QuickTime™ and a decompressor are needed to see this picture.

DAEδALUS

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Physics Seminar

University of Ljubljana

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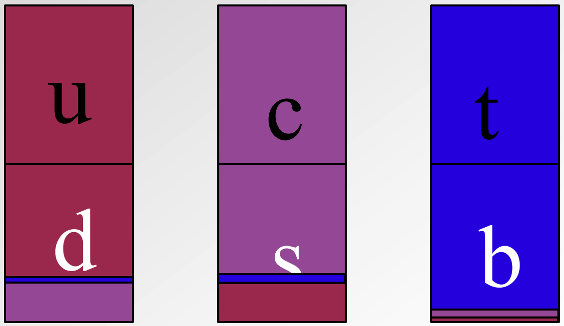
What is DAEδALUS ?
Search for CP violation in the neutrino sector

Decay
At rest
Experiment
for δ_{cp} studies
At the
Laboratory for
Underground
Science

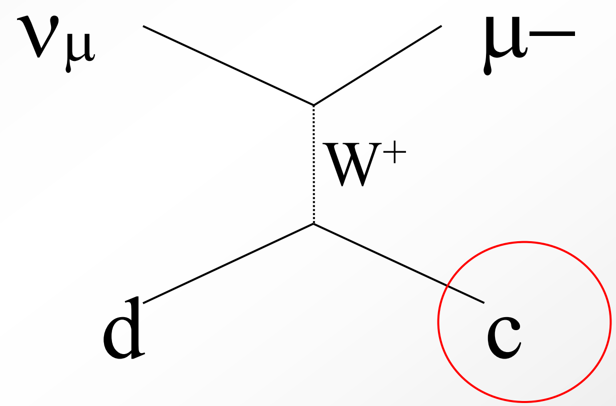
Use *decay-at-rest neutrino beams*,
& the planned *300 kton H_2O detector* (Gd doped) at DUSEL

Source: J. Conrad

The quark sector has “mixing”
quark mass eigenstates ≠ quark weak eigenstates



Small effect, but clearly seen in weak interactions...



QuickTime™ and a
decompressor
are needed to see this picture.

... and
kaon decays,
D meson decays,
etc.

Mixing shows up in processes with 2 diagrams to the same final state ==> interference term in the decay probability

Source: J. Conrad

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Does the lepton sector show similar phenomena?

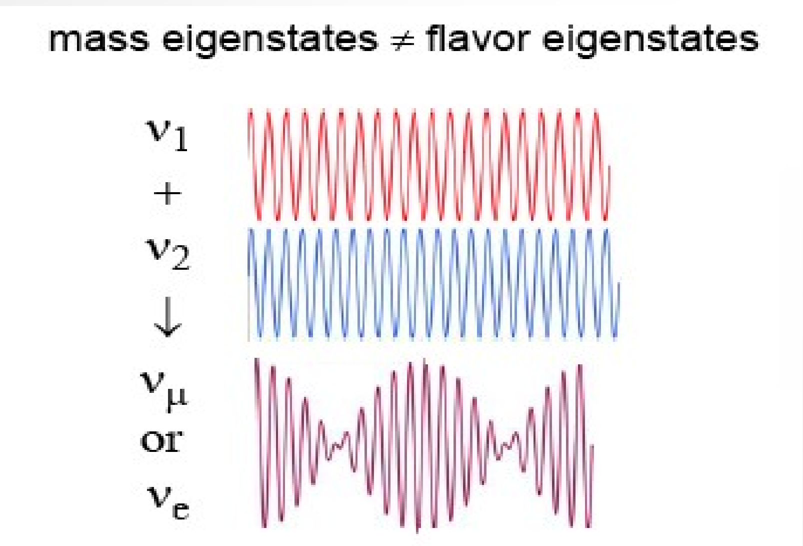
Observation of one type of neutrino changing into another type would imply:

1. Neutrinos have mass with a mass difference, Δm

2. Lepton number (electron, muon, tau) is not conserved
   - (⟨ e□ ⟩, ⟨ □ ⟩, ⟨ e□ ⟩)

3. The *Weak Eigenstate* is a mixture of the *Mass Eigenstates* with mixing angle θ

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



Experimental parameters:

Propagation distance, L

Neutrino energy, E

Fundamental parameters θ & Δm^2

$$P_e = 1 - \sin^2 2\theta \sin^2(\Delta m^2 L/E).$$

Source: M. Shaevitz

Neutrino oscillations due to mixing was observed in the Kamland experiment

QuickTime™ and a
decompressor
are needed to see this picture.

$$P_e = 1 - \sin^2 2\theta \, \sin^2(\Delta m^2 L/E).$$

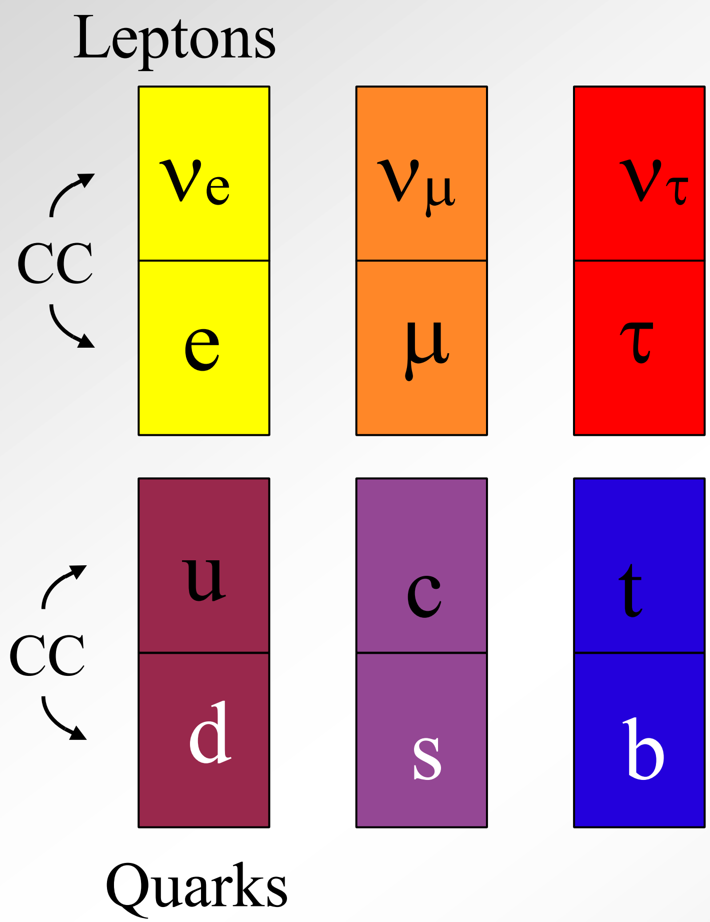
Ratio of background & geo-neutrino subtracted anti-neutrino spectrum to expectation for no-oscillation as a function of L/E.

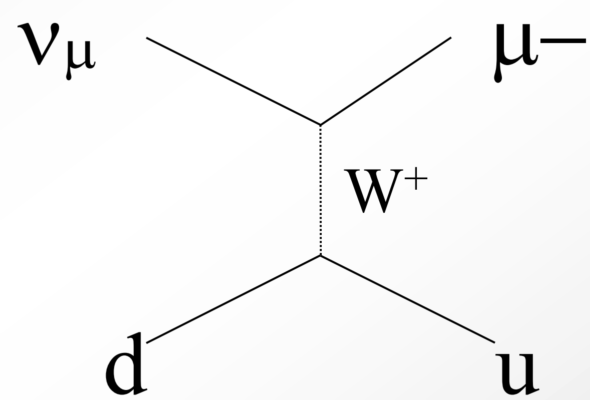
L is the effective baseline taken as a flux-weighted average (L=180km).

Histogram & curve account for distances to 55 individual reactors, the time-dependent flux variations & efficiencies.

Source: Kamland website

In the Standard Model, neutrinos are part of three weak lepton doublets





We identify the neutrino *flavor* via the Charge Current interaction

Source: J. Conrad

The three families of leptons: e, μ, and τ, □□□ 3x3 neutrino mixing matrix

$$\begin{pmatrix} Flavor \\ Eigenstate \end{pmatrix} = (Mixing \quad Matrix) \begin{pmatrix} Mass \\ Eigenstate \end{pmatrix}$$

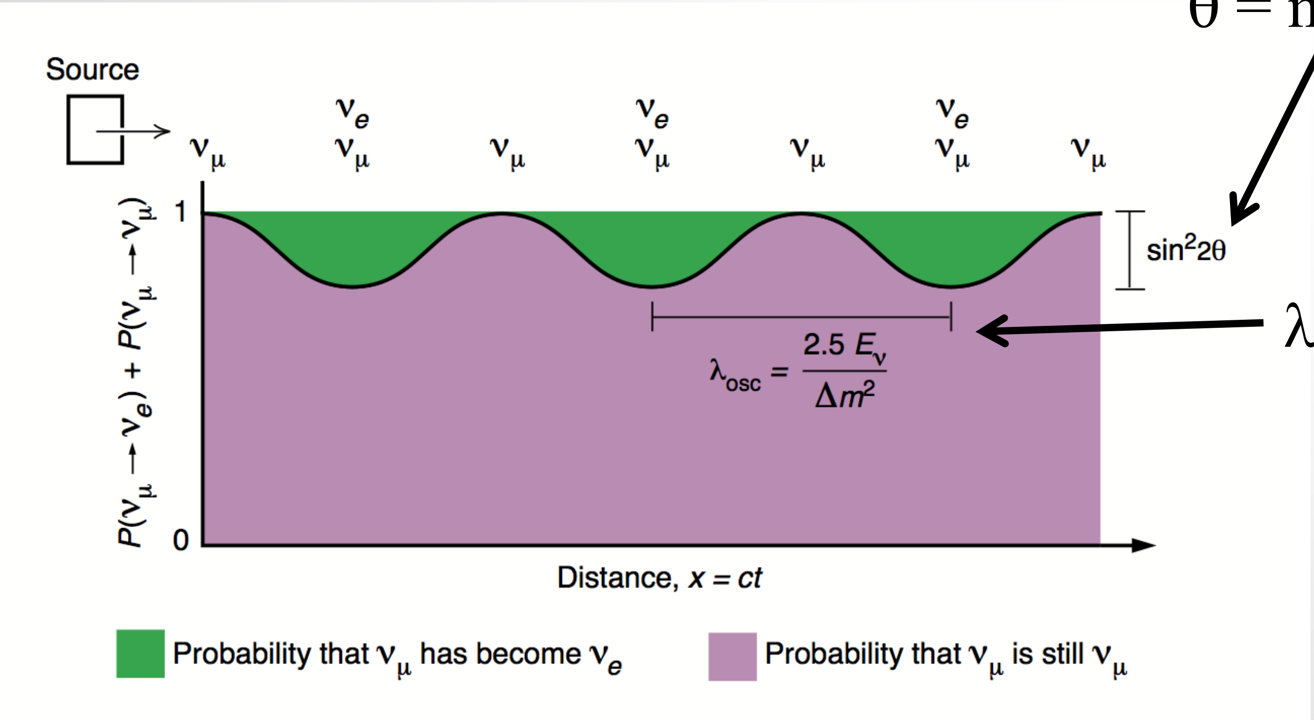
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} e^{i\delta} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\Delta m_{12}^2 = \Delta m_{Solar}^2 = m_1^2 - m_2^2 \quad , \quad \Delta m_{31}^2 \approx \Delta m_{32}^2 = \Delta m_{Atmospheric}^2 = m_3^2 - m_1^2$$

Atmospheric neutrinos result from the interaction of cosmic rays with nuclei in the Earth's atmosphere

Solar neutrinos are ν_e originating from nuclear fusion in the Sun

Neutrino oscillations



θ = mixing angle

λ = oscillation frequency

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

The quark mixing matrix must be unitary, but it doesn't have to be "simple"

Any 3 × 3 unitary matrix has

3 associated free parameters (Euler angles)

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

& can have a complex phase

QuickTime™ and a
decompressor
are needed to see this picture.

This "CP violating phase" $\boldsymbol{\delta}$ can lead to a different decay rate for matter vs. antimatter

For example neutral kaon decays (factor of ~1000 in lifetime)

Source: J. Conrad

We can break the mixing matrix apart

Super K, K2K, MINOS, soon T2K…

Daya Bay
Double Chooz
will measure
"θ_{13}"

Super K, SNO, KamLAND

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

3-mixing angles

Solar: $\theta_{12} \sim 33°$

"Little mixing angle, θ_{13}"
$\sin^2 2\theta_{13} < 0.2$ at 90% CL
(or $\theta_{13} < 13°$) and $\delta = ??$

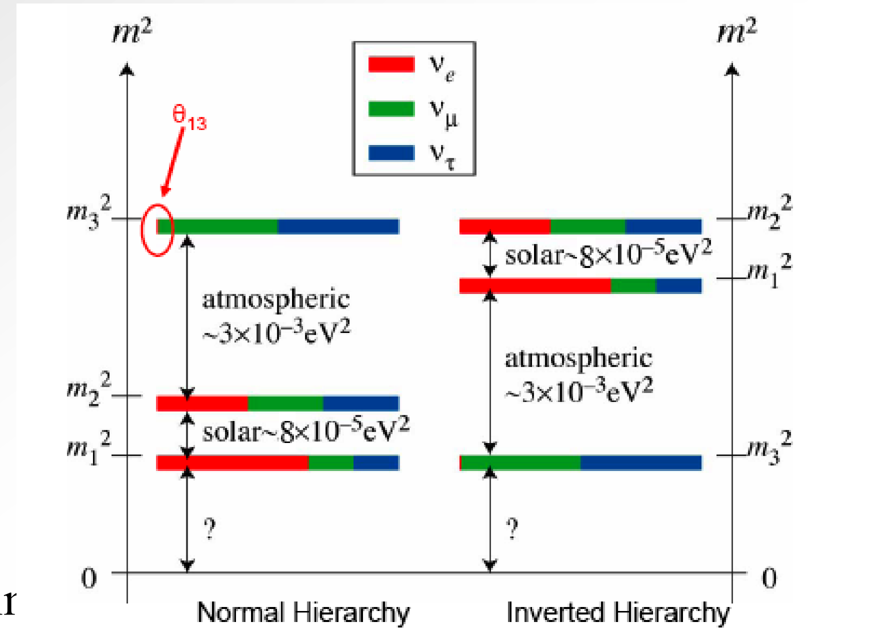
Atmospheric: $\theta_{23} \sim 45°$

Source: J. Conrad

Current knowledge of mixings & mass differences

solar atmospheric

Current Measurements: $\Delta m^2_{21} = 8 \times 10^{-5}\ \text{eV}^2$, $\Delta m^2_{31} \approx \Delta m^2_{32} = 2.5 \times 10^{-3}\ \text{eV}^2$



- Current experi
  - Measure θ_{13} mixing angle
  - Determine mass hierarchy
  - Search for CP violation & measure δ_{CP}

Source: J. Conrad

Neutrino oscillations can reveal the CP violation phase

- Muon neutrinos change to electron neutrinos as they propagate through space
- CP Violation ⇒
- Two next generation experiments $\boxed{\text{Prob}(\nu_\mu \rightarrow \nu_e) \neq \text{Prob}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$
  - Long baseline neutrino/antineutrino experiment (LBNE) – Conventional Approach
    - Send beam from Fermilab to DUSEL (South Dakota)
    - LBNE has *one beam* with a near (1 km) and a far detector (1300 km)
    - Far detector is a very large (300 kton water Cerenkov detector with phototubes)
  - Daedalus – A New Powerful Approach
    - One detector and multiple antineutrino sources at different distances (1.5 km, 8 km, 20 km)
    - Use same large water detector (300 kton water with phototubes)

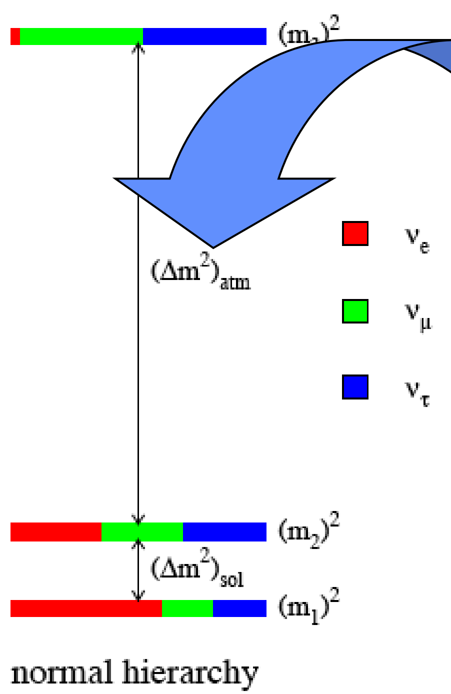
Source: M. Shaevitz

The conventional approach,
if you have the Tevatron

The Probability for Oscillations...

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

P is maximized when $\Delta m^2(L/E) \sim 1$



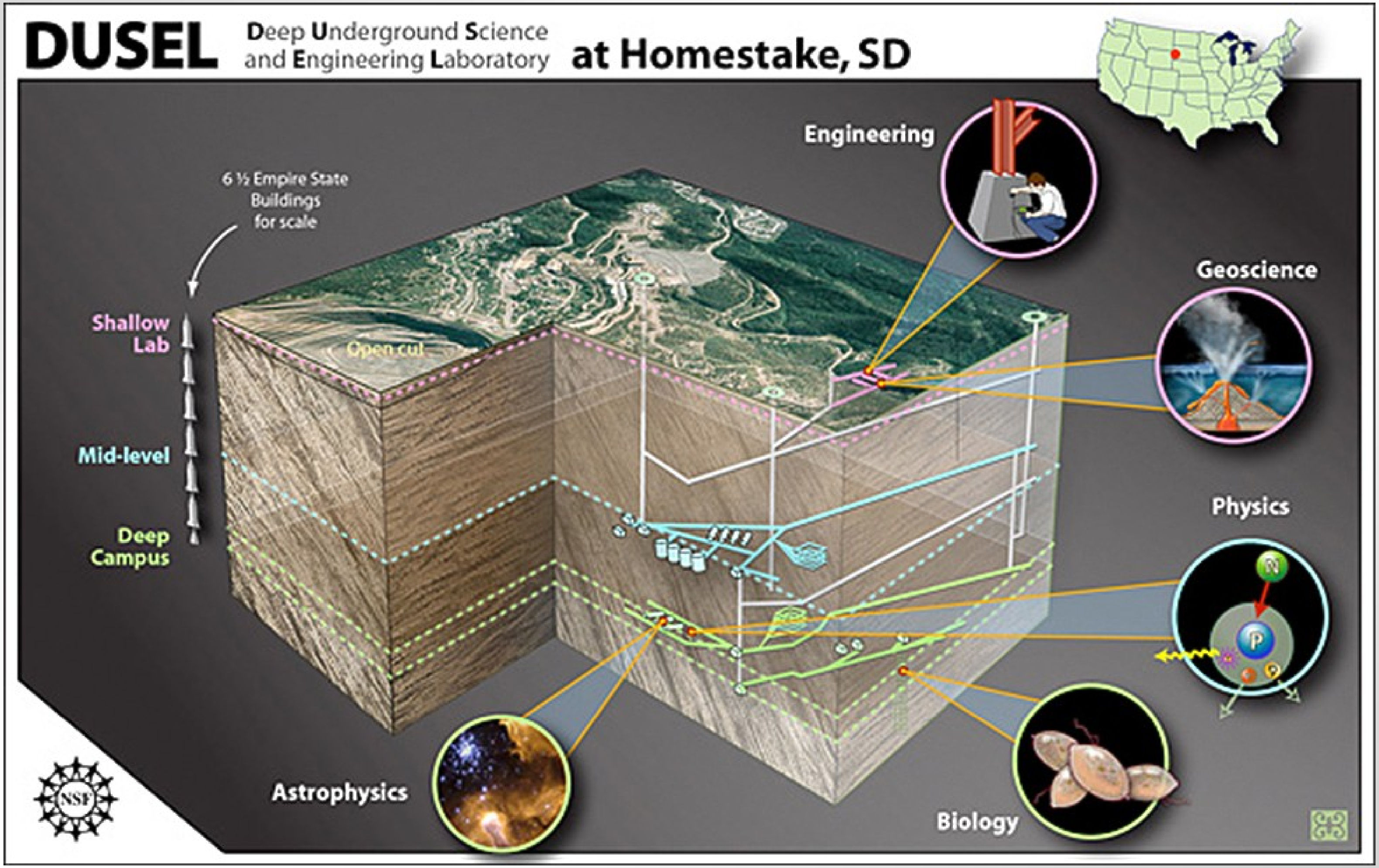
The atmospheric $\Delta m^2 \sim 0.001\ eV^2$

E_{ave} from a convention beam is ~ 1 GeV

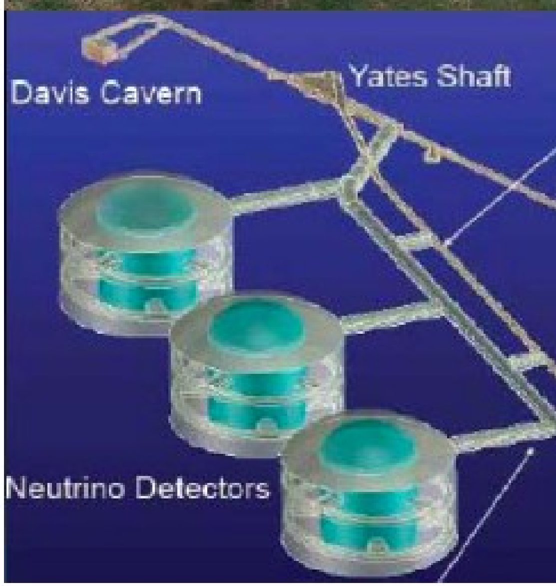
So $L \approx 1000$ km !!!

Source: J. Conrad

Both approaches use DUSEL



Conventional approach: LBNE @ DUSEL



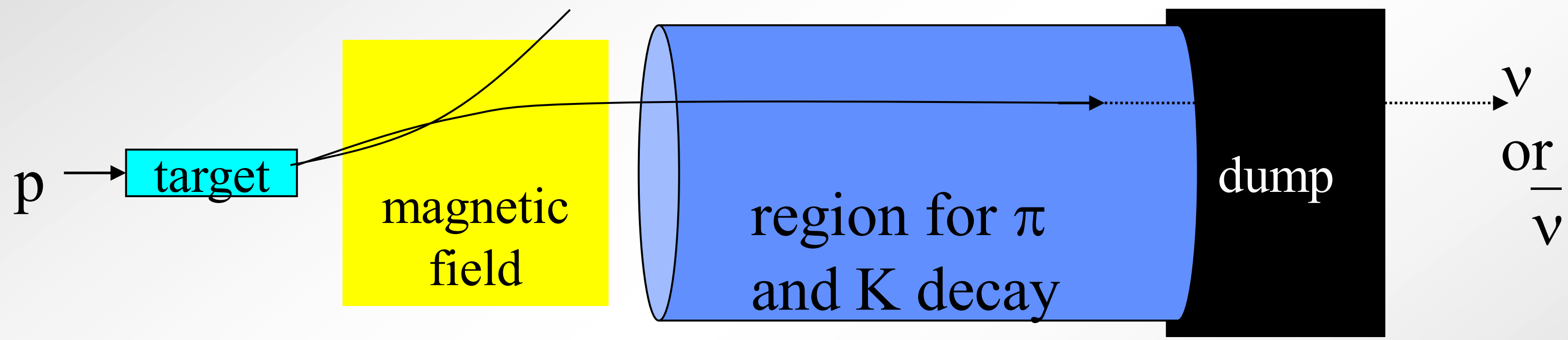
Experimental comments:

- Large neutrino flux covering 1st and 2nd oscillation max points (0.8 and 2.4 GeV)
- Fairly pure ν_μ flux with small ν_e contamination
- Minimize flux with energy above 5 GeV that causes background
- But substantial neutral current π^0 events that mimic ν_e events

Source: M. Shaevitz

The LBNE search for CP violation shoots neutrinos through 1300 km of *matter*

The easiest way to make a high-flux beam which switches from ν to $\bar{\nu}$:



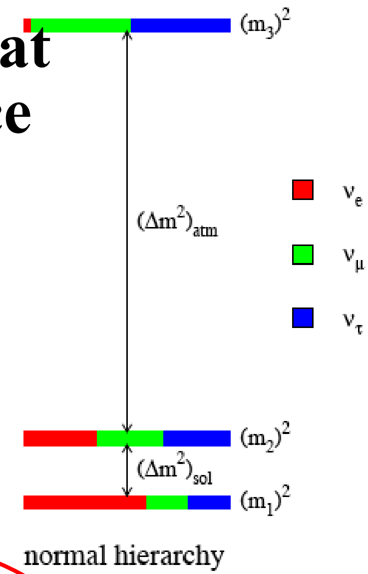
"Conventional neutrino beam" -- 100's of MeV to a few GeV

The ground is made of *matter* (electrons) not *antimatter* (positrons) & Forward scattering affects neutrinos differently than antineutrinos

All long-baseline experiments must introduce a model for matter effects, before they can study CP-violation

Source: J. Conrad

Oscillation of muon-flavor to electron-flavor at $(\Delta m^2)_{atmos}$ may show CP-violation dependence



In vacuum…

QuickTime™ and a decompressor are needed to see this picture.

We want to see if δ is nonzero

terms depending on mixing angles

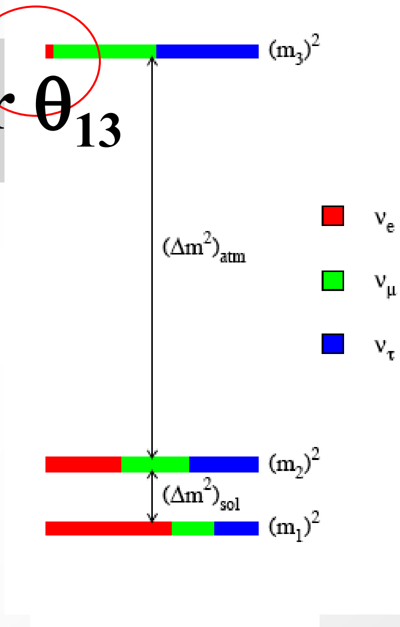
terms depending on mass splittings

QuickTime™ and a decompressor are needed to see this picture.

The δ-dependent terms arise from
interference between the $\Delta m_{13}{}^2$ and $\Delta m_{12}{}^2$ oscillations

Source: J. Conrad

Parameters are well known except for θ_{13}



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decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

N/A

N/A

Therefore quote sensitivity
as allowed regions in both θ_{13} and δ

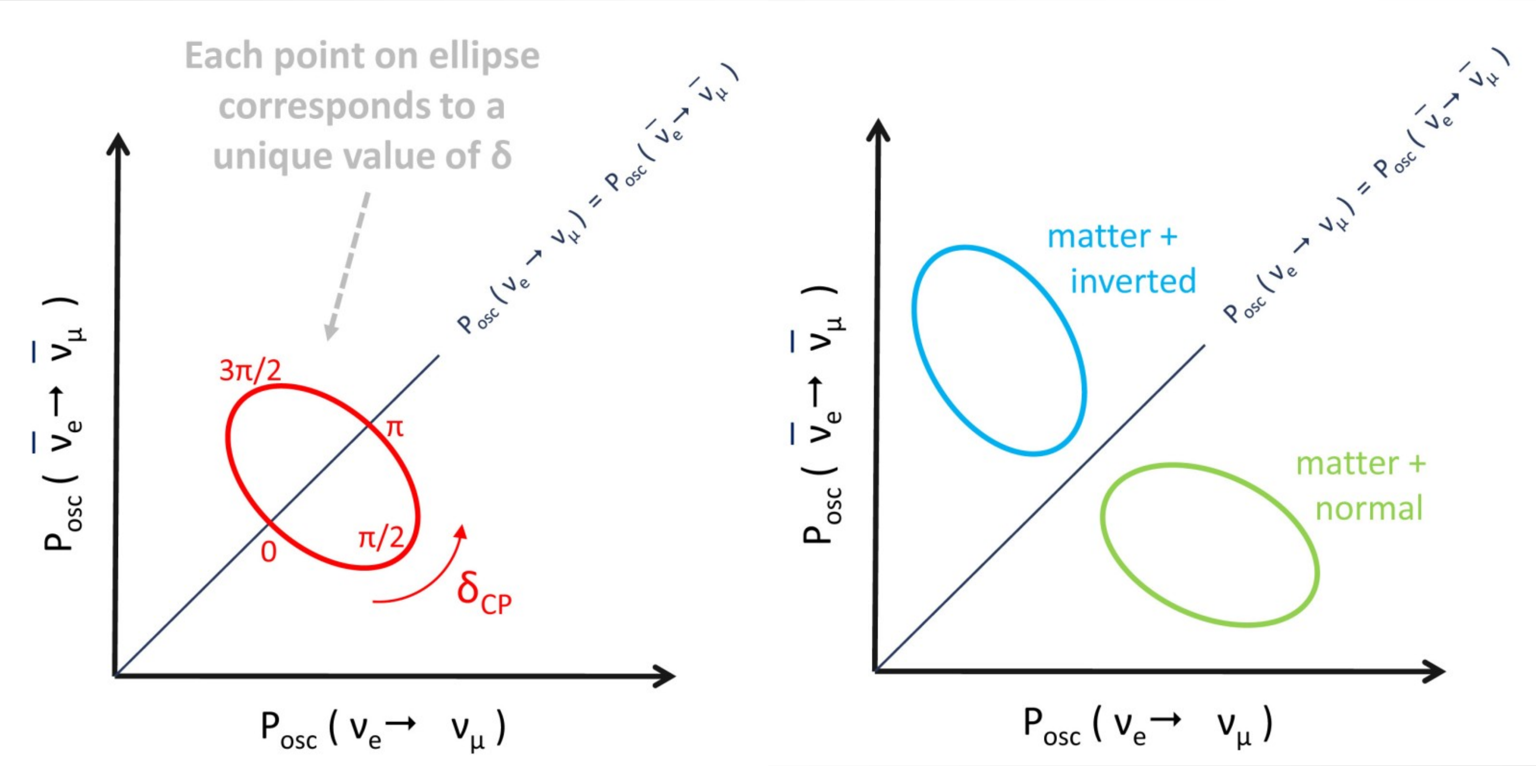
Source: J. Conrad

Terms depending on δ change the oscillation wave L dependence.

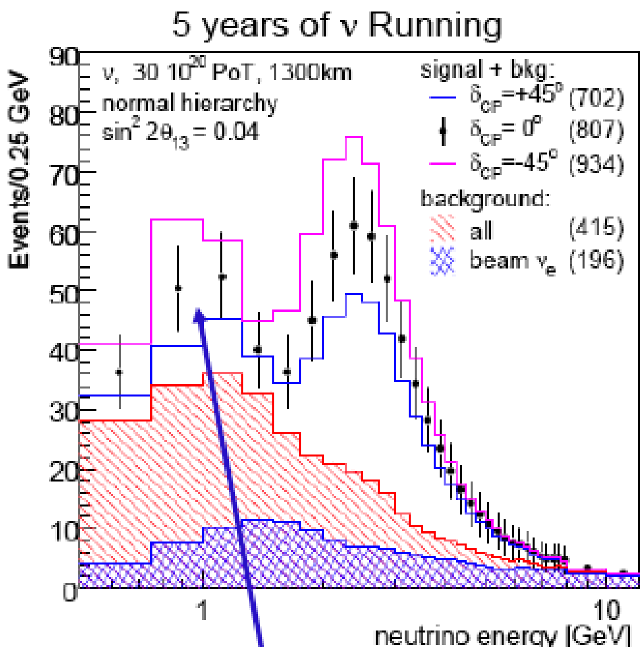
QuickTime™ and a
decompressor
are needed to see this picture.

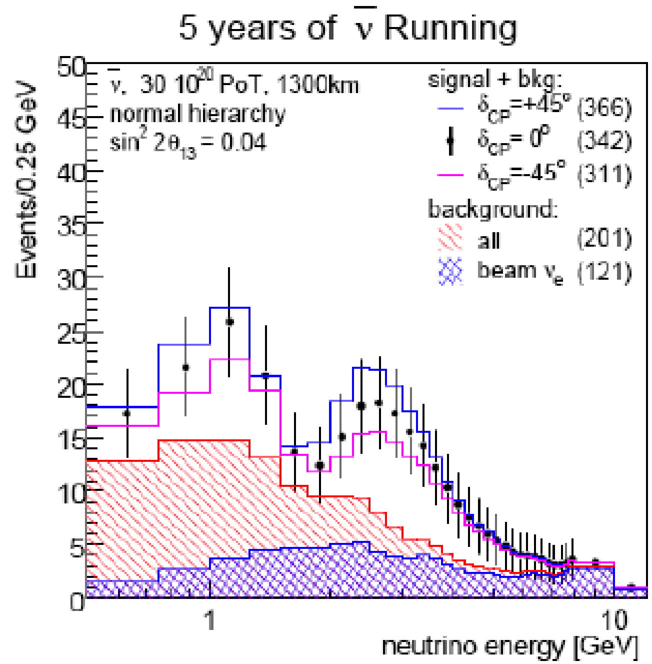
Measurement at 3 points constrains the CP violating contribution

The usual technique and matter effects



Expected LBNE Events in 300 kton Water Detector





Difficult to collect large antineutrino statistics

Second maximum can help the δ_{CP} measurement since Δm^2_{12} terms bigger but large backgrounds and low statistics

Normal Hierarchy

Source: J. Conrad

Expectation for inverted hierarchy

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decompressor
are needed to see this picture.

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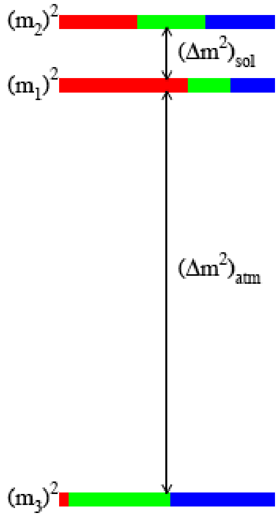
decompressor
are needed to see this picture.



inverted hierarchy

Source: J. Conrad

What do we know about δ vs θ_{13} ?

The actual values could be anywhere in this region!

QuickTime™ and a decompressor are needed to see this picture.

This region ruled out by Chooz and Palo Verde

Source: J. Conrad

If we observe a signal, what would this plot look like?

"jelly bean"

Imagine the real values are:

$\delta = 80°$

$\sin^2 2\theta_{13} = 0.05$

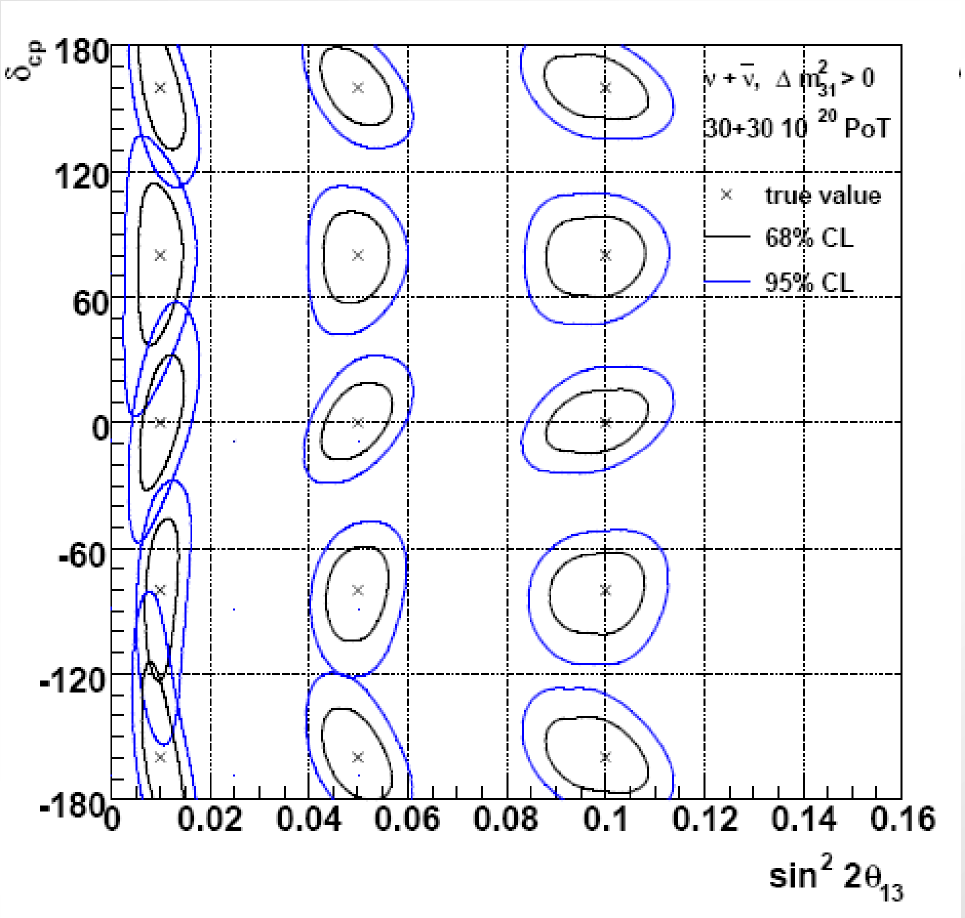
QuickTime™ and a decompressor are needed to see this picture.

1 sigma error

2 sigma error

Source: J. Conrad

“Jelly bean plots” identify hypothetical values of δ & θ_{13} & show the expected contours at 1σ and 2σ



If we know the mass hierarchy, this is how well LBNE can do in 10 years of running *(e.g. without Project X)*

Source: J. Conrad

New DAEδALUS Multi-Source Approach

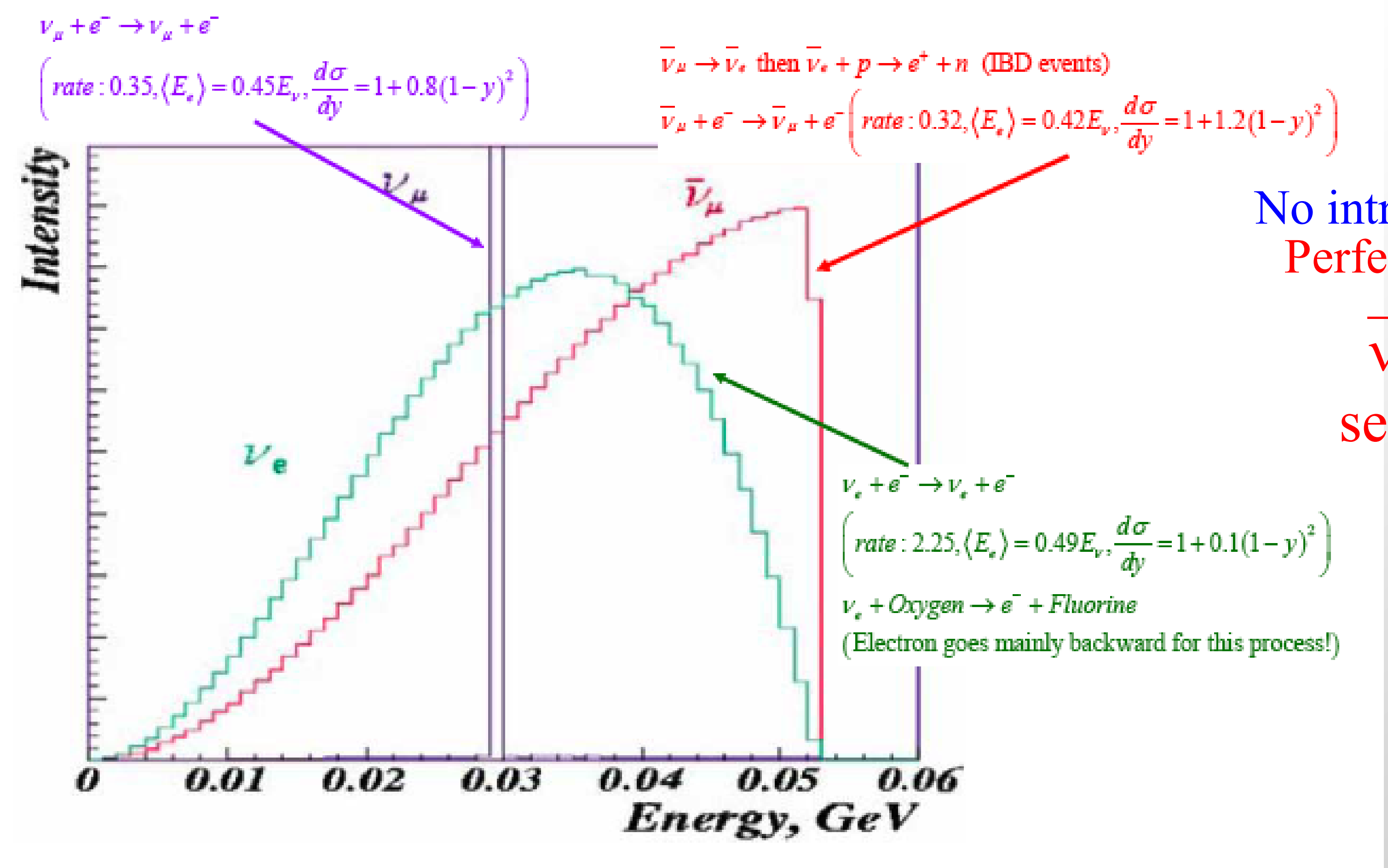
"Eliminate" matter effects

Use a narrow spectrum neutrino beam from decays at rest

For a π^+ decay at rest beam, shape is driven by nature - only the normalization varies

$p + C \rightarrow$

QuickTime™ and a decompressor are needed to see this picture.

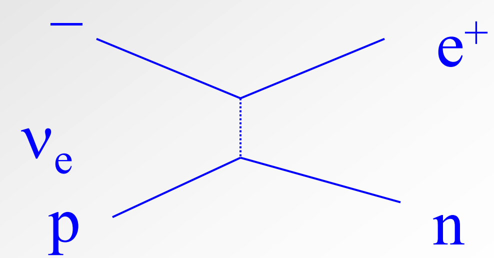


No intrinsic $\bar{\nu}_e$

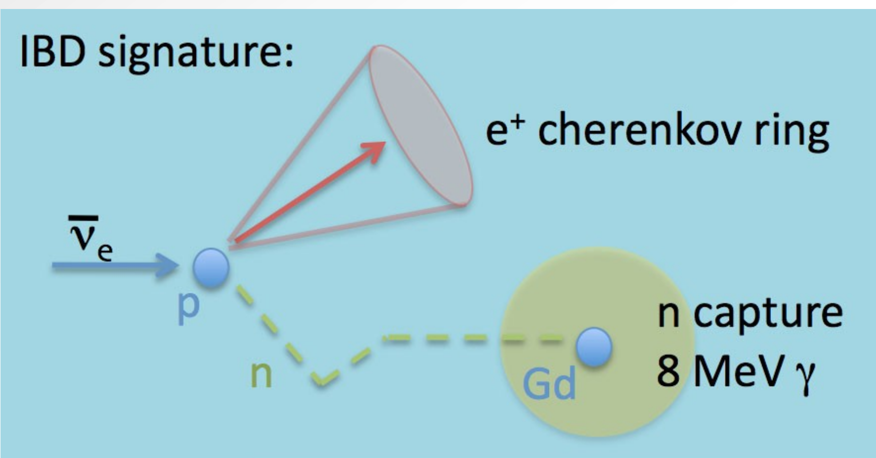
Perfect for a $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search

Source: M. Shaevitz

The signal: inverse beta decay in H_2O detector



$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Event range is

$20 < E_\nu < 55$ MeV

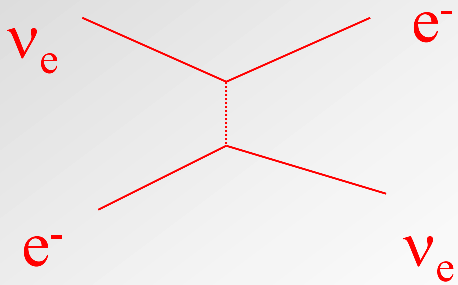
QuickTime™ and a decompressor are needed to see this picture.

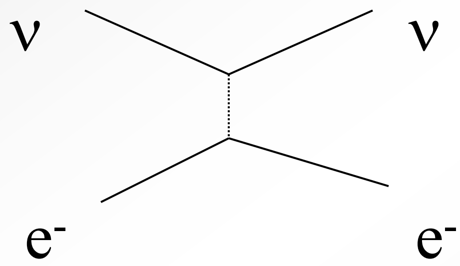
20 MeV

55 MeV

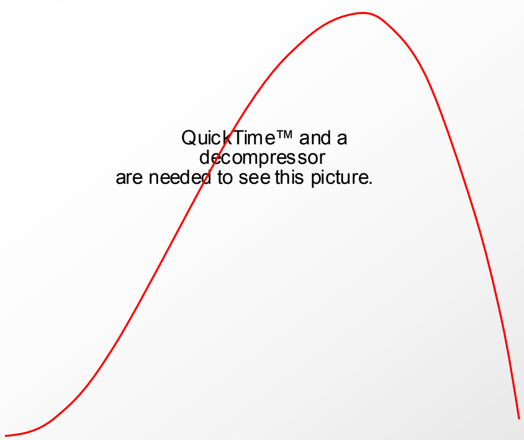
Source: J. Conrad

Neutrino-electron scattering is critical





Provides the normalization of the flux since the cross-section is known to 1%



Mostly from ν_es

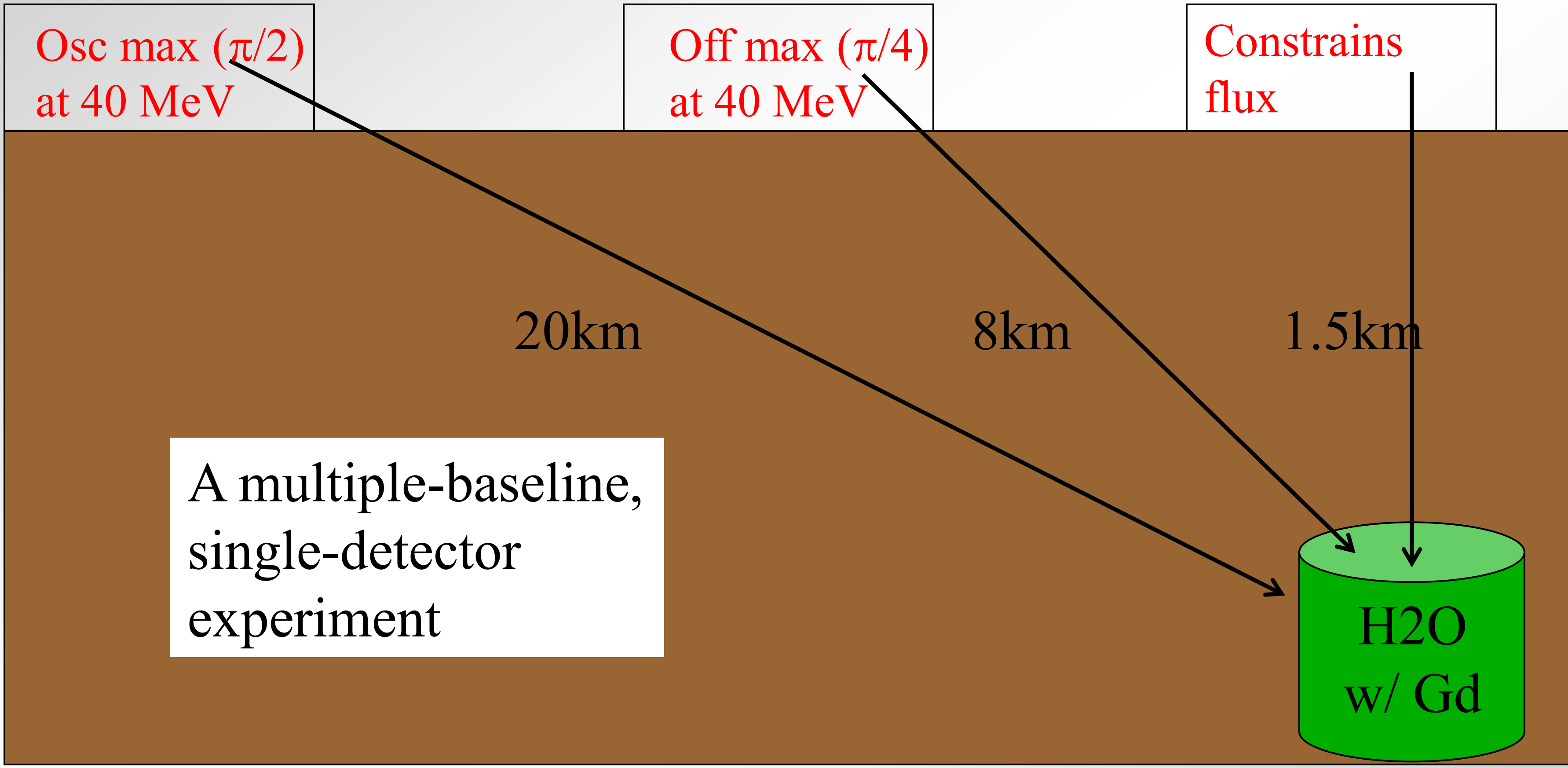
about 20% from muon flavor

Source: J. Conrad

Measurement strategy

- Determine the $\bar{\nu}_\mu$ flux from observed neutrino-electron elastic scatters ($\nu_e + e^- \rightarrow \nu_e + e^-$)
  - Every decay-at-rest π^+ gives one ν_μ, one ν_e, and one $\bar{\nu}_\mu$ with an isotropic distribution thus measuring the ν_e constrains the other fluxes
    - Use events with visible energy > 10 MeV
  - This assumes that other contributions such as $\pi^\pm$ decay-in-flight are negligible (calculations put them at the 10^{-4} level)
  - Outgoing electron very forward peaked so easy to separate
  - Well understood process with small cross section and experimental uncertainties (largest uncertainty is 2% energy scale error.)
- Using this flux, determine the predicted number of signal inverse-beta decay events ($\bar{\nu}_e + p \rightarrow e^+ + n$) (plus background)
  - Well known cross section
  - Good experimental handle for isolating this process
    - See energy signal from positron (use visible energy > 20 MeV cut to reduce backgrounds)
    - See delayed coincidence with 8 MeV energy signal from capture of the neutron on Gd
- Compare observed and predicted events versus the physics parameters: θ_{13} , δ_{CP} etc.

We need 3 distances & we cannot have three 300-kton detectors



We take advantage of the fact that Nature assures decay-at-rest beams will be identical in flavor & energy

Source: J. Conrad

But the neutrino cross section is small! How many neutrinos do we need?

- For phase 1 (five years) we need
  - 4E+22 neutrinos per year from the near site
  - 8E+22 neutrinos per year from the mid-site,
  - 1.2E+23 neutrinos per year from the far site
  - with each site having a 20% duty factor
- Recall the production reaction

$$p + C \rightarrow \pi^+ + X$$

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$

$$\mu^+ \rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

- At 1 GeV, roughly 10 % of protons produce a π^+

==> ***This means a lot of protons!***

What proton energy? At "Δ plateau" one trades E_p for current to get same rate of ν/MW

<600 MeV
too little π^+
production

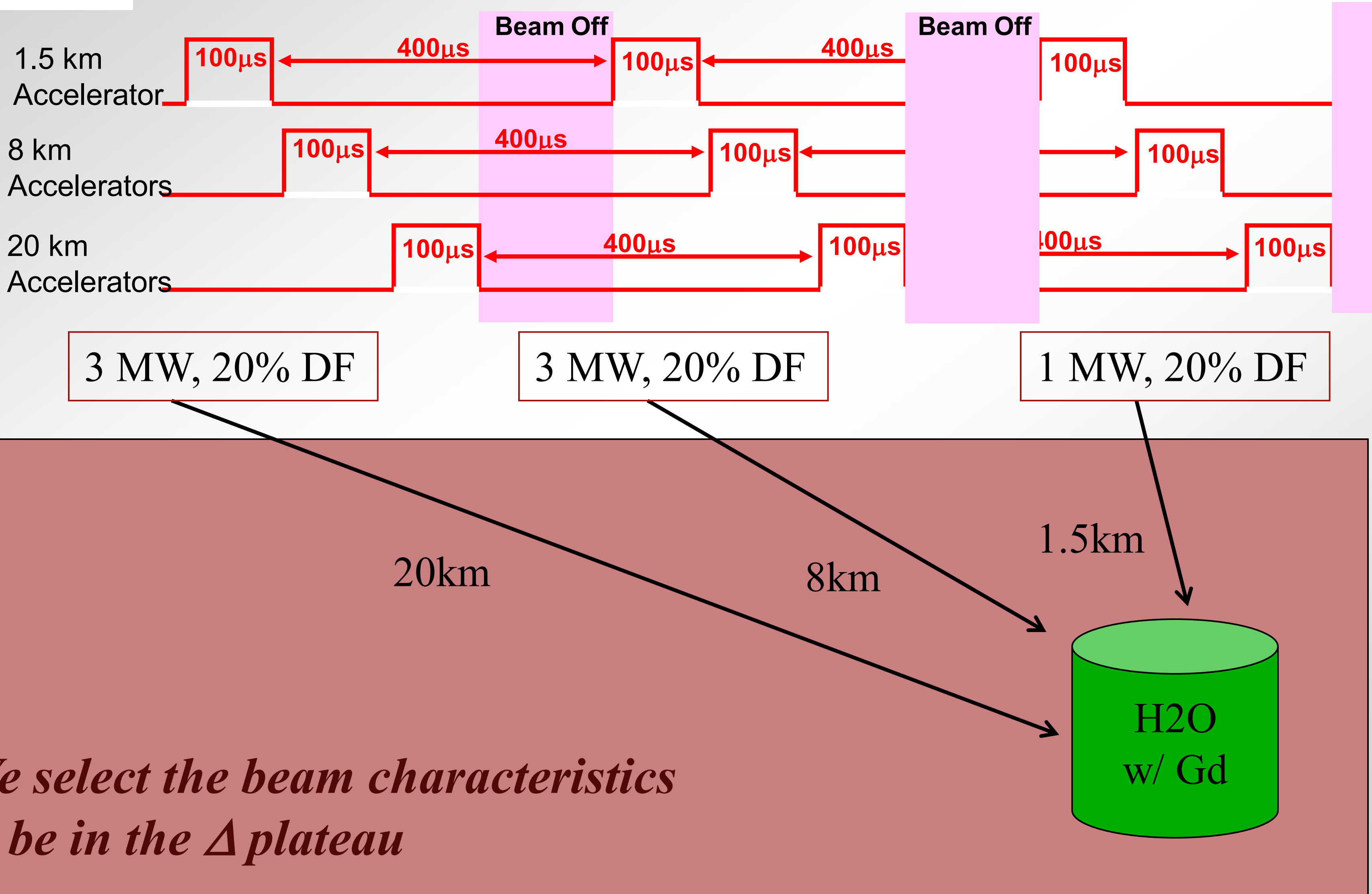
"Δ Plateau"

~ 1240 events in 5 years

>1500 MeV, energy goes into producing other particles besides π^+ at a significant level

These are NOT small beam powers per accelerator

Determine distance for an event by timing



We select the beam characteristics to be in the Δ plateau

Expected results from DAEδALUS

QuickTime™ and a decompressor are needed to see this picture.

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The DAEδALUS accelerator complex

- Performance essentials
  - Seven ~ 1 MW beam proton beams
  - ~1 MW of protons with energy 600 MeV $<E_p<$1500 MeV
  - Efficient acceleration
  - High reliability (~95%)

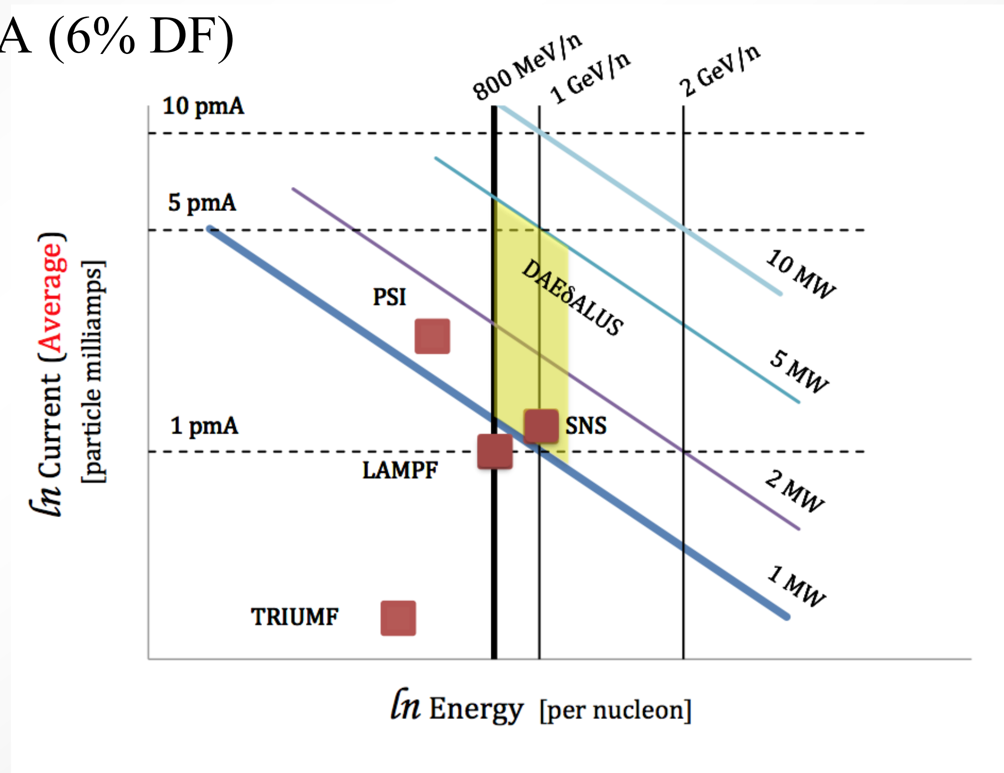
- What we do not need
  1. Fancy time structure
     - Quasi-CW is fine (100 μs on & 400 μs off)
  2. Ability to inject into another accelerator or ability to make clean secondary beams.
  3. Flexibility with respect to beam energy

And all this at a "reasonable" price

DAEδALUS Needs vs. Existing Machines
(Average Power Needs)

- LAMPF (Linac): 800 MeV, 1 mA (12% DF)
- PSI (Cyclotron): 590 MeV, 2.2 mA (100% DF)
- SNS (Linac): 1 GeV, 1 mA (6% DF)

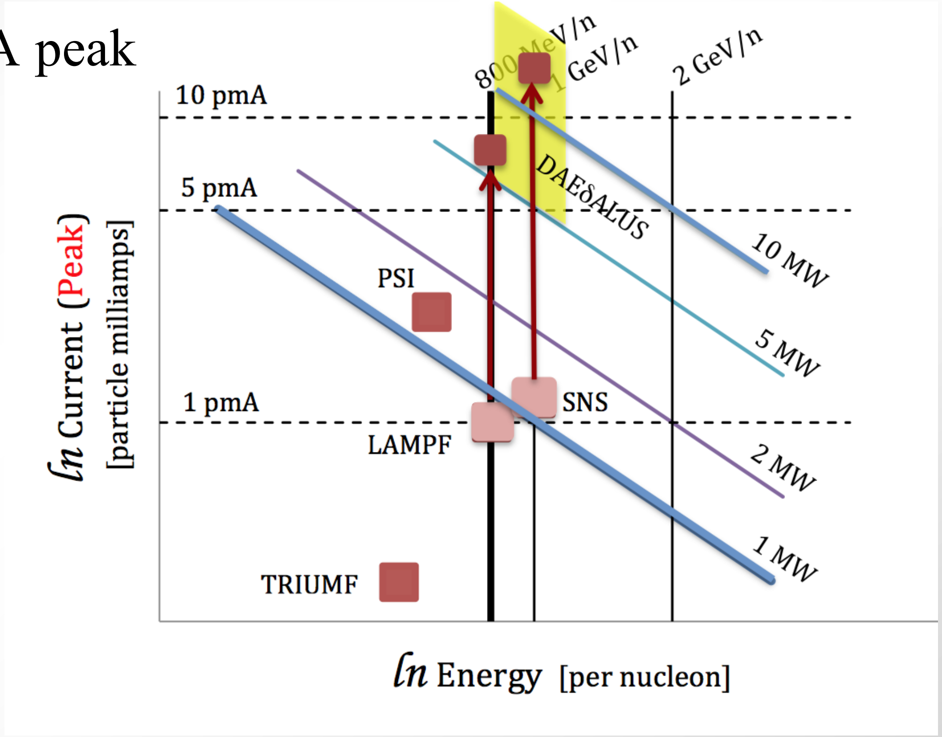
- DAEδALUS:
  Near ~ 1 mA (20% DF)
  Far ~ 5 mA (20% DF)



DAEδALUS vs. Existing Machines
(Peak Power adjusting for duty factor)

- **LAMPF** (Linac): 800 MeV, 8 mA peak
- **PSI** (Cyclotron): 590 MeV, 2.2 mA
- **SNS** (Linac): 1 GeV, 17 mA peak

- DAEδALUS
  Near ~ 5 mA peak
  Far ~ 25 mA peak



Accelerator options

- Proton linac
  - SNS made simple
- Rapid cycling synchrotron
  - JPARC-like at lower energy and higher current
- Cyclotrons
  - PSI-like (1 MW @ 650 MeV)
  - Compact SC cyclotron
  - $H2^+$ ring cyclotron
  - Stacked cyclotrons
- FFAG
  - Requires extensive R&D

The SC Linac Option

- Most conservative choice:
  - Copy SNS as much as possible
  - “Eliminate” re-engineering
- Performance parameters
  - 800 MeV
  - 70 mA of H^+ @ 6% duty factor
  - 2 ms spills at 50 Hz
- Other features
  - One accelerator feeds three targets
  - Conceptually straight-forward upgrade path for Phase II running
- Negatives
  - Size
  - Cost of conventional facility

Rapid cycling synchrotrons

- Characteristics
  - Limit to ALS sized (~100 m circumference)
  - Ignoring the extraction gap, ~ 200 bunches
  - 20 nC/bunch ==> 2.4e13 protons per fill
  - Rapid cycling operation at ~100 Hz ==> 400 μA on target
  - At 1.5 GeV ==> 0.6 MW on the target, significantly less than required.
- Machine diameter is still ~ 30 m with at 10 m tail for the injection linac.
- All features would be pushed to the technical limits,
  - Moreover, there would be no head-room in overall performance.

Consequently, we have ruled out this design from further consideration.

1 MW cyclotrons exist

- Why not copy the PSI design?
  - Very large
  - 580 MeV, 1.8 mA
  - ~300 - 500 M$ per copy (?)
  - High efficiency (~40%)
  - Very low losses (0.01%)
  - More complex than needed
    - One is paying for flexibility

QuickTime™ and a
decompressor
are needed to see this picture.

- Are there other cyclotron approaches at the 1 MW level?

Why superconducting cyclotrons?

- Cyclotrons are efficient users of acceleration voltage (MV/m)
  - High E-fields not required to reach high energy
- Cyclotrons have been around for 8 decades
  - They are well characterized & quantitative
- Superconducting cyclotrons have been around for 3 decades
  - They are robust, have established a scaling in which plant cost decreases 3x when the B field is approximately doubled
- Superconducting Cyclotrons have never required feasibility demonstrations
  - Beam dynamics & magnet designs are quantitative & predictive

One can again double the B field without increasing risk or diminishing performance

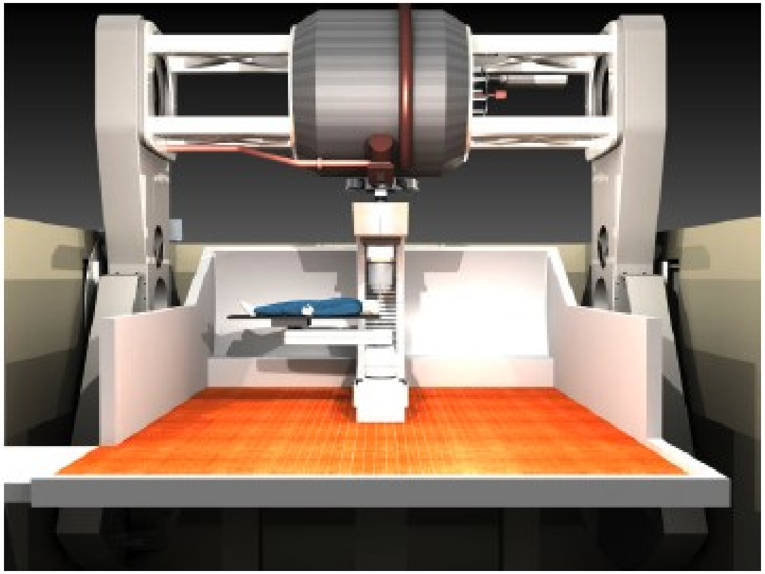
Compact SC Isochronous Cyclotrons: Our initial motivation for DAEdALUS

- Potentially low-cost
  - Single stage acceleration
  - High magnetic field, isochronous design
  - Small-footprint, single stage, mA-current
  - under development at MIT for the Defense Threat Reduction Agency
- High current operation relatively insensitive to final beam energy. Limiting intensity depends on
  - 1) Ability to capture a high current beam at low energy into stable orbits at the cyclotron center
  - 2) Suppression of beam loss due to resonant instabilities during acceleration
  - 3) Ability to extract beam without high losses
- Can non-resonant self-extraction work at high energy & high efficiency?

All relevant design issues will be addressed in DTRA-sponsored research at MIT that is aimed at beam parameters very similar to DAEdALUS parameters.

Example: MIT Designed Proton Cyclotron for Proton Radiotherapy

Still River Monarch 250 MeV



- Cost of PBRT is reduced an order of magnitude ($150M to $20M)
  - First system goes into Hospital June 2010
  - 5 are in various stages of production simultaneously
  - 15 are on order

DTRA sponsored demo: 250 MeV, 1mA

- 4 Sector, Superconducting Isochronous cyclotron
- $B_0 \approx 5.6T$, $B_f \approx 7T$
- Rpole ≈0.4m ; 37 tons
- 84.5 MHz, h=1, 2 dees in valleys, V0 ≈ 160 kV; 450 kW
- External ECR and axial injection
- Non-resonant extraction; passive magnetic channels

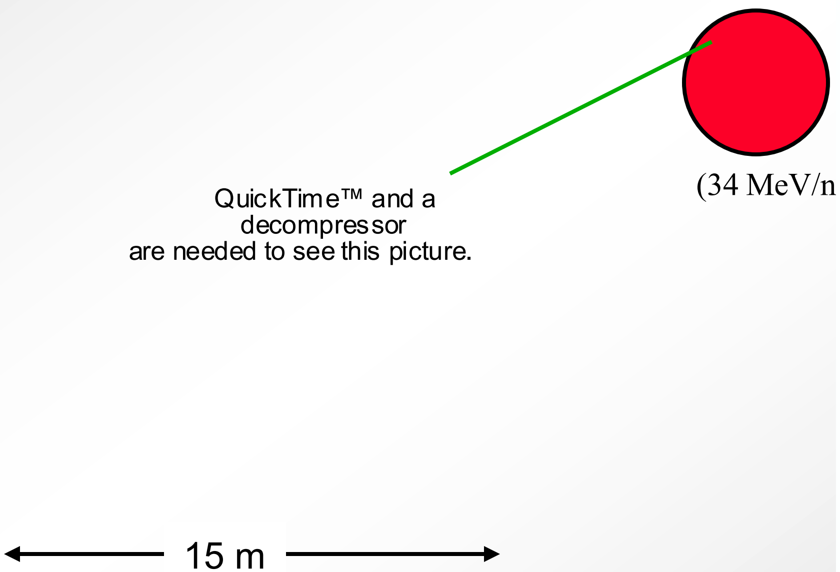
Are we done?
2010 workshop identified issues

- Injection
  - For axial injection inflection may be problem
    - lose factor of 10; heat dissipation
  - Longitudinal phase space acceptance depends on extraction strategies
- Magnet questions
  - Isochronicity requirements, control of field variations & control – flutter
- Extraction
  - Self-extraction, IBA, 14 MeV H+, mA beam (is this energy the limit)
  - Turn separation is much lower at higher energies,
  - RF manipulation could induce resonances? Relating to beam energy?
  - Need tune close to gamma (~2 for 1 GeV)
  - Can one get 1 cm/turn?
  - Septum placement, definition of extraction channel?
  - Beam loss specification for component survival & maintainability?

Is controlled extraction possible?

Non-Liouvillian extraction is possible

- An SC $H2^+$ ring cyclotron originally for Accelerator driven reactors is being designed by INFN, Catania
- 800 Mev/n, 1 mA
- Stripper foil dissociates the $H2^+$, changing the rigidity.

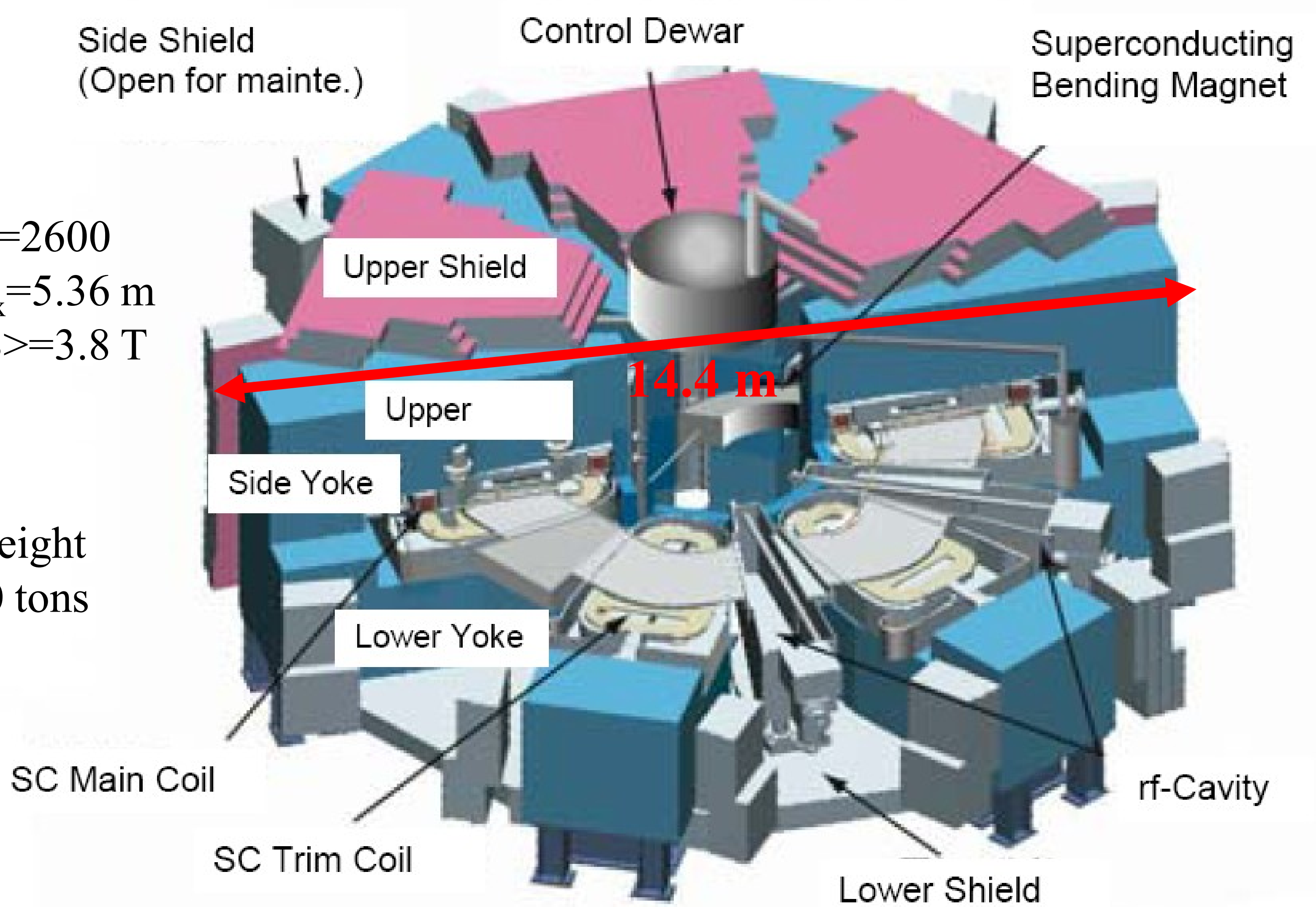


Superconducting Ring Cyclotron			
E_{inj}	34 MeV/n	E_{max}	800 MeV/n
R_{inj}	1.4 m	R_{ext}	4.5 m
$\langle B \rangle$ at R_{inj}	1.2 T	$\langle B \rangle$ at R_{ext}	2.17 T
sectors	9	Accel. Cavities	6
RF	53.7 MHz	Harmonic	6th
V-peak	220 kV	ΔE/turn	1.950 MeV
ΔR at R_{inj}	15 m	ΔR at R_{ext}	2.7 mm
Injector Cyclotron			
E_{inj}	50 keV/n	E_{max}	34 MeV/n
R_{inj}	5.5 cm	R_{ext}	1.4 m
$\langle B \rangle$ at Rinj	1.2 T	$\langle B \rangle$ at R_{ext}	2.17 T
sectors	3	Accel. Cavities	3
RF	26.85 MHz	Harmonic	3rd
V-inj	70 kV	V-ext	180 keV
ΔE/turn	1080 keV	ΔR at R_{ext}	11 mm

RIKEN Superconducting Ring Cyclotron (SRC)

K_b=2600
R_{ex}=5.36 m
<B>=3.8 T

Iron weight
8000 tons



And then there is the beam dump
Deposition of a 2 GeV, 4 MW beam in C

QuickTime™ and a
decompressor
are needed to see this picture.

We would put no more than 1 MW on each dump

Measurement strategy:

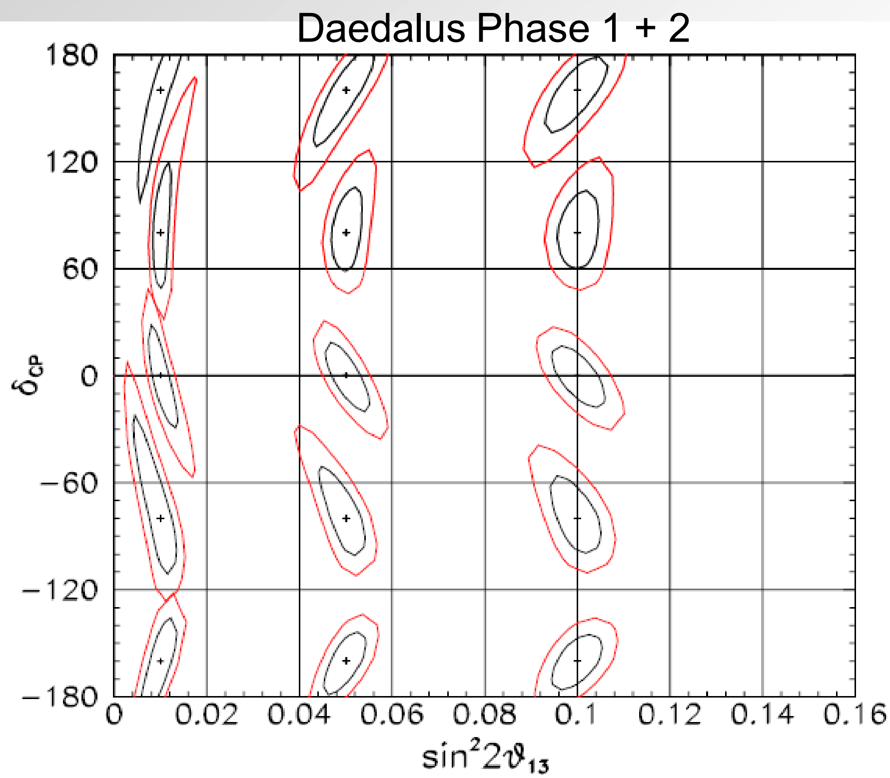
Using **near accelerator**
measure **absolute flux normalization** with ν-e events to ~1%,
Also, measure the ν_eO event rate.

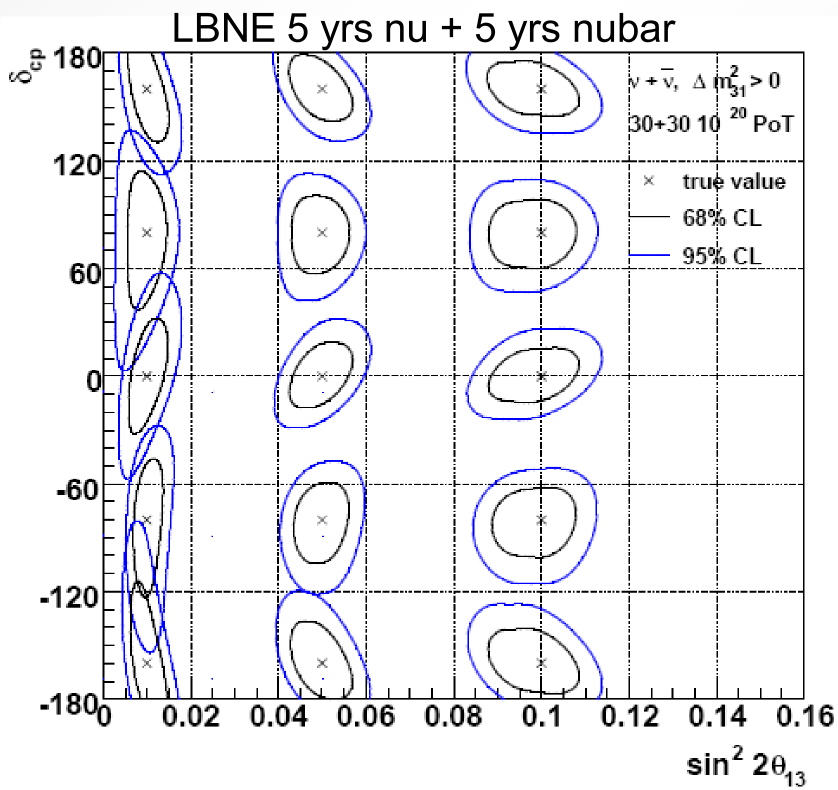
At far and mid accelerator,
Compare predicted to measured ν_eO event rates
to get the **relative flux normalizations between 3 accelerators**

In all three accelerators,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with free parameters: **θ_{13} and δ**

Source: J. Conrad

By construction our capability equals LBNE's
But DAEδALUS has different systematics





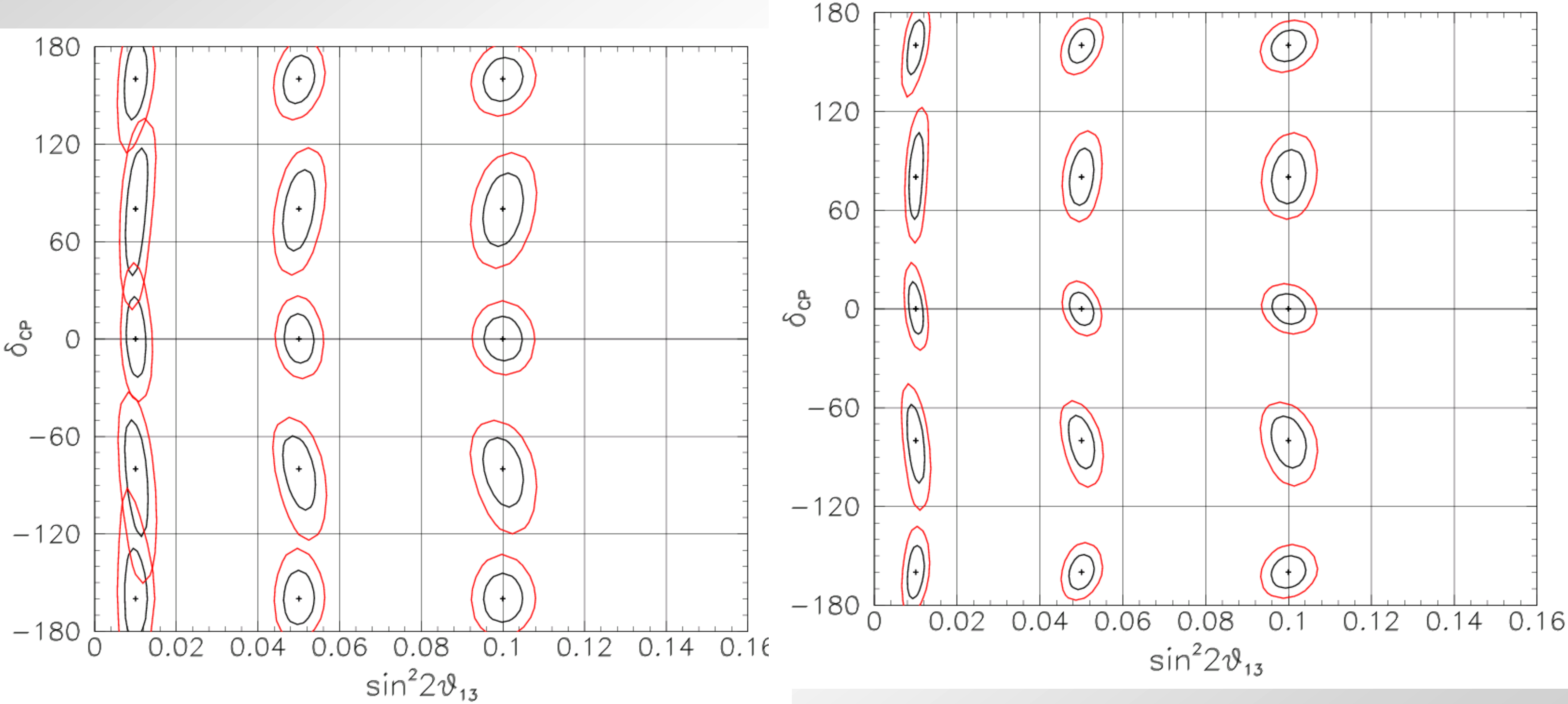
What the combined experiments can do!

5yr Combined Running

Daedalus Phase 1 plus LBNE 5yr nu

10yr Combined Running

Daedalus Phase 1&2 plus LBNE 10yr nu



Comparable to the expectation for 2nd generation Super-beam facilities

Source: J. Conrad

The 3-phase run-plan consists of

1. Learn: Run the near accelerator to learn more about operations, as well as to make useful preliminary cross section measurements
2. Discover: Run in the 1-2-3 MW configuration to discover the value of δ_{CP} while maintaining flexibility of design
3. 3. Measure: Run for the remainder of the experiment with the most optimal accelerator design.

A tentative schedule for discussion…

QuickTime™ and a
decompressor
are needed to see this picture.