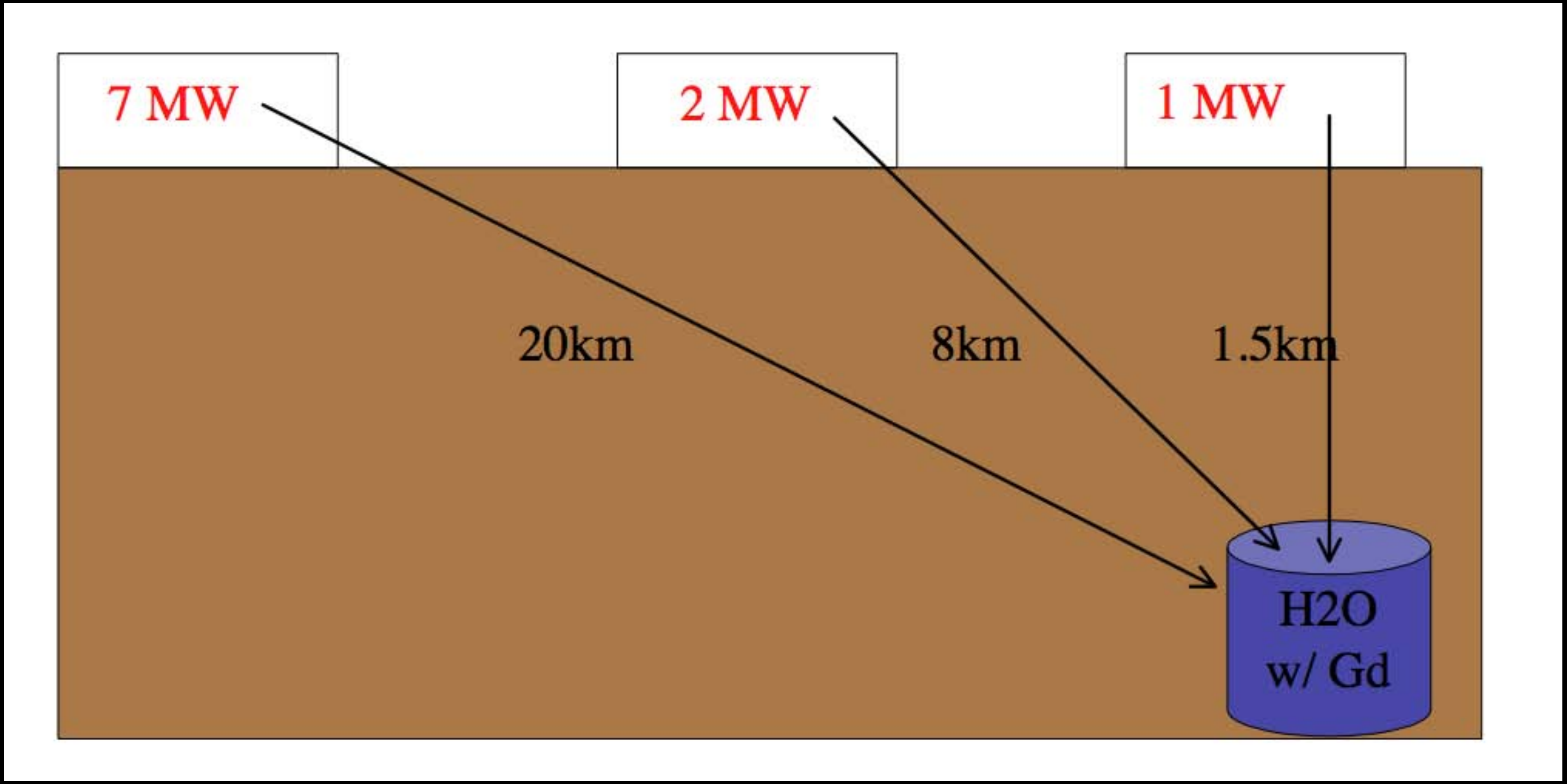
LBNE - Long Baseline Neutrino Experiment



MIT / Sanford Laboratory

Short Baseline - DAEδALUS

DAR (Decay At Rest) – antineutrino source



MIT / Sanford Laboratory

Can one Compare LBNE, DAEδALUS?

Recall: $1/\Delta m^2 \sim \lambda/E_\nu$

Can one Compare LBNE, DAEδALUS?

Recall: $1/\Delta m^2 \sim \lambda/E_\nu$

LBNE: λ = 1000 km, $E_\nu \sim$ 10 GeV

DAEδALUS: $\lambda \sim$ 1-10 km, $E_\nu \sim$ 10 MeV

Can one Compare LBNE, DAEδALUS?

Recall: $1/\Delta m^2 \sim \lambda/E_\nu$

LBNE: λ = 1000 km, $E_\nu \sim$ 10 GeV

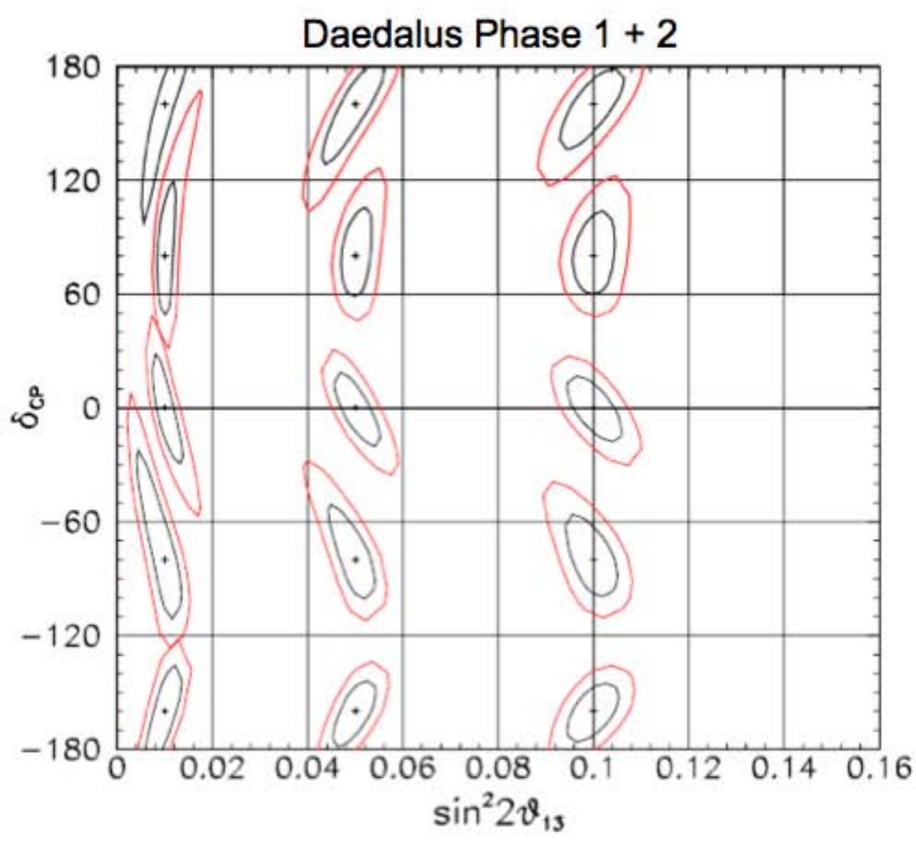
DAEδALUS: $\lambda \sim$ 1-10 km, $E_\nu \sim$ 10 MeV

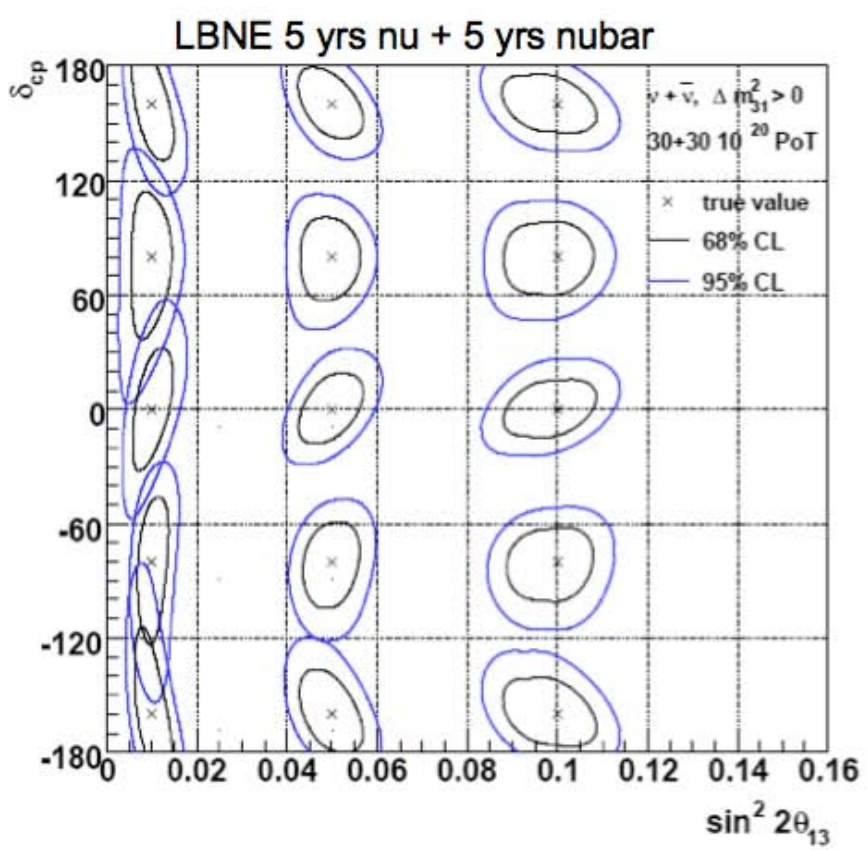
Presto! Cyclotrons have aroused the interest of the "Big Boys" (and Girls)!

Expected Results

DAEδALUS

LBNE

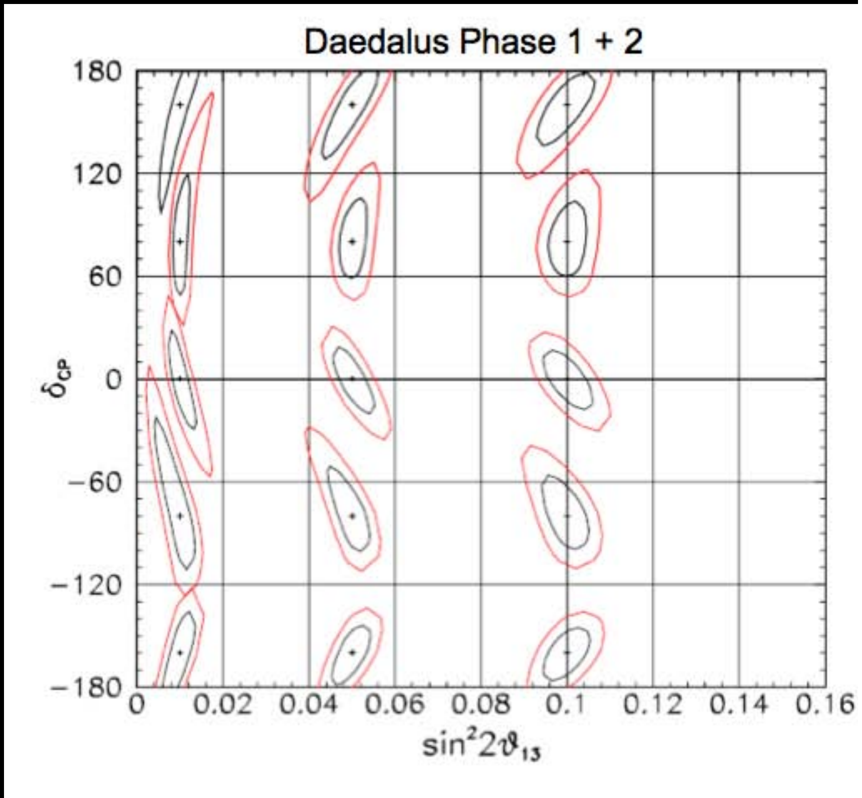




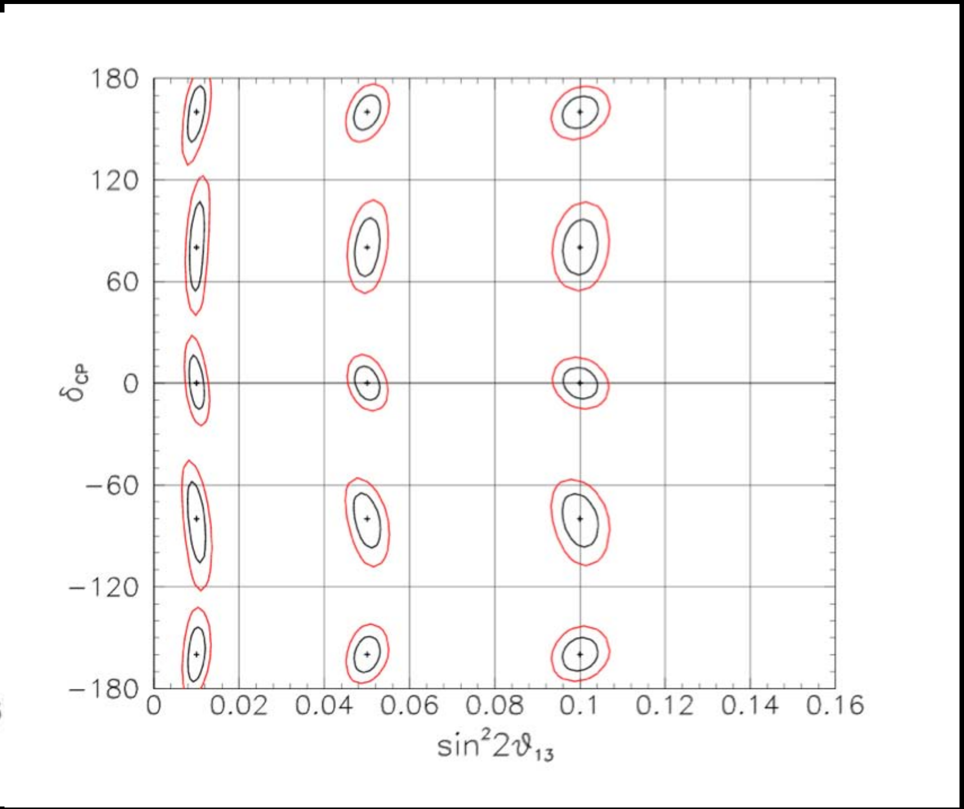
MIT / Sanford Laboratory

Combining: Strengths of Both

DAEδALUS alone



DAEδALUS + LBNE



MIT / Sanford Laboratory

Accelerator Requirements

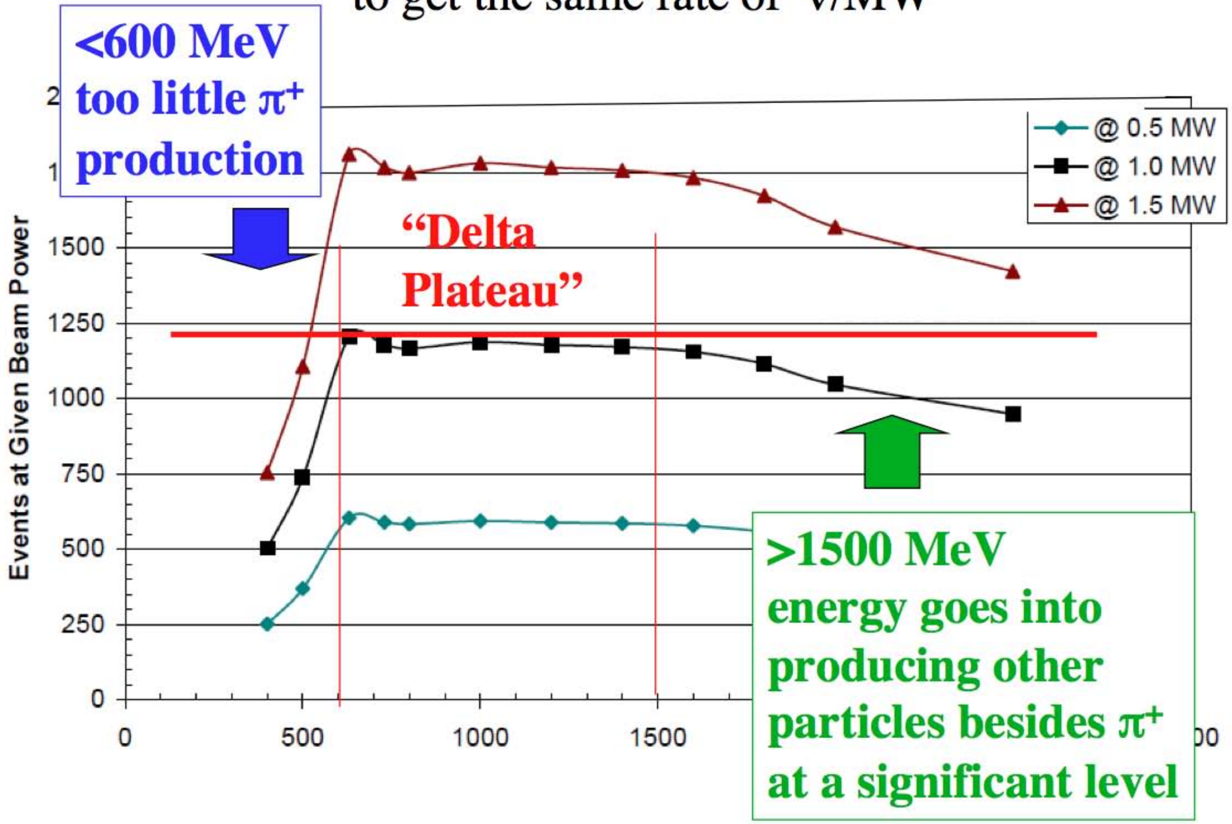
Sanford
Underground Laboratory @ Homestake

Basic Requirements

- Energy ~ 1 GeV ± 400 MeV
- Power ~ 1-5 MW (may need > 1 machine)
- Cost ….   As low as possible!

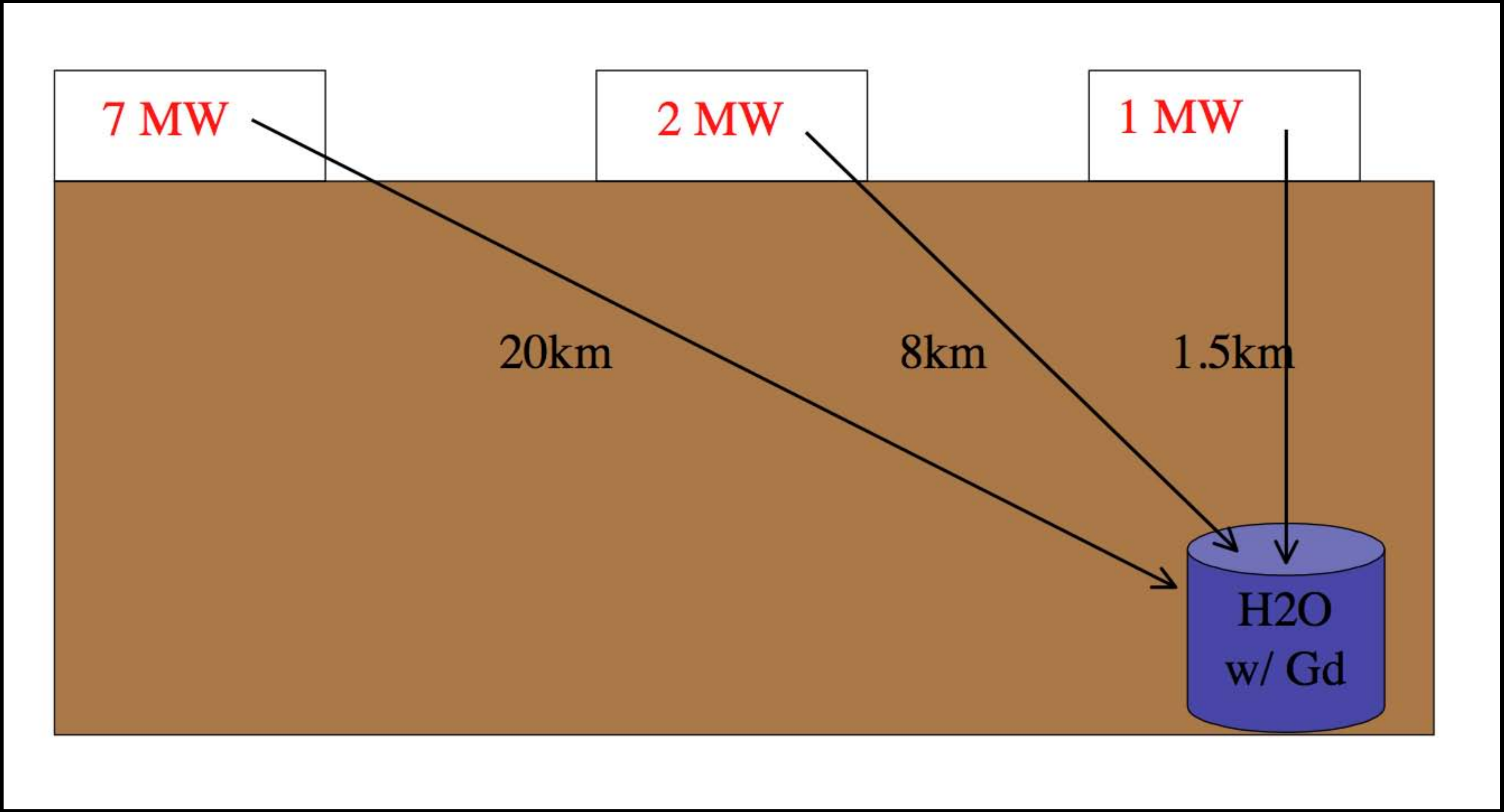
Energy

What proton energy is required?
There is a "Delta plateau" where you can trade energy for current to get the same rate of ν/MW

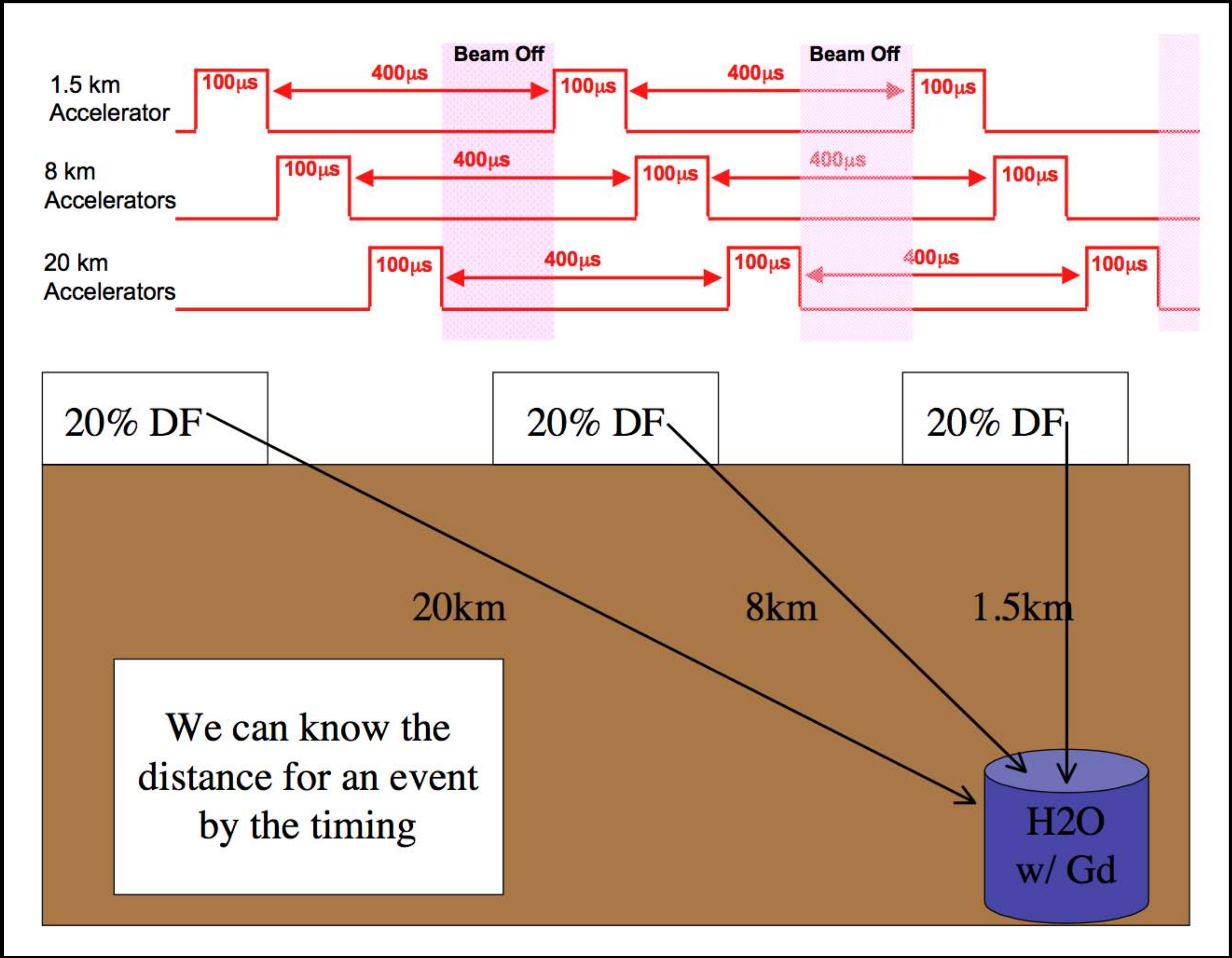


MIT / Sanford Laboratory

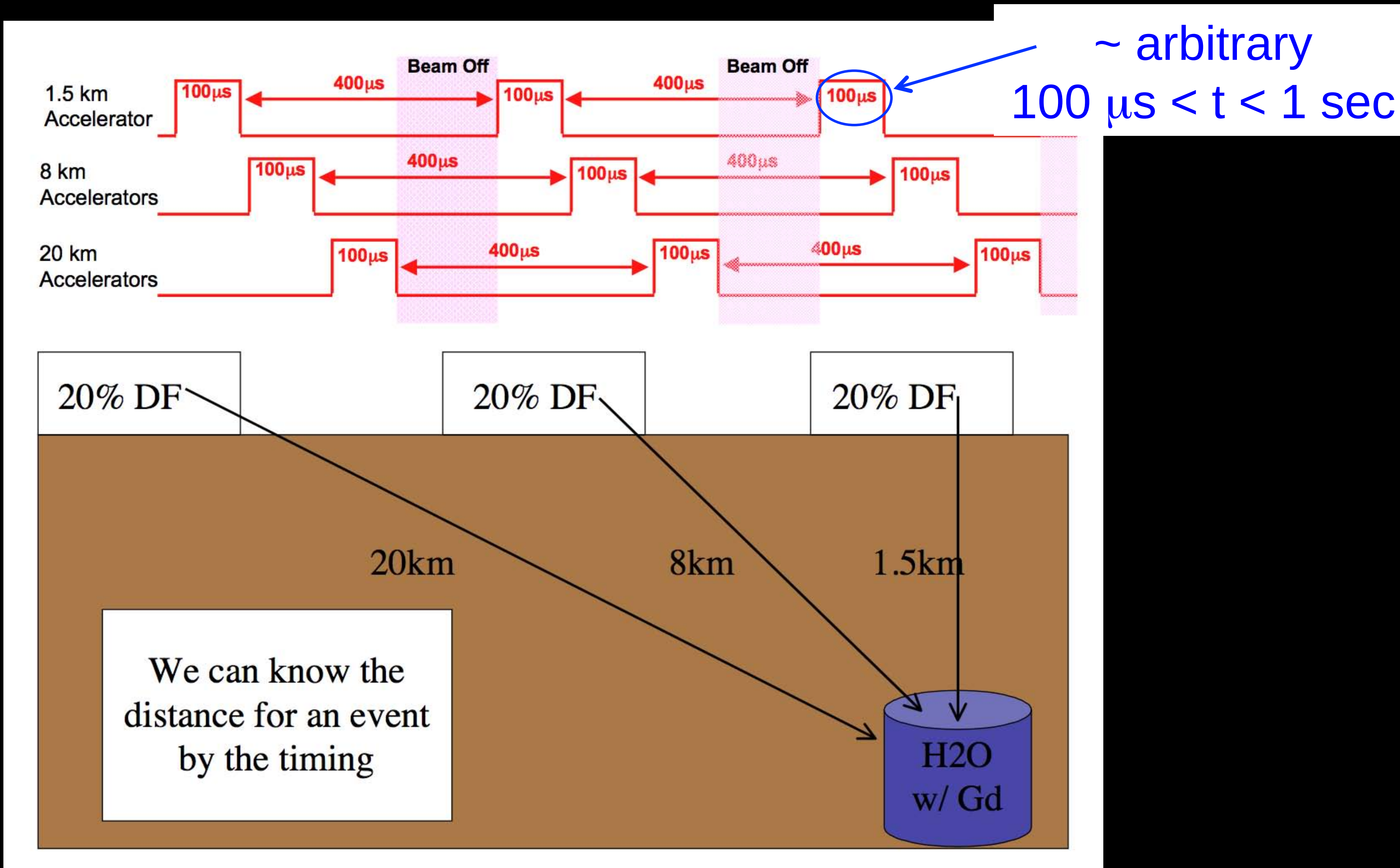
Power (beam current)



Time Structure



Time Structure



Candidates

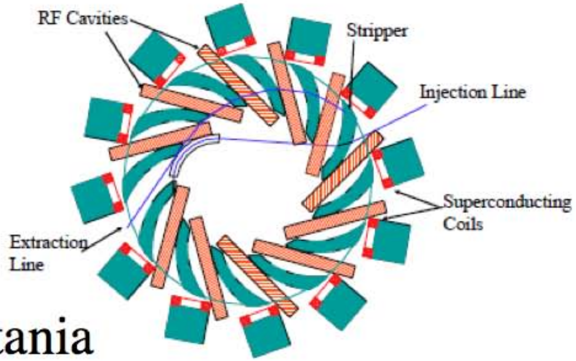
Approaches using cyclotrons:

The compact cyclotron with self-extraction

under development for DTRA at MIT

An H2+ accelerator

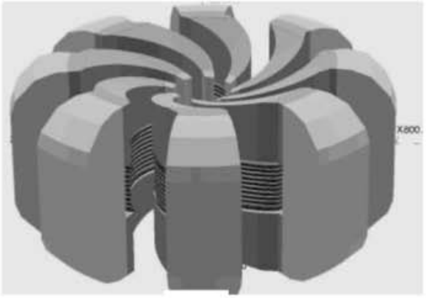
for ADS applications



Under dev. by INFN, Catania

The stacked cyclotron:

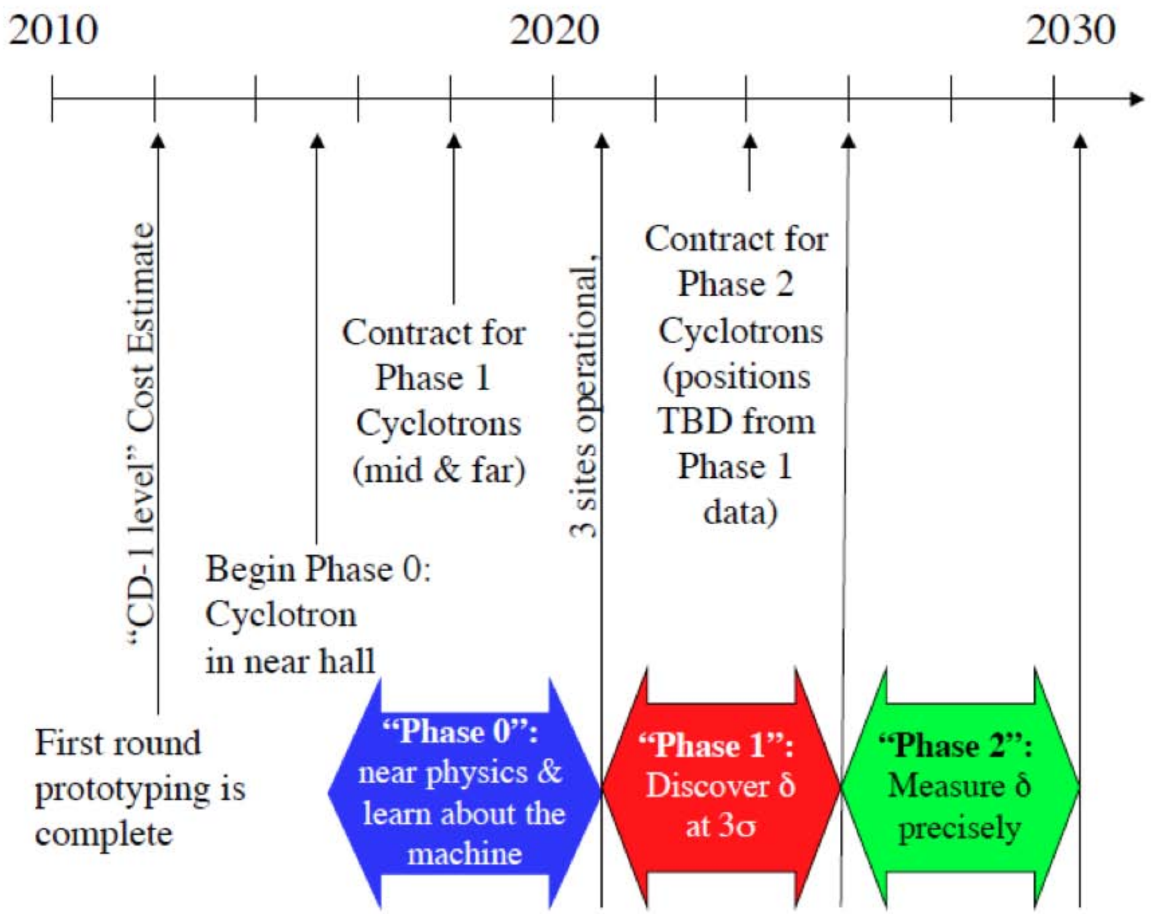
7 cyclotrons in one flux return



Under dev. for ADS at TAMU

Project Timing

Our schedule is tied to when the large H_2O detector exists



Summary Comments

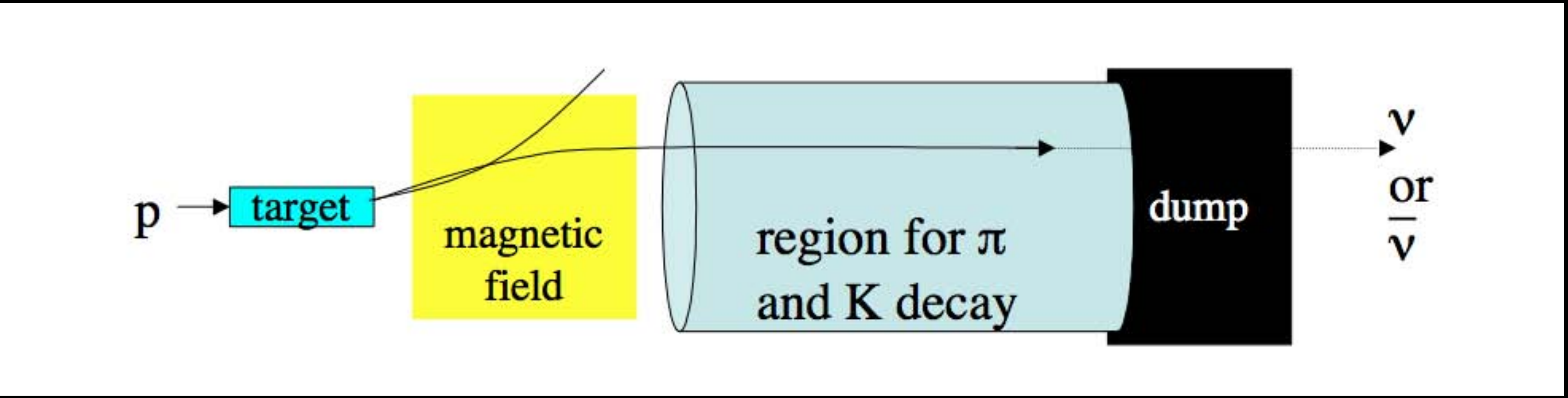
- High-Power High-Energy machines have MANY applications
  - Neutrinos now add to the list…

- Would greatly welcome greater contacts with the Cyclotron community!


Thank You!

LBNE Neutrino Beam

$$p + \{tgt\} \longrightarrow \begin{cases} \pi^+ \longrightarrow \mu^+ + \nu_\mu \\ \pi^- \longrightarrow \mu^- + \overline{\nu}_\mu \end{cases}$$



MIT / Sanford Laboratory

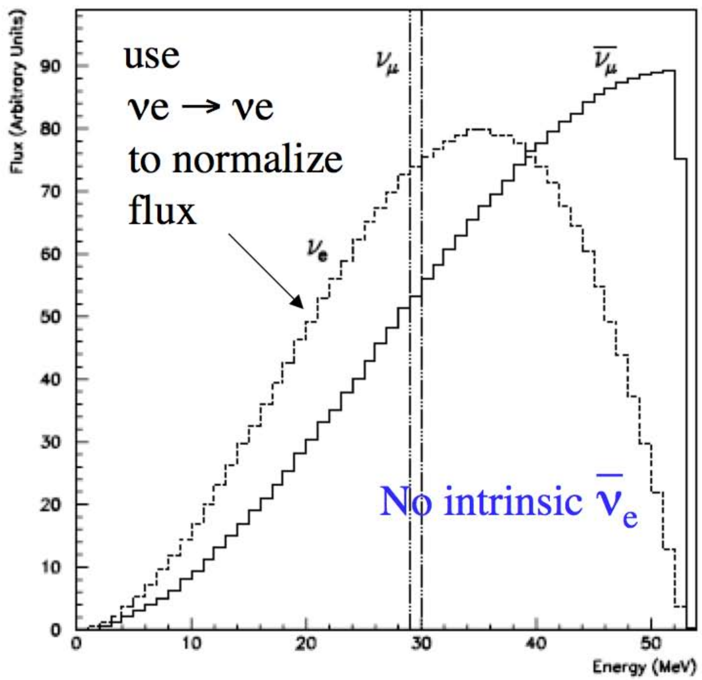
DAEδALUS Neutrinos

A π^+ decay at rest beam:

$$p+C \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e,$$

Shape driven by nature!

Only the normalization varies from beam to beam

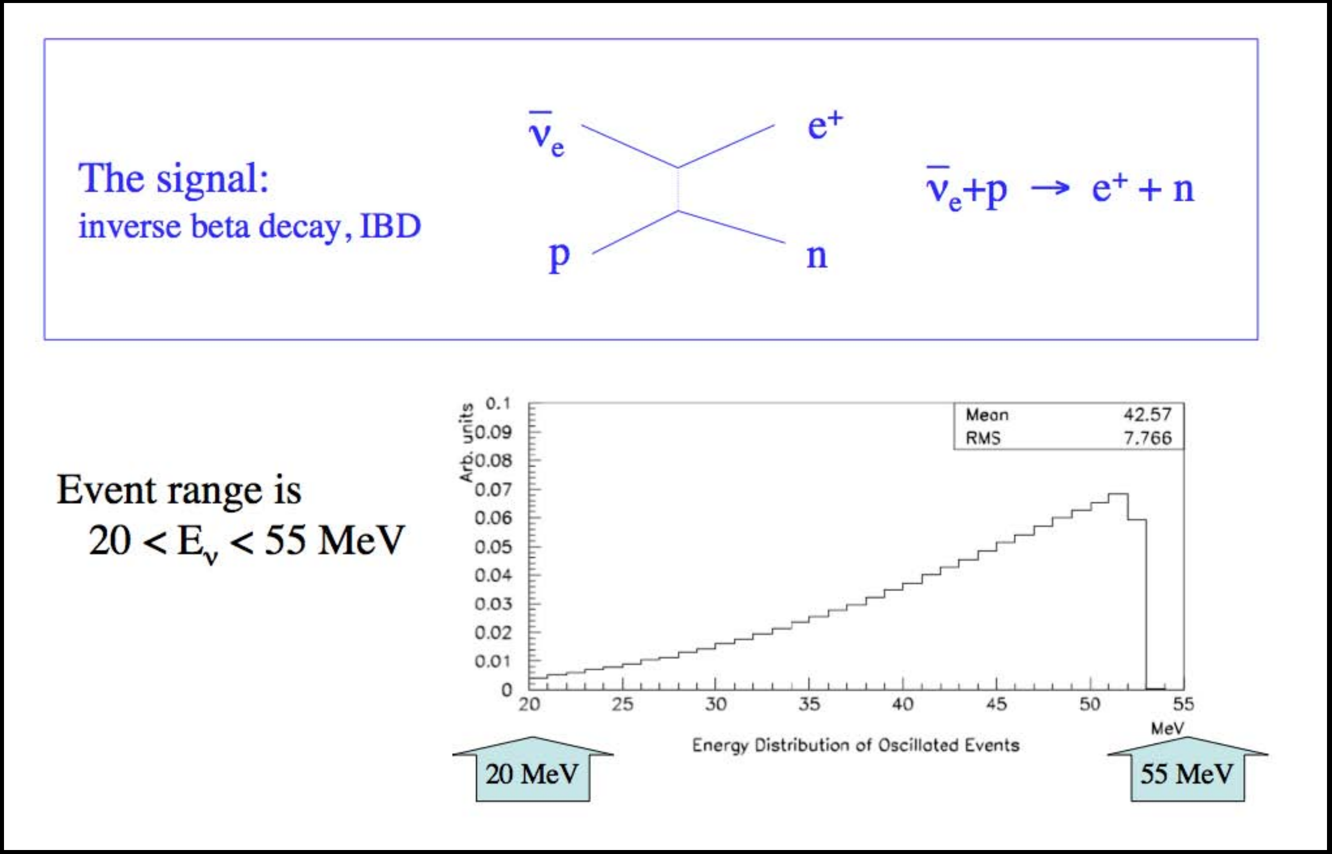


Perfect for a $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search

MIT / Sanford Laboratory

Detection Mechanism

- Inverse Beta Decay (IBD)



Detection…

- IBD for antineutrino enhanced by capture of free neutron
  - Delayed coincidence
  - Would really like Gd doping…
- LBNE also relies on IBD, mainly in Oxygen

  $p \rightarrow n$ for $\bar{\nu}_e$

  $n \rightarrow p$ for ν_e

  - High energy, difficult to tell ν_e from $\bar{\nu}_e$

Limits…

DAEδALUS:

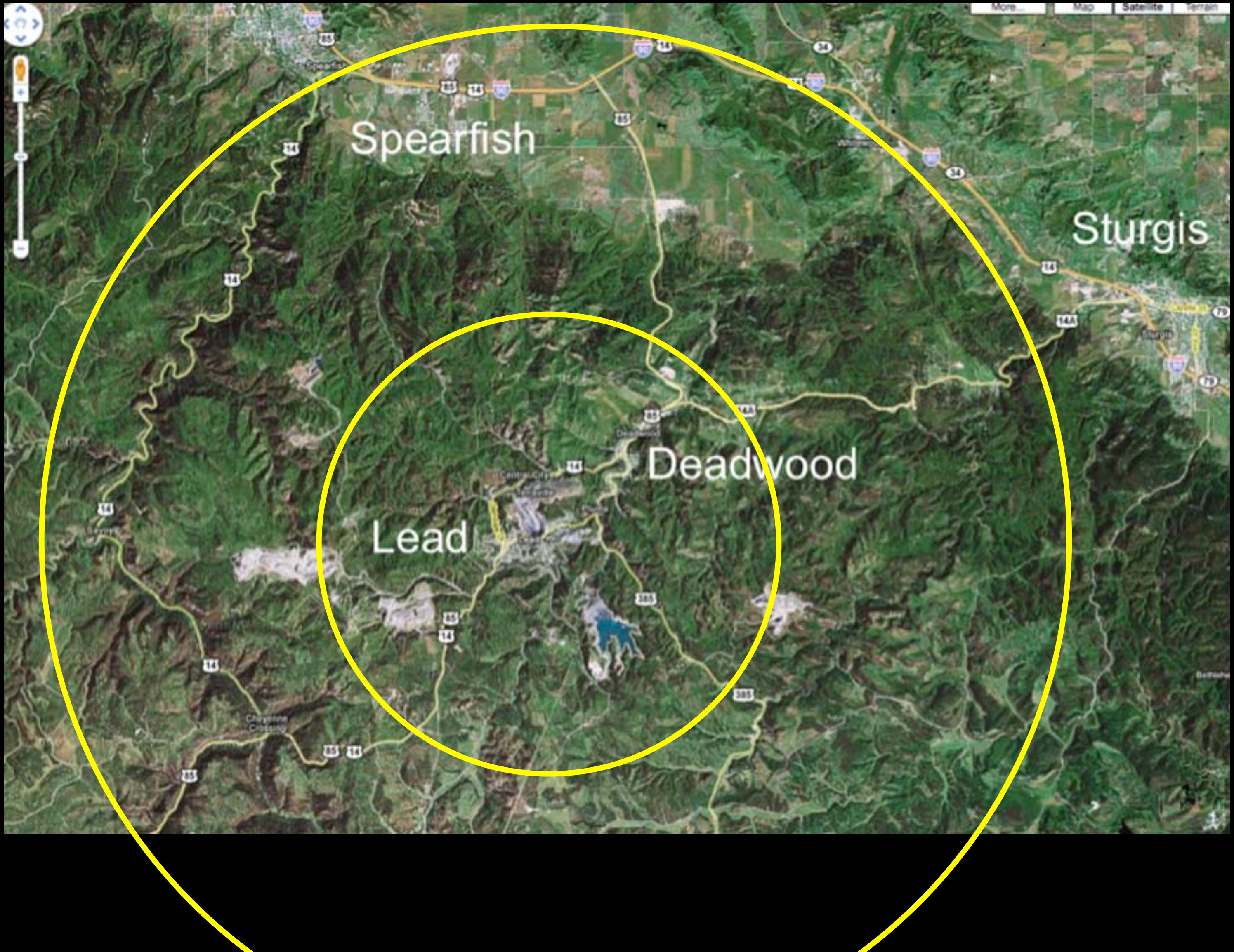
- Excellent sensitivity for $\bar{\nu}_e$ (only)
- Poor sensitivity to low θ_{13}
- No comparison of $\bar{\nu}_e$ / ν_e rates

LBNE:

- Intrinsically can't tell ν from $\bar{\nu}$
  - Rely on beam selection at source (Magnet polarity)
- High background in $\bar{\nu}$ channel

(~25% contamination of ν)

Black Hills Geography



Comparisons*

Accelerator	Energy	Power (Beam loss control)	Technical Risk	Cost
Compact	Moderate	Difficult	Difficult	Low
H_2^+	Moderate	Good(1-2 MW)	Moderate	Moderate
Stacked	Moderate	Moderate	Moderate	Moderate

*My subjective assessment

Comparisons*

Accelerator	Energy	Power (Beam loss control)	Technical Risk	Cost
Compact	Moderate	Difficult	Difficult	Low
H_2^+	Moderate	Good(1-2 MW)	Moderate	Moderate
Stacked	Moderate	Moderate	Moderate	Moderate
SC Linac*	Easy	Moderate (lo β)	Low-Moderate	Very High

* Too big to fit on Near site

*My subjective assessment