DAEδALUS

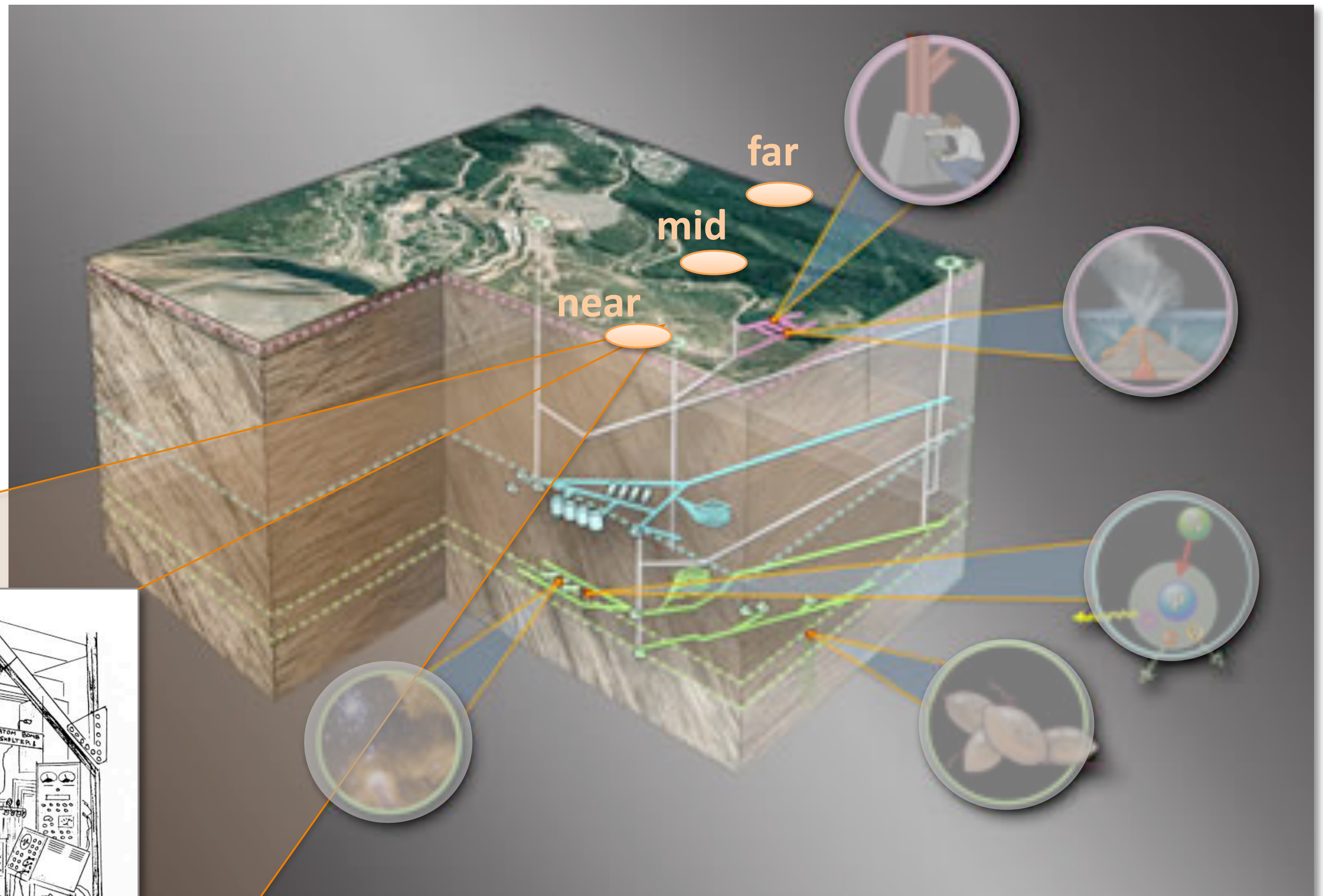
…CP-violation and Beyond!

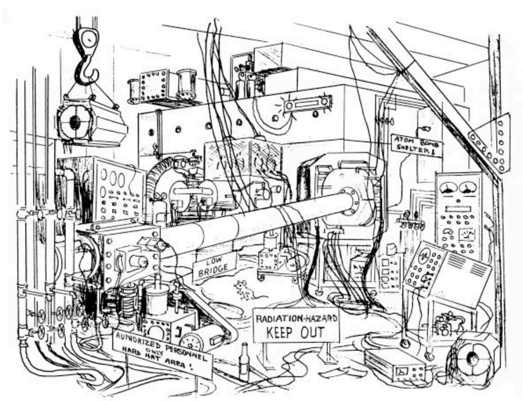
Georgia Karagiorgi, Columbia University
DAEδALUS Collaboration

Intensity Frontier Workshop / Nov. 29 – Dec. 2, 2011

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

A **new antineutrino (multi-)source** for a large Gd-doped water cherenkov at SURF





The cyclotron as seen by... the visitor.

[LBNL Image Library]

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A **new antineutrino (multi-)source** for a large Gd-doped water cherenkov at SURF

- **Enhanced oscillation program**
- **New experiments possible**

Complementary to the long baseline proposals

- **Comparable measurements for osc. parameters**
- **Much improved measurements by combining DAEδALUS and long-baseline!**

Associated with forefront accelerator R&D in developing high-power, high-intensity cyclotrons

Goal: Independent measurement of θ_{13} and δ_{CP}

Strong hints!!!

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability in vacuum:

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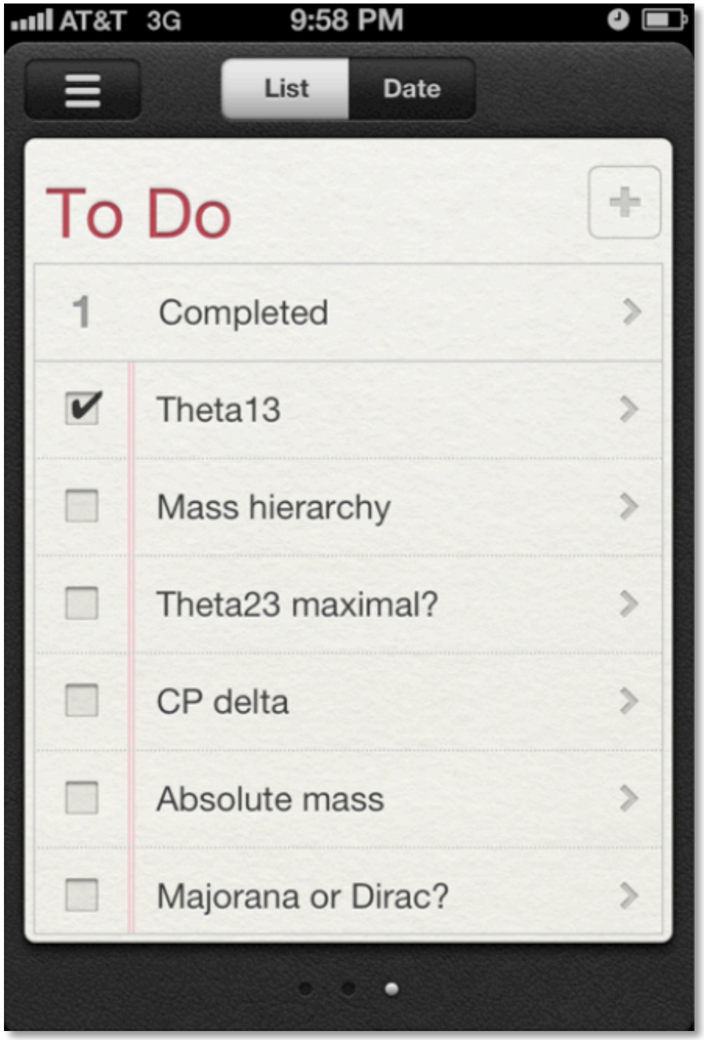
\end{aligned}
$$

We want to know if $\delta=0$?


AT&T 3G
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List
Date
To Do
1 Completed
Theta13
Mass hierarchy
Theta23 maximal?
CP delta
Absolute mass
Majorana or Dirac?

K. Scholberg

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We want to know if δ=0?

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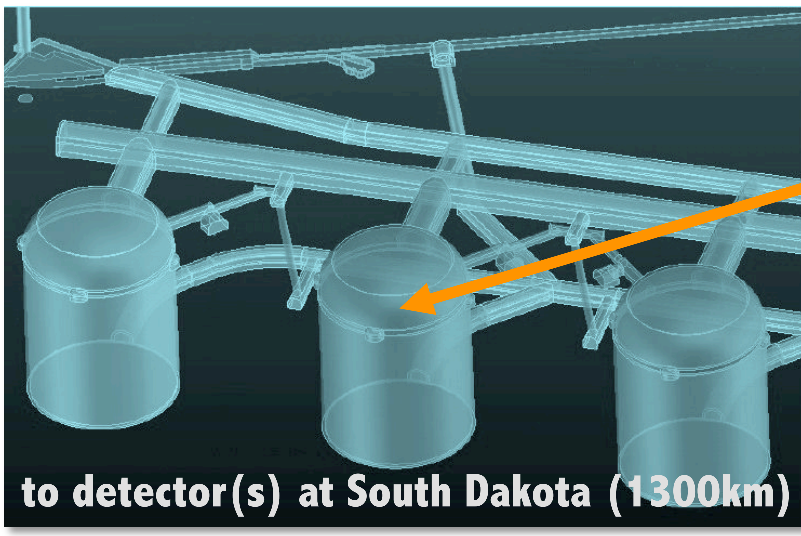
Conventional approach: LBNE

→ uses ν and $\bar{\nu}$ beams over long baseline

→ exploits sign flip in CP-violating term in oscillation probability



L/E ~ 400 km/GeV

→ probes atmospheric Δm^2

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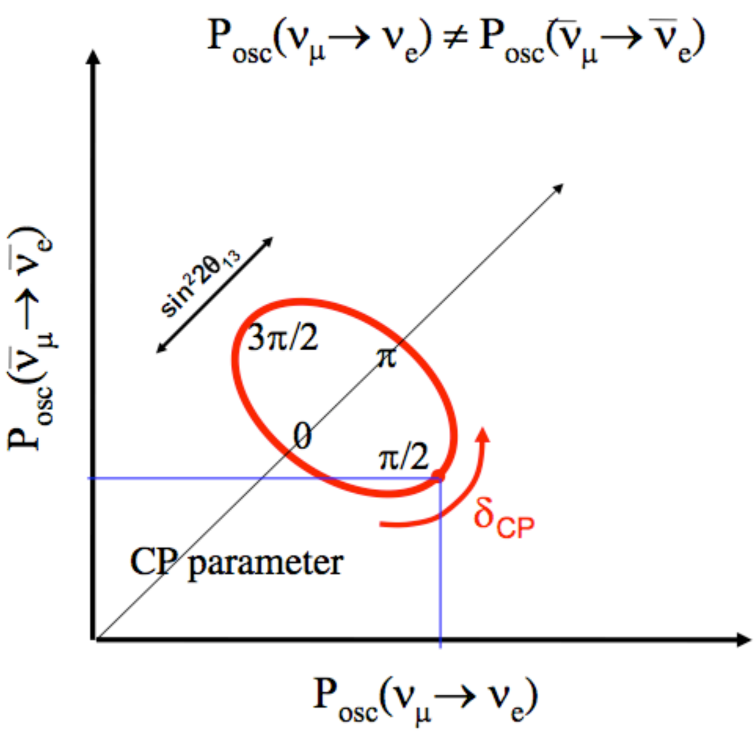

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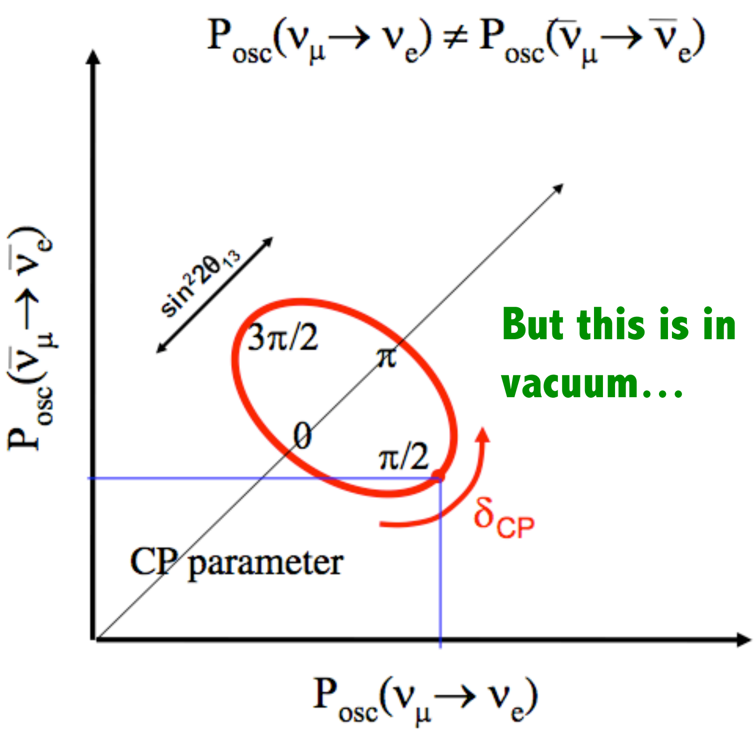
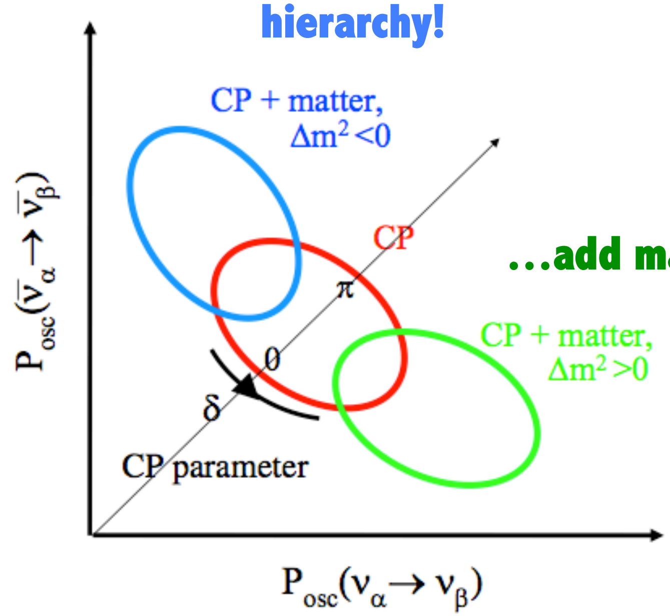


But this is in vacuum…

…and ambiguity from mass hierarchy!



…add matter…

Conventional approach: LBNE

→ uses ν and $\bar{\nu}$ beams over long baseline

→ exploits sign flip in CP-violating term in oscillation probability

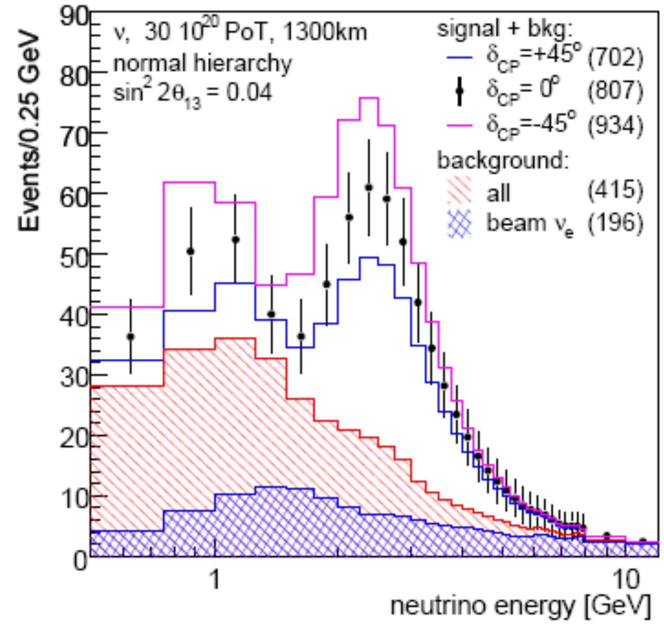
Limitations (water cherenkov):

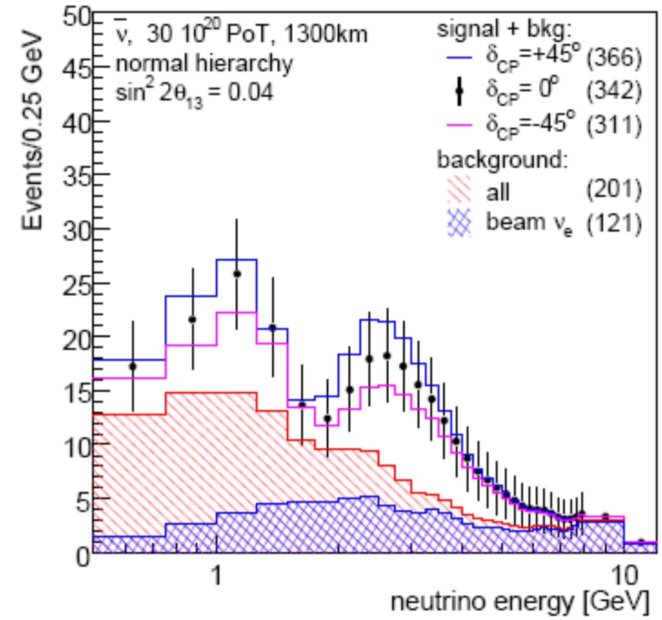
– Matter effect → degeneracies

– Substantial neutral current π^0 events that mimic ν_e (or ν_e) events

– Low antineutrino statistics

– Significant neutrino contamination in antineutrino mode





CP Violating Observables

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$

Non-CP terms

Changes sign for antineutrinos

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$

CP violating

$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp}\,\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13}L}{2}\right)$$

$$\tilde{J} \equiv c_{13}\,\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \qquad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|,\ A = \sqrt{2}G_F N_e$$

$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

A. Cervera et al., Nuclear Physics B 579 (2000)

More complicated...

Mass hierarchy affects nu/nubar via matter effects (need long L)

Need precision measurements of parameters....

Multiple measurements **(ν's and $\bar{\nu}$'s) at different L, E needed to resolve intrinsic ambiguities**

K. Scholberg

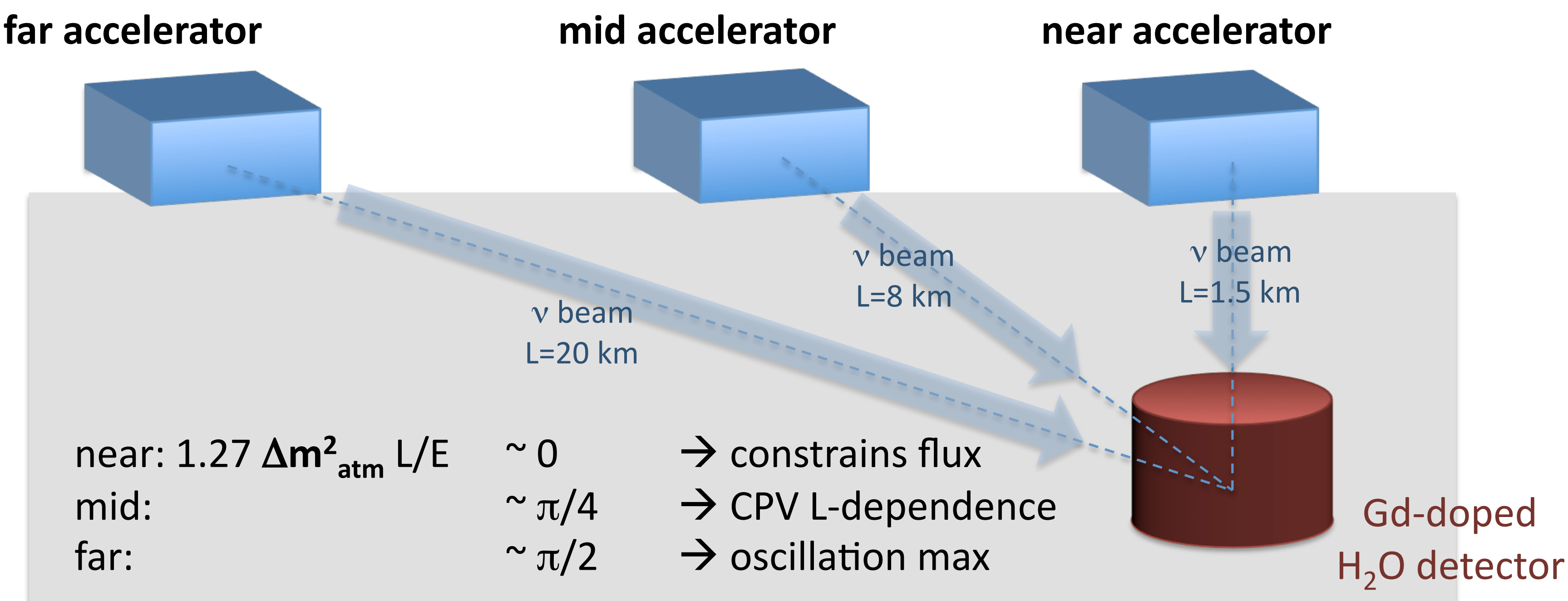
DAEδALUS:

Concept: multiple-baseline, single detector

→ use only antineutrino beams

→ exploit L/E dependence of CP-violating terms

Low energy beam (up to 52 MeV) → need short distances (no matter effects!)



DAEδALUS:

Collaboration of Particle and Accelerator Experimentalists and Theorists Exploring How to Realize a New Neutrino Source for DUSEL

Amherst College, Amherst, MA 01002, USA
Argonne National Laboratory, Argonne, IL 60439, USA
Black Hills State University, Spearfish, SD 57799, USA
University of California, Irvine, CA 92697, USA
Centro Siciliano di Fisica e Struttura della Materia, I-95123, Italy
University of Chicago, Chicago, IL 60637, USA
The Cockcroft Institute for Accelerator Science &
the University of Manchester, Oxford Road, Manchester M13 9PL, UK
Columbia University, New York, NY 10027, USA
Duke University, Durham, NC 27708, USA
Imperial College London. London, SW7 2AZ, UK
Instituto De Fisica Corpuscular, E-46071 Valencia, Spain
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, I-95123, Italy
Iowa State University, Ames, IA 50011, USA
Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
Los Alamos National Laboratory, Los Alamos, NM 87545, USA
Massachusetts Institute of Technology, Cambridge, MA 02139, USA
Michigan State University, East Lansing, MI 48824, USA
New Mexico State University, Las Cruces, NM 88003, USA
North Carolina State University, Raleigh, NC 27695, USA
Northwestern University, Evanston, IL 60208, USA
Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
University of South Carolina, Columbia, SC 29208,USA
Texas A&M University, College Station, TX 77843, USA
University of Texas, Austin, TX 78712, USA
University of Tokyo, Kashiwa, 277-8583, Japan
Yale University, New Haven, CT 06520 USA

Spokespersons: J. Conrad, M. Shaevitz

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Expression of Interest:* *arXiv:1006.0260

See also…

- Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector, arXiv:0912.4079

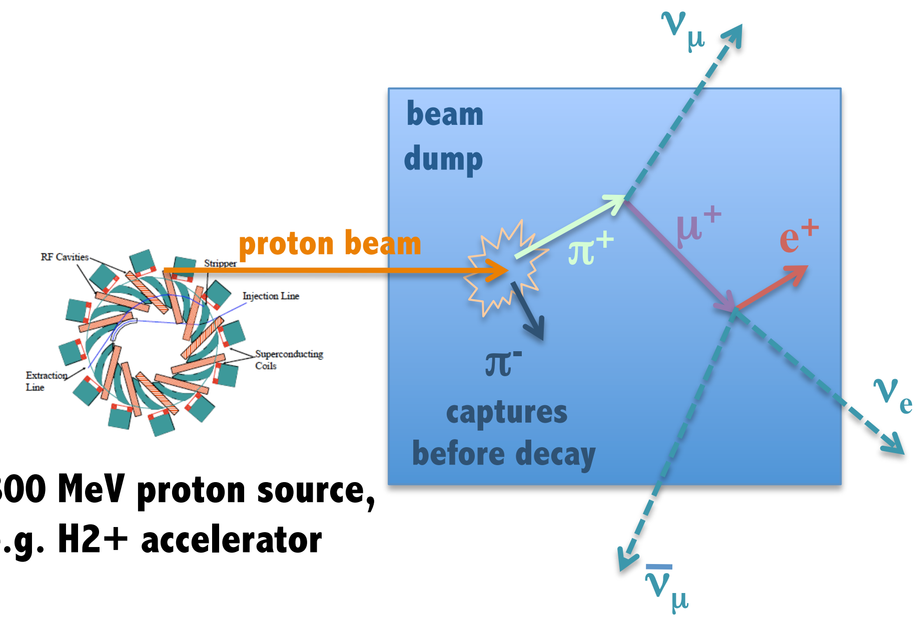
- A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEdALUS, arXiv:1008.4967

- A Multi Megawatt Cyclotron Complex to Search for CP Violation in the Neutrino Sector, arXiv:1010.1493

Ingredients:

Antineutrino beam: identical for all three baselines

$\pi^+ \rightarrow \mu^+$ decay-at-rest:



800 MeV proton source, e.g. H2+ accelerator

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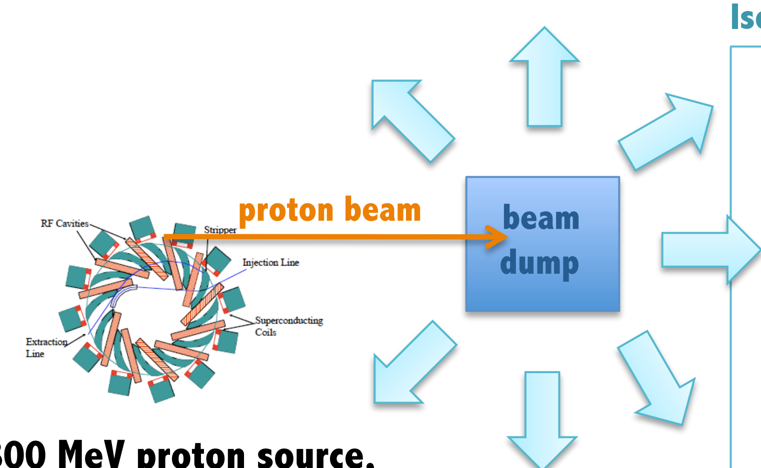

800 MeV proton source,
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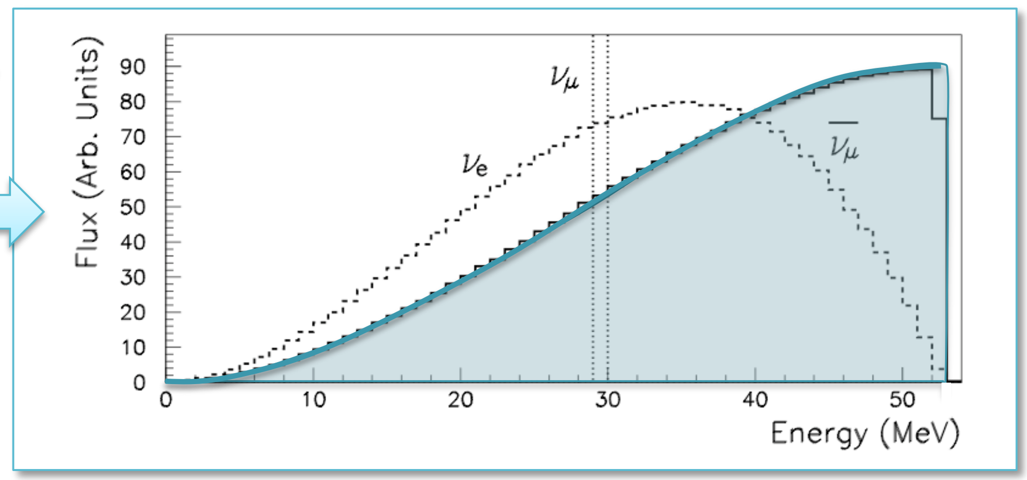
Isotropic neutrino flux: 4×10^{22} ν/flavor/yr



Negligible $\bar{\nu}_e$ contamination
→ ideal for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search!

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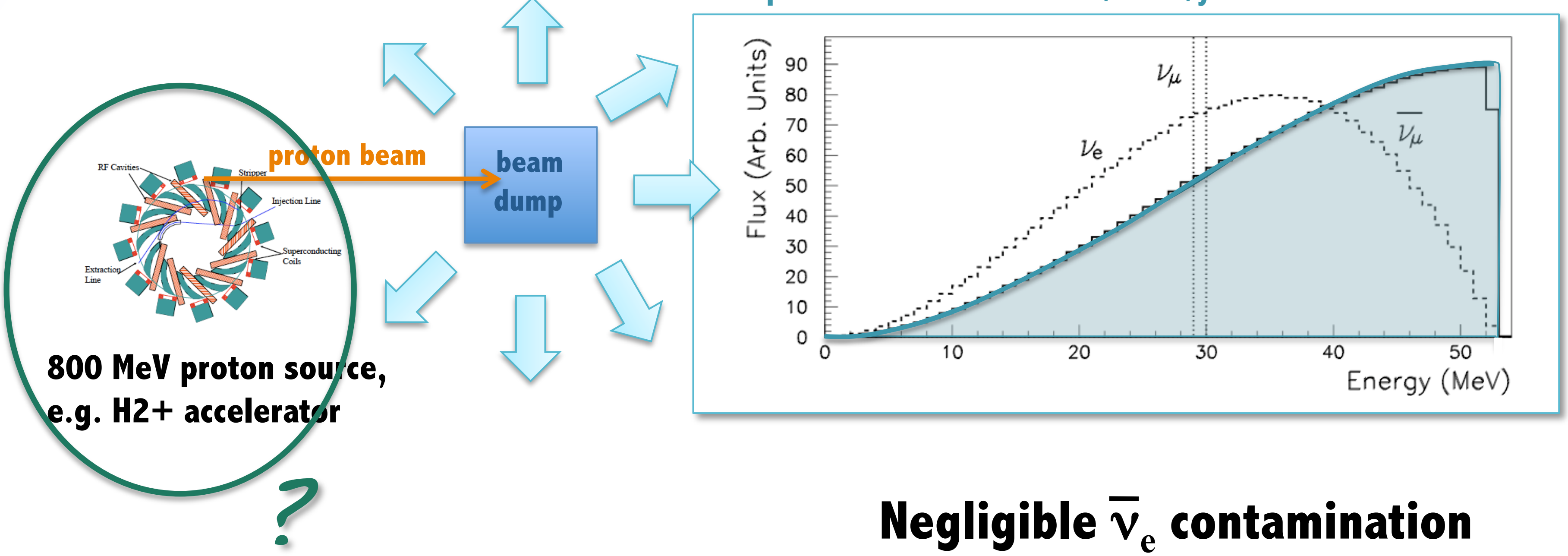

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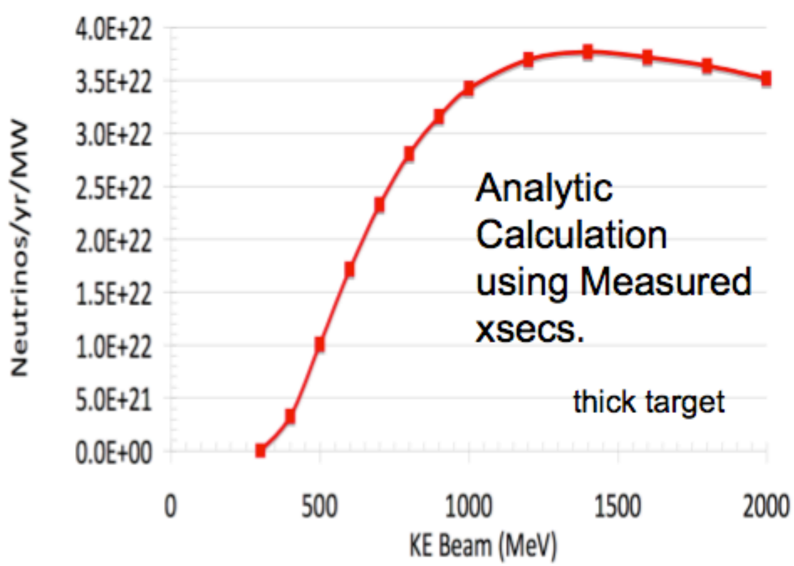
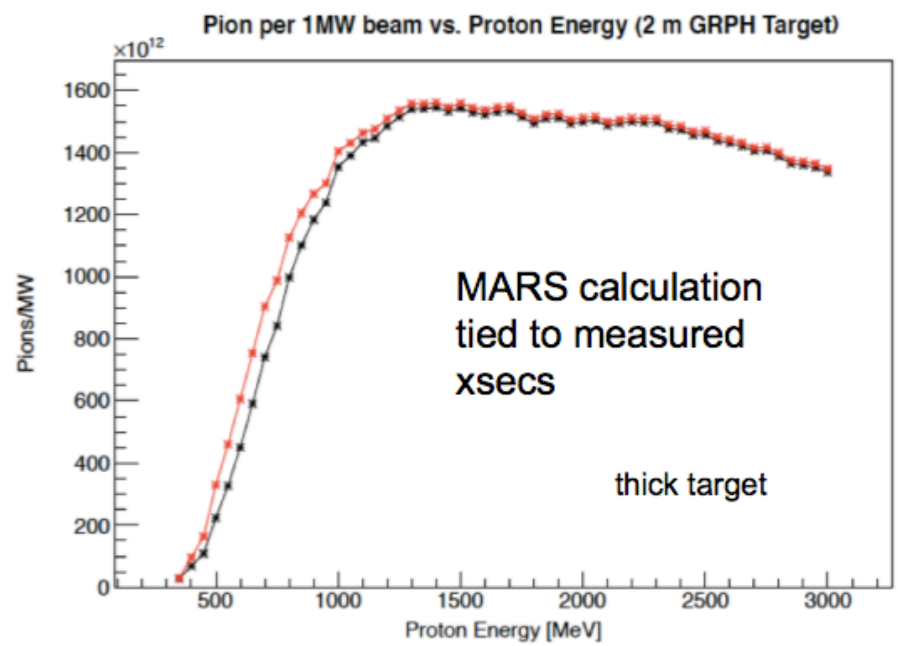
Proton source choice:

Optimal p energy (Δ plateau): ~1200 MeV

800 MeV chosen as baseline energy

$$p + C \rightarrow \Delta + X \;\Rightarrow \Delta \rightarrow N + \pi$$

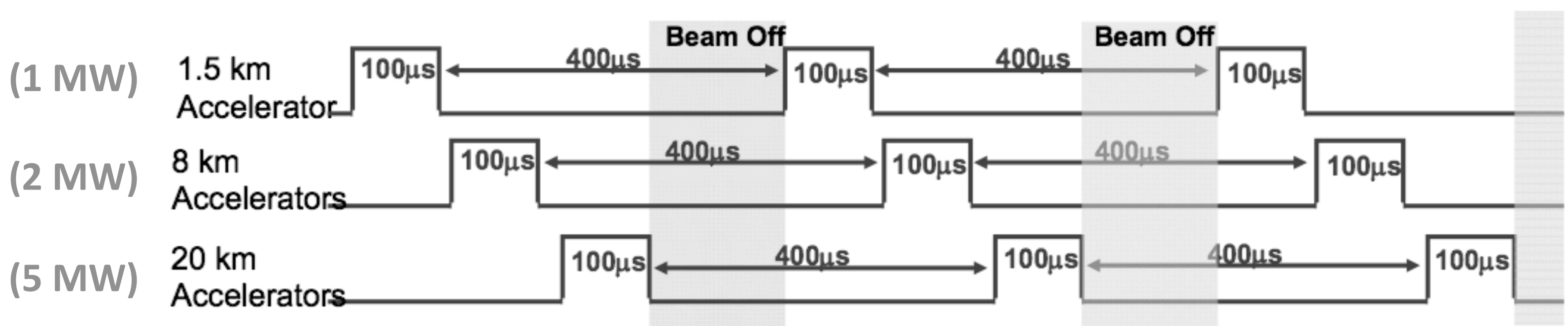




Proton source choice:

Beam requirements:

- Need 800 MeV proton energies to efficiently produce π^+
- Need to run three sites at different times so one knows the L associated with each event
- Need 1-2 MW power for each beam dump
- 20% duty factor means instantaneous beam power and current are x5 higher than average



Proton source choice:

Other requirements:

- Flexibility of source placement
- $$$... We need something not too expensive!

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Cyclotrons?

- Well-known conventional cyclotron designs are quite well-suited as **reliable and economical solutions** for a plant which requires a **peak beam power of 1-5 MW** [Cala1999a, Jong1999].
- For higher peak power, important problems for a ring cyclotron design must be addressed:
  - space charge effects
  - extraction systems
  - power dissipation in each of the accelerating RF cavities
- To overcome these problems the traditional solution is to increase the radius of the cyclotron and the number of cavities.
  But this significantly increases the plant cost…

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Associated with forefront accelerator R&D in developing high-power, high-intensity cyclotrons

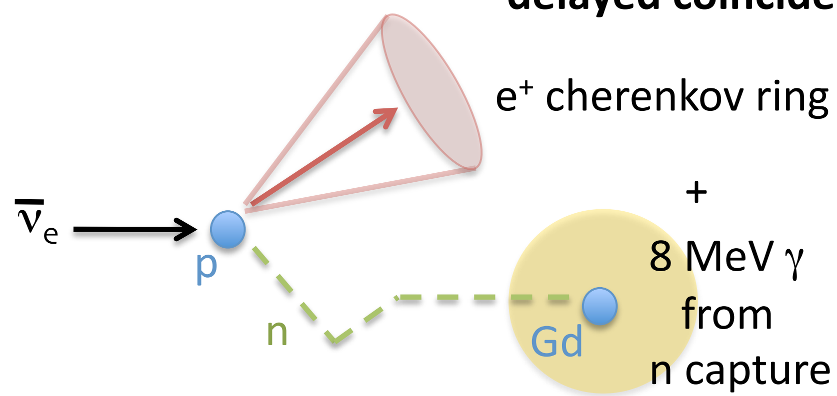
Proton source choice:

- Cyclotron concept:
  H_2^+ source design with stripping extraction of 2 protons
  [arXiv:1107.0652].
- Ongoing R&D to establish feasibility and understand costs in ~1 year timescale.
- Efforts by INFN-LNS (Catania) and PSI (Villigen).
- Workshop of cyclotron experts in Erice (Sicily) in December 2011 to further the design efforts.
- For further info: L. Calabretta, J. Alonso.

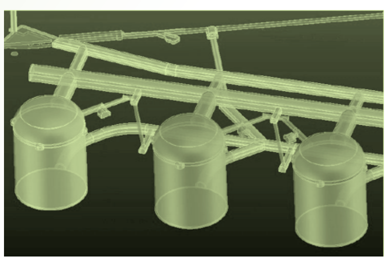
Ingredients:
Detector: optimized for $\bar{\nu}_e$

Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
via inverse beta decay (IBD):
(well known x-sec)

IBD signature:
delayed coincidence



(assumed efficiency: 67%)



Assumes (proposed) H_2O cherenkov detector (Gd-doped)

→ High-statistics, well-understood event samples!

Event Type	1.5 km	8 km	20 km
IBD from Intrinsic $\overline{\nu}_e$ ($E_\nu > 20$ MeV)	600	42	17
IBD Non-Beam ($E_\nu > 20$ MeV)			
atmospheric $\nu_\mu p$ "invisible muons"	270	270	270
atmospheric IBD	55	55	55
diffuse SN neutrinos	23	23	23
ν_e−e Elastic ($E_\nu > 10$ MeV)	16750	1178	470
ν_e−Oxygen ($E_\nu > 20$ MeV)	101218	7116	2840

no-oscillations predictions (backgrounds)

Absolute flux and relative normalization of each source is constrained by
ν-e elastic scattering (~20k events, very forward, near detector)
and **ν_e-O events**, respectively.

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IBD Oscillation Events ($E_\nu > 20$ MeV)			
$\delta_{CP} = 0^0$, Normal Hierarchy	763	1270	1215
" , Inverted Hierarchy	452	820	1179
$\delta_{CP} = 90^0$, Normal Hierarchy	628	1220	1625
" , Inverted Hierarchy	628	1220	1642
$\delta_{CP} = 180^0$, Normal Hierarchy	452	818	1169
" , Inverted Hierarchy	764	1272	1225
$\delta_{CP} = 270^0$, Normal Hierarchy	588	870	756
" , Inverted Hierarchy	588	870	766

no-oscillations predictions (backgrounds)

expected oscillation signal ($\sin^2 2\theta_{13} = 0.05$)

Advantages of the DAEδALUS design:

• Nature forces the neutrino flux energy distribution to be the same; allows for **flux normalization constraint**

• The important neutrino **cross sections are very well known** (IBD, ν-e; <1% error)

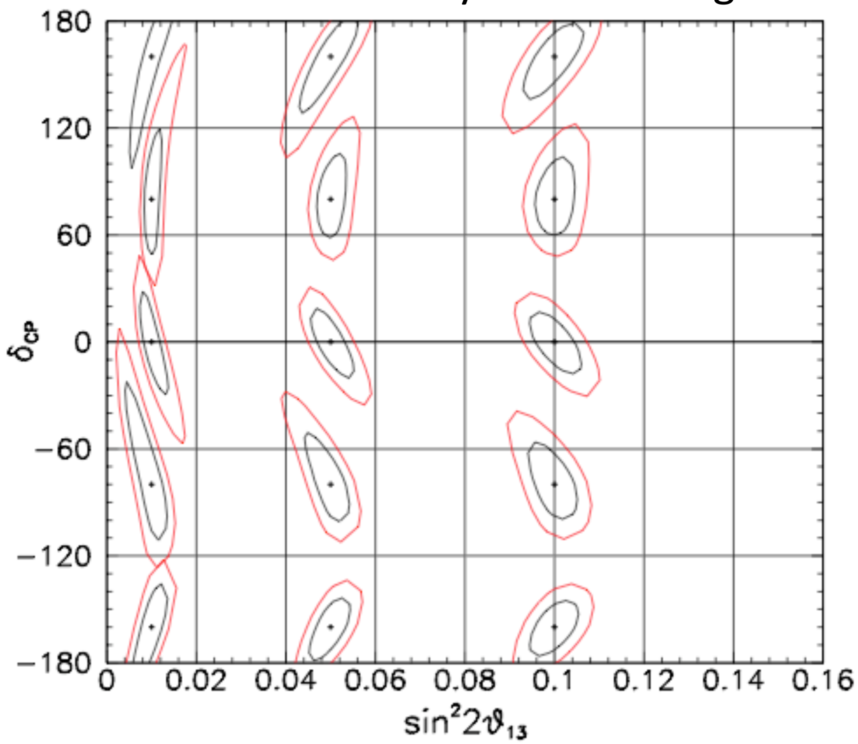
• The **detector systematics are identical** for all baselines (single detector)

• The backgrounds are expected to be very low and will be **measured** directly.

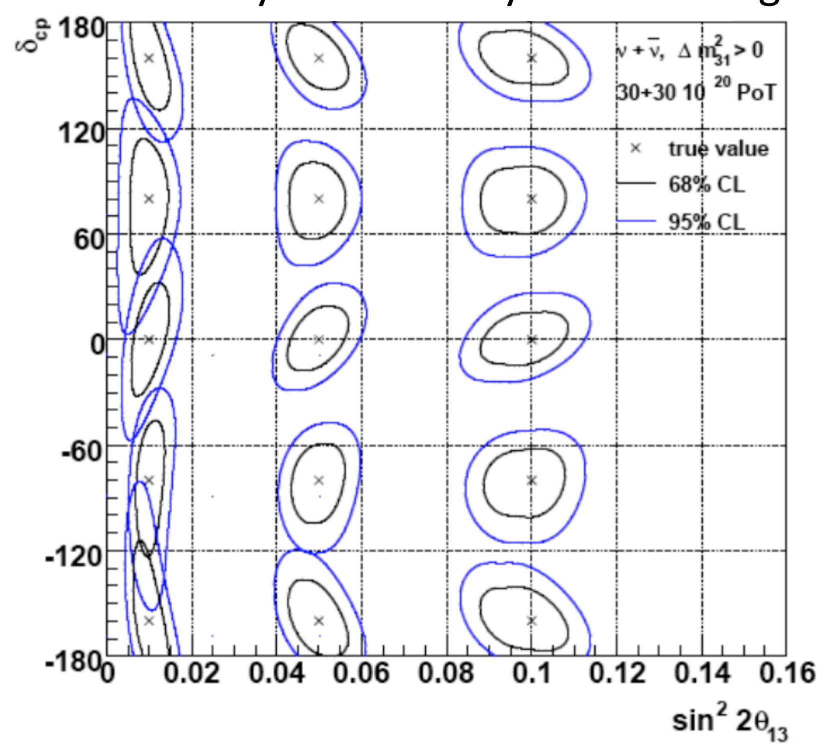
Measurement is
statistics- rather than systematics-limited
+
not sensitive to matter effects (low E)

DAEδALUS' "performance" ?

DAEδALUS 10 year $\bar{\nu}$ running



LBNE 5 year ν and 5 year $\bar{\nu}$ running



Comparable sensitivity to LBNE (by construction).

Not a competition!

Complementary to LBNE:

LBNE has matter effects

DAEδALUS does not

LBNE is mainly a ν experiment (low antineutrino statistics)

DAEδALUS is entirely $\bar{\nu}$ (high antineutrino statistics)

LBNE is a high energy experiment (300 MeV - 10 GeV)

DAEδALUS is a low energy experiment

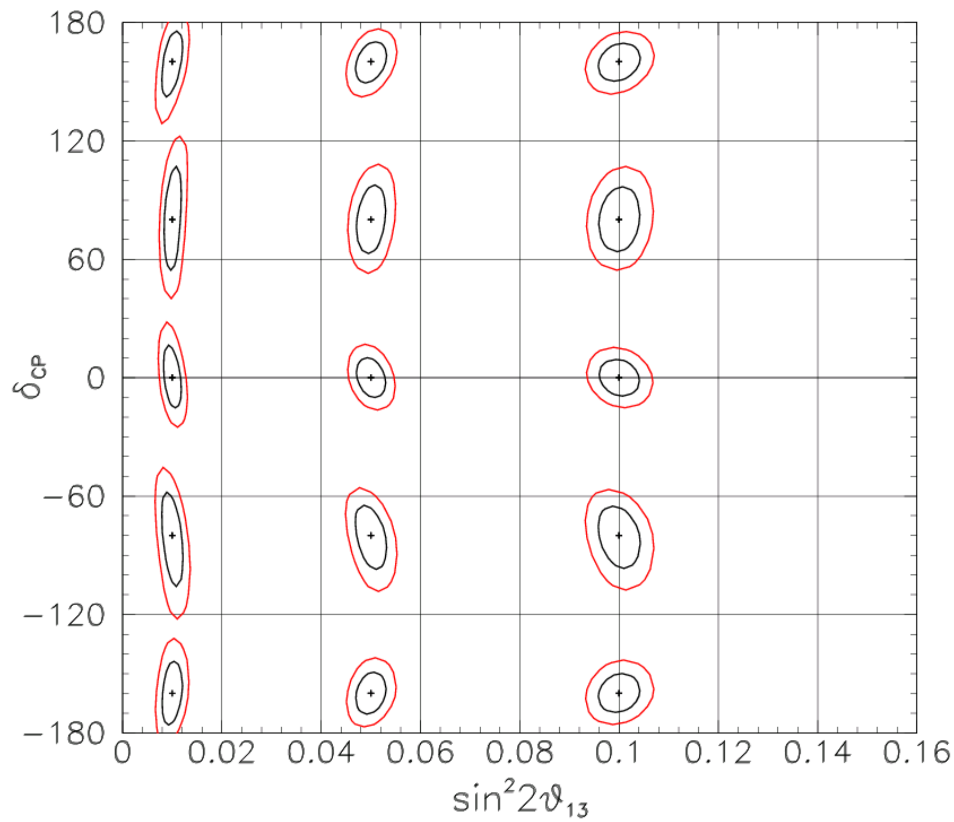
LBNE varies beam energy

DAEδALUS varies beam distance

What happens when we combine the two?

Complementary to LBNE:

DAEδALUS 10 year $\bar{\nu}$ running
+
LBNE 10 year ν running

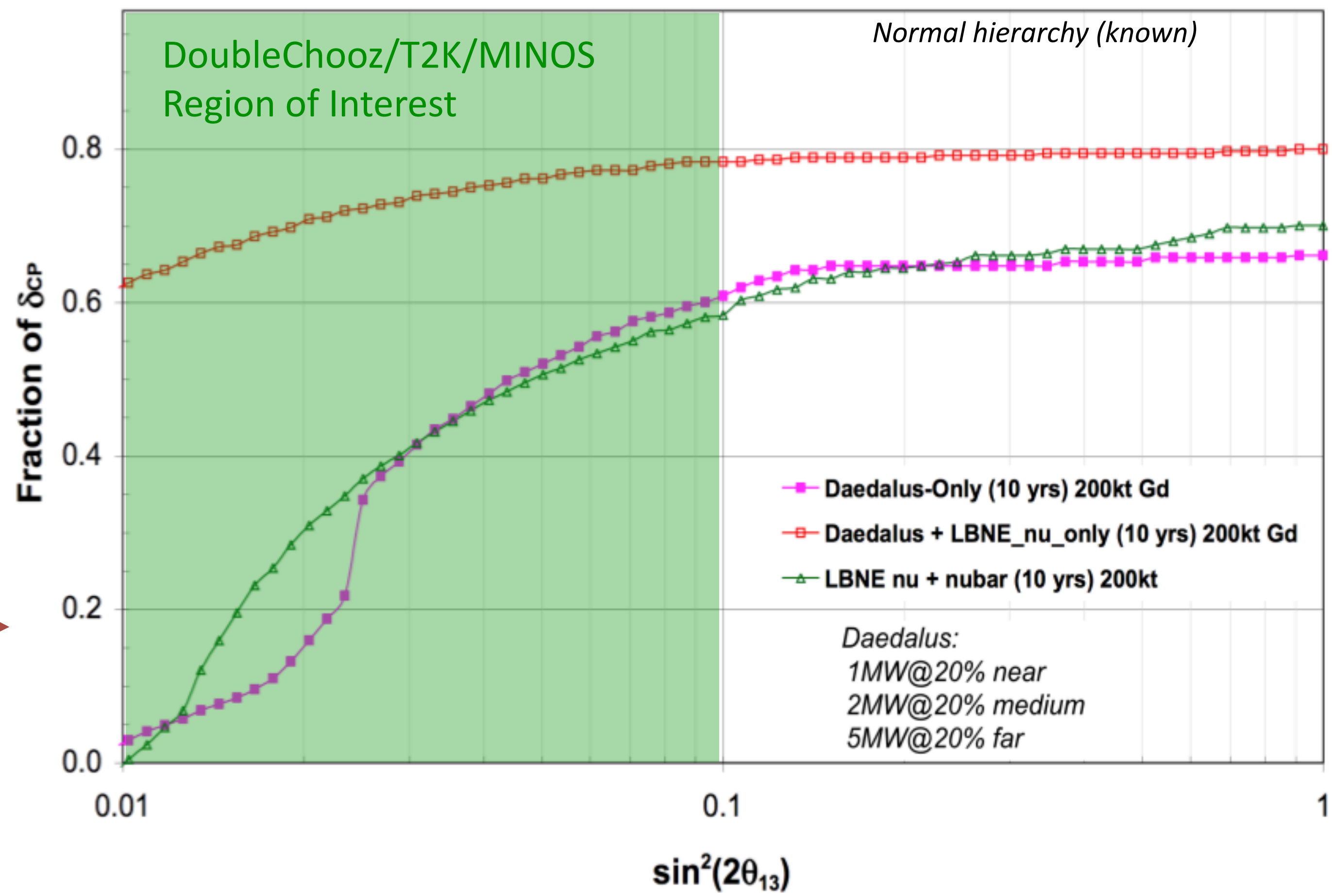


Complementary to LBNE:

Quantifying measure:

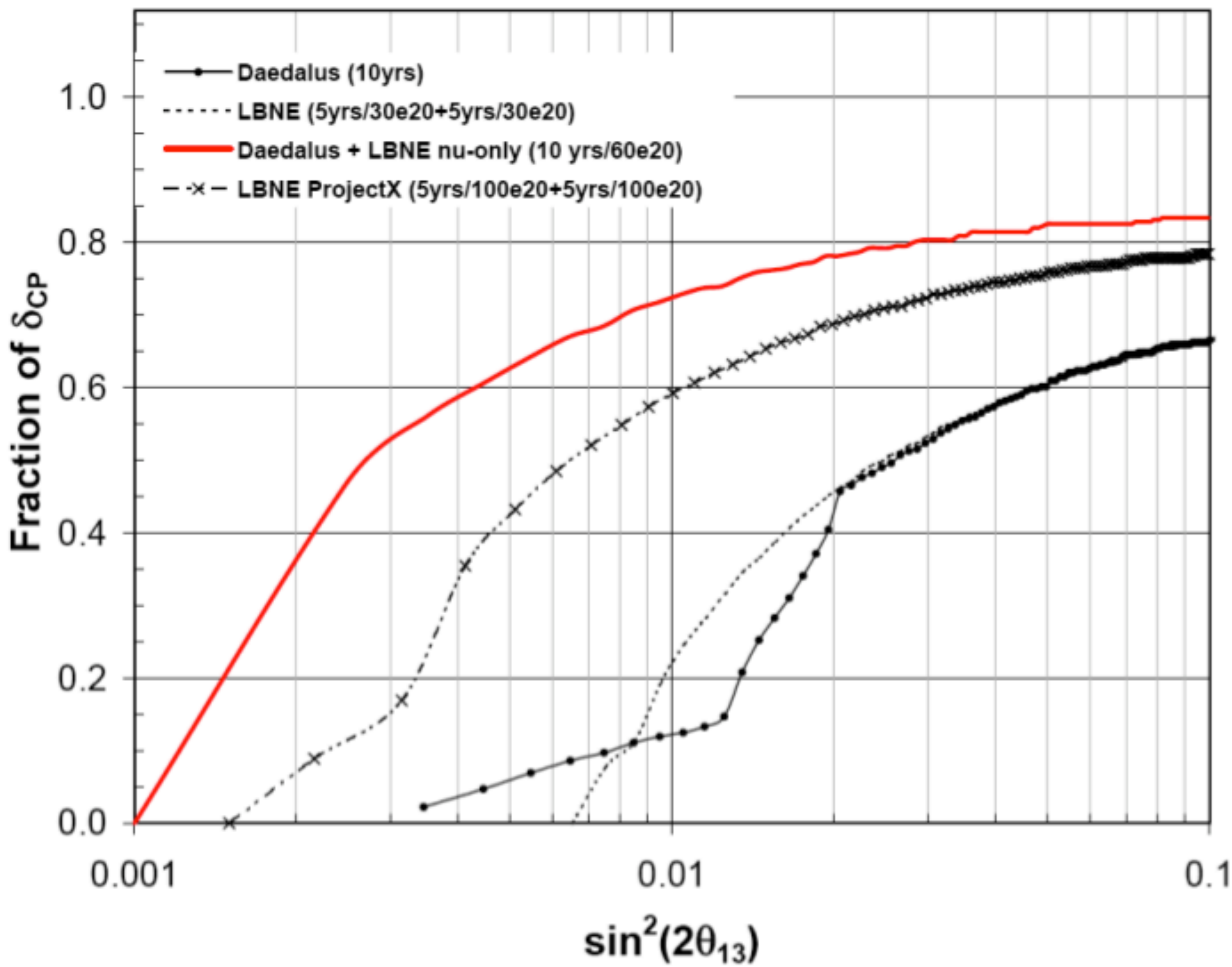
Fraction of δ_{CP} space where δ_{CP}=0 or 180° (no CP violation) can be excluded at 3σ

Excellent δ_{CP} sensitivity down to small $\sin^2 2\theta_{13}$ values



Combined running substantially better than either LBNE or DAEδALUS alone!

Complementary to LBNE:



Combined capability exceeds ProjectX!

The case for DAEδALUS (I):

Even though DAEδALUS can make neutrino oscillation measurements as a standalone experiment,

independent confirmation of θ_{13} and δ_{CP}

the real **strength comes from combining** the high-statistics, low-systematics DAEδALUS antineutrino sample with a high-statistics neutrino sample from LBNE and/or Project-X.

+ enhanced sensitivity to θ_{13} and δ_{CP}

The case for DAEδALUS (II):

+ more physics!

By construction, detector requirements overlap with <100 MeV physics searches: **supernova relic neutrinos, proton decay,...**

(see talk by B. Marciano)

A new accelerator facility (near), and neutrino (multi-)source at SURF provides opportunities for new experiments and enhancement of the SURF neutrino program…

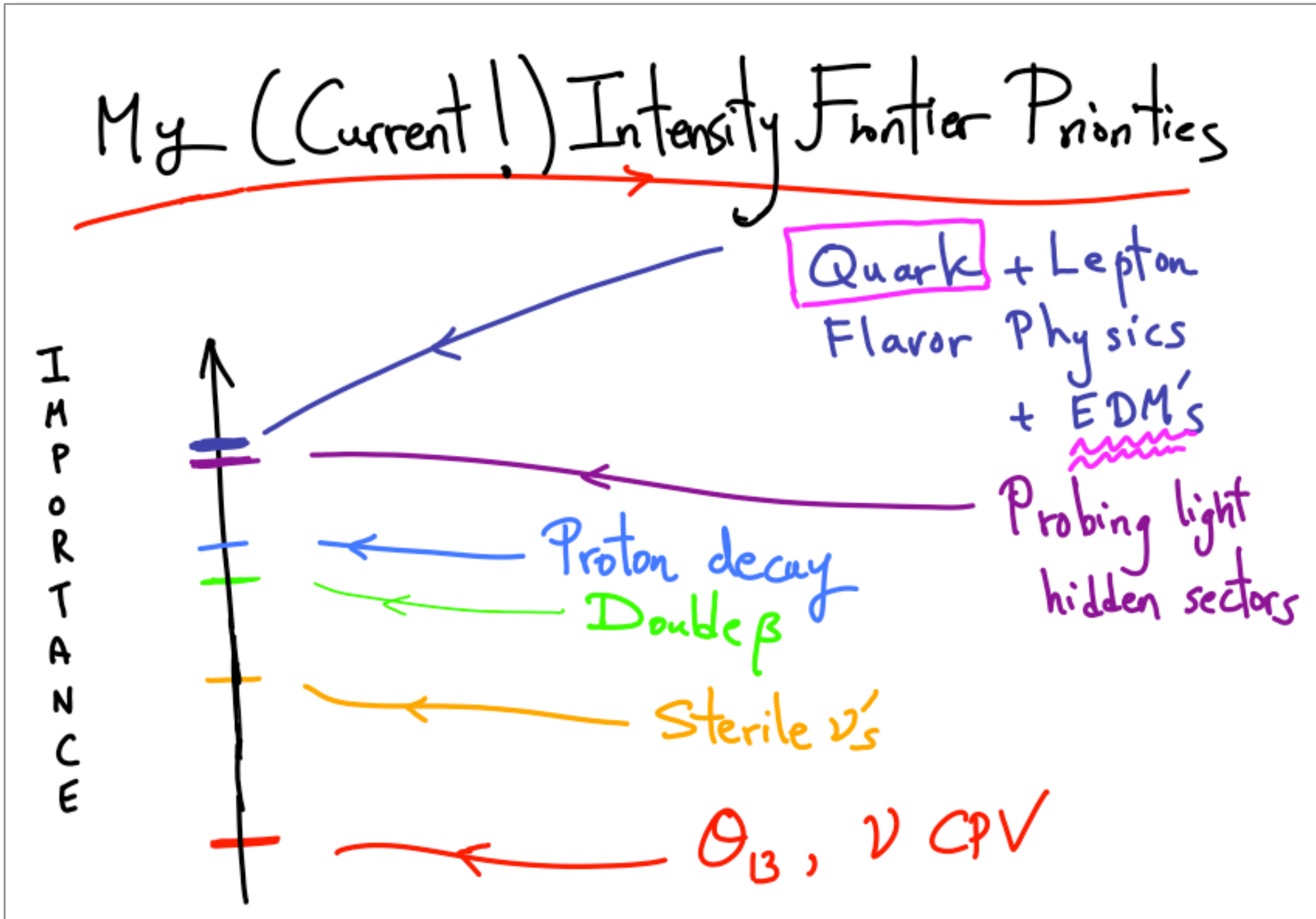
The case for DAEδALUS (II):

+ more physics!

Contributed ideas:

- Coherent neutrino-nucleus scattering
- Searches for non-standard neutrino interactions
- $\sin^2\theta_w$ measurement
- High-Δm^2 oscillation searches
- Axion searches
- Etc…

Just one example…



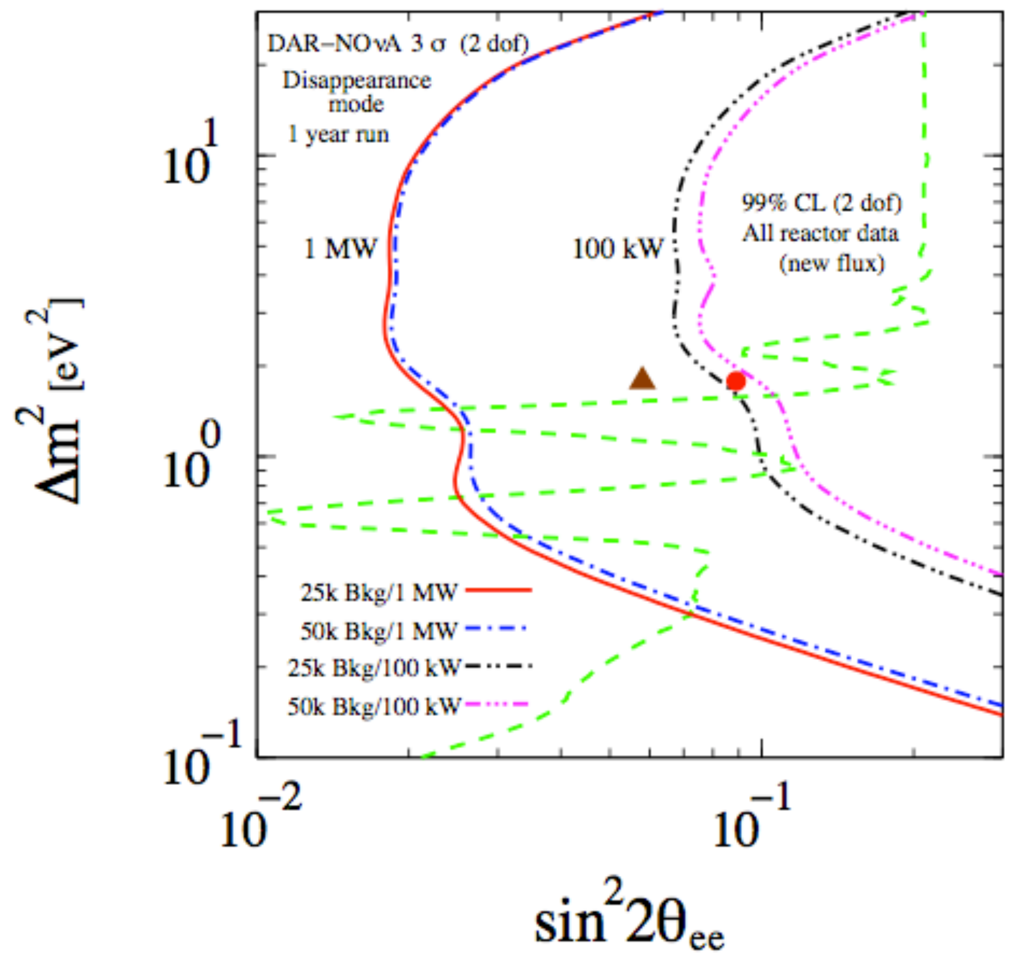
N. Arkani-Hamed

Just one example…

ν_e disappearance:

[arXiv:1105.4984]

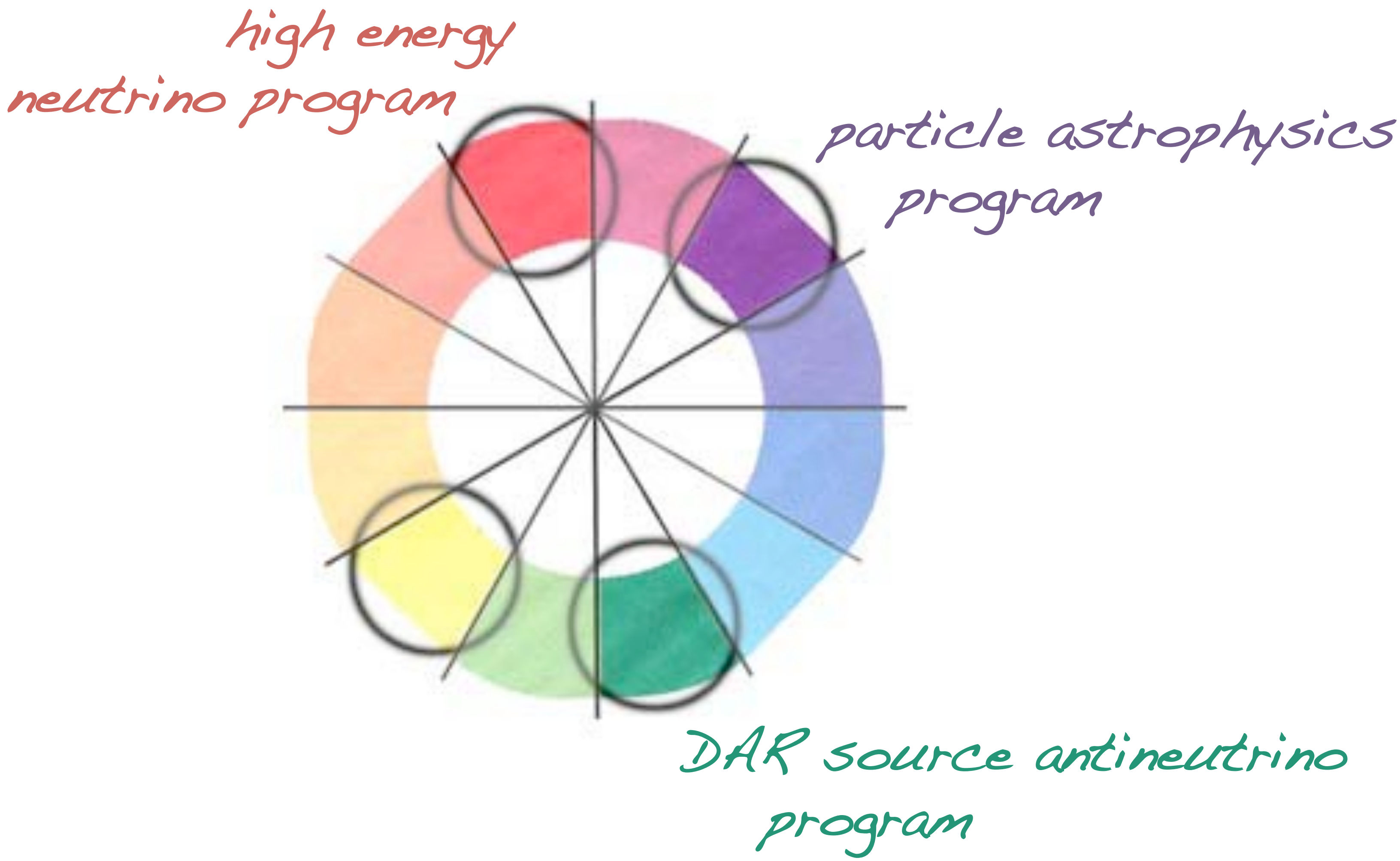
E.g.: NOνA
15 kton fiducial mass - 65m long
Look for oscillatory change in
ν_e-C rate vs. L/E



Cover "Reactor Anomaly" at 3σ with 100 to 1000 kW in 1 year!

This could be done at a shorter time scale, with a single low-power 800 MeV cyclotron!

LBNE + large detector at SURF + DAEδALUS



Backup

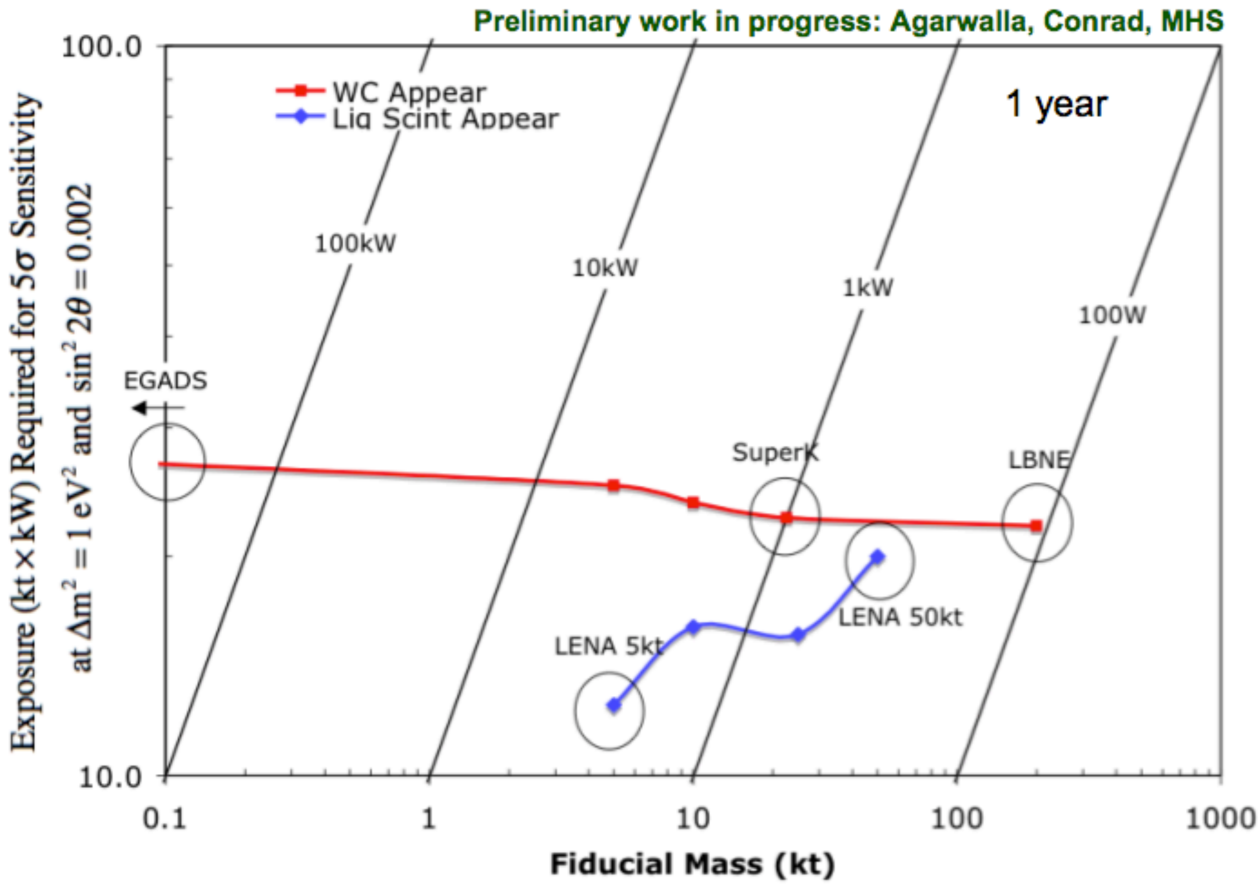
- Each Cyclotron properties:
  - Instantaneous: 800 MeV @ 6.25ma = 5 MW_{inst}
  - Average Power per cyclotron = 5 $MW_{inst} \times$ 20% DF = 1 MW_{AVG}

- Distributions of cyclotrons:
  - Near site: 1 cyclotron 20% DF $\Rightarrow P_{total}$ = 1 MW_{AVG}
  - Mid site: 2 cyclotron 20% DF $\Rightarrow P_{total}$ = 2 MW_{AVG}
  - Far site: 5 cyclotron 20% DF $\Rightarrow P_{total}$ = 5 MW_{AVG}
  - Beam off running with 40% DF to measure backgrounds

- Possible options
  - Have only near and far sites (keep each cyclotron at 1MW_{AVG})
    - Near (30% DF 4.2 ma_{inst}) Far (40% DF 3.12 ma_{inst}) Beam-off 30%
  - Raise average power limit per cyclotron from 1MW_{AVG} to 2MW_{AVG}
    - Near (20% DF 6.25 ma_{inst}) Far (50% DF 5.0 ma_{inst}) Beam-off 30%
    - Can reduce cyclotrons by two or get x2 more integrated power
  - Reduce beam off running from 40% to 20%
    - Can then reduce instantaneous power/current

VSBL $\bar{\nu}_e$ Appearance: Source Power and Detector Size for LSND Coverage at 5σ

Exposure = Detector Size (kton) × Cyclotron Power (kW)



VSBL ν_e Disappearance: Source Power and Detector Size for x10 Better Sensitivity Than Current

Exposure = Detector Size (kton) × Cyclotron Power (kW)