The DAEδALUS at Hyper-K Experiment: Searching for CP Violation

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for the DAEδALUS Collaboration

4th Open Meeting for the Hyper-Kamiokande Project

27-28 January 2014

DAEδALUS / IsoDAR Program

- DAEδALUS is a program to develop a new resource for Neutrino Physics.
  - The goal is to produce small sized and relatively inexpensive cyclotron-based decay-at-rest neutrino sources.
- This frees the program from being forced to match detectors to accelerator sites and opens up interesting new physics opportunities.
- This is a phased program with physics output at each stage
  - IsoDAR experiment is the second phase.
  - Full DAEδALUS for CP measurements as the final phase

The DAEδDALUS Collaboration

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[2]Argonne National Laboratory, Argonne IL, U.S.
[3]Bartoszek Engineering, Aurora IL, U.S.
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[8]Duke University, Durham NC, U.S.
[9]University of Huddersfield, Huddersfield, U.K.
[10]INFN-LNS, Catania, Italy
[11]Institute for the Physics and Mathematics of the Universe, Kashiwa, Japan
[12]Massachusetts Institute of Technology, Cambridge MA, U.S.
[13]New Mexico State University, Las Cruces NM, U.S.
[14]Northwestern University, Evanston IL, U.S.
[15]Paul Scherrer Institute, Villigen, Switzerland
[16]RIKEN, Wako, Japan
[17]University of Tennessee, Knoxville TN, U.S.
[18]Tohoku University, Sendai, Japan

Composed of particle, accelerator, and engineering physicists from universities, companies, and national labs.

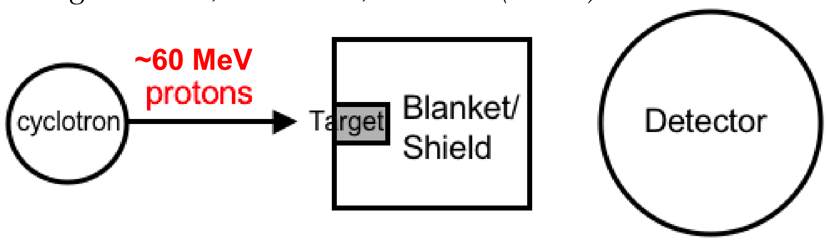
Daeδalus and IsoDAR Experiments

("Cyclotrons as Drivers for Precision Neutrino Measurements" - arXiv:1307.6465)

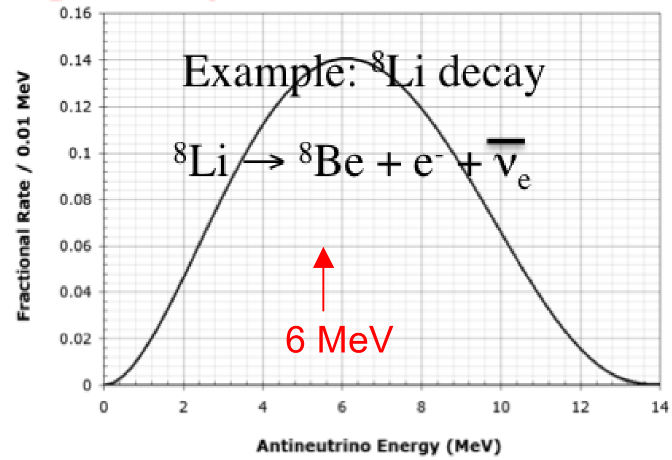
IsoDAR Setup:

Very short baseline search for sterile neutrinos

A. Bungau et al., PRL 109, 141802 (2012)



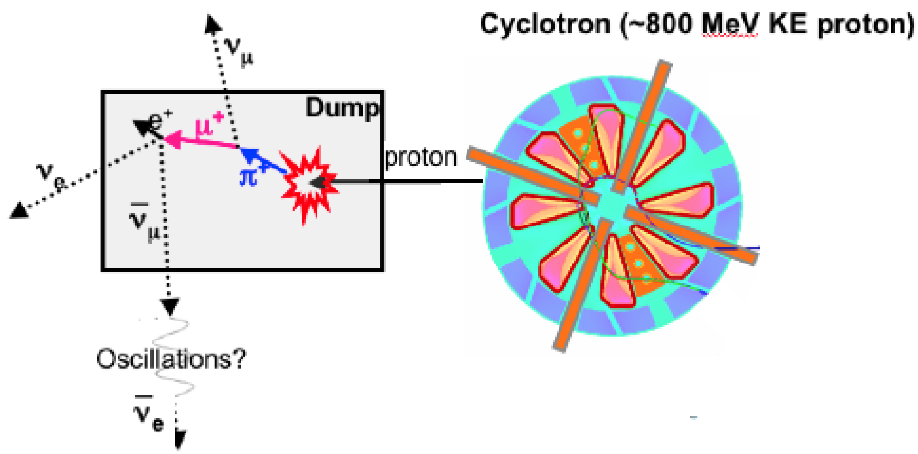
Isotope decay-at-rest



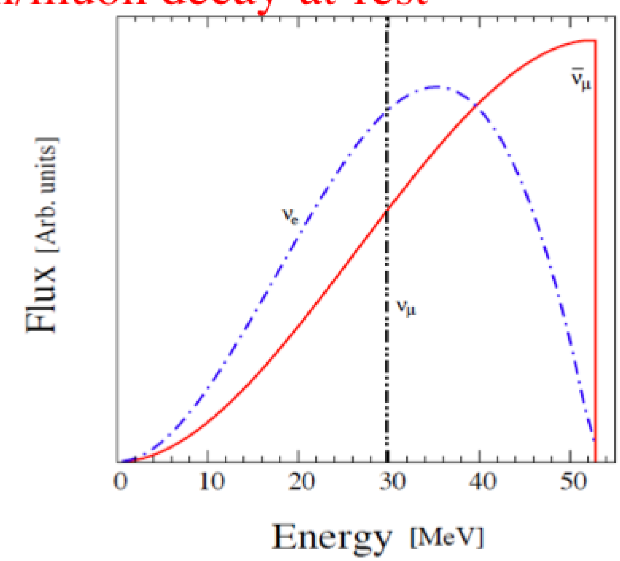
Daeδalus Setup:

A new way to search for CP violation in the ν-sector

J.M Conrad and M. H. Shaevitz, PRL 104, 141802 (2010)

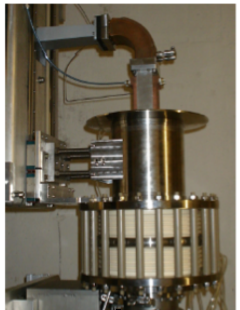


Pion/muon decay-at-rest



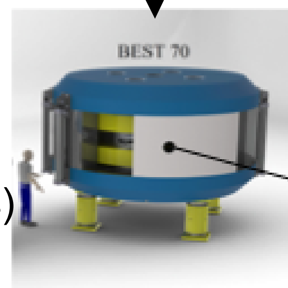
DAEδDALUS High Power (~1 MW) 800 MeV Cyclotron System (Under Development with Lab and Industrial Partners)

H_2^+ Ion Source

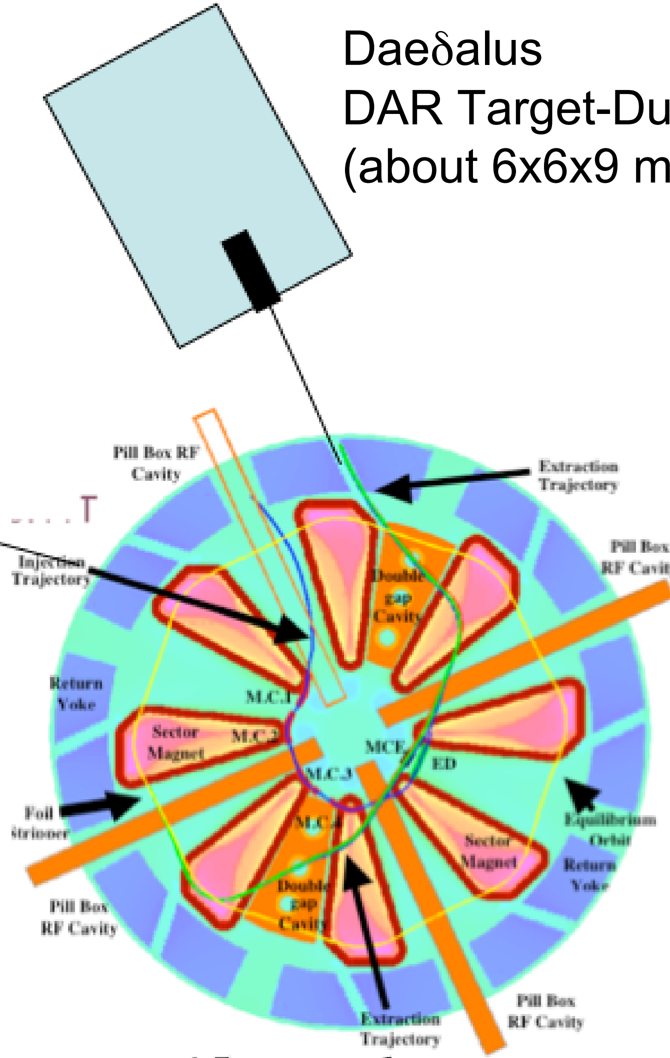


IsoDAR Cyclotron

Injector Cyclotron (Resistive Isochronous)



Daeδalus DAR Target-Dump (about 6x6x9 m^3)



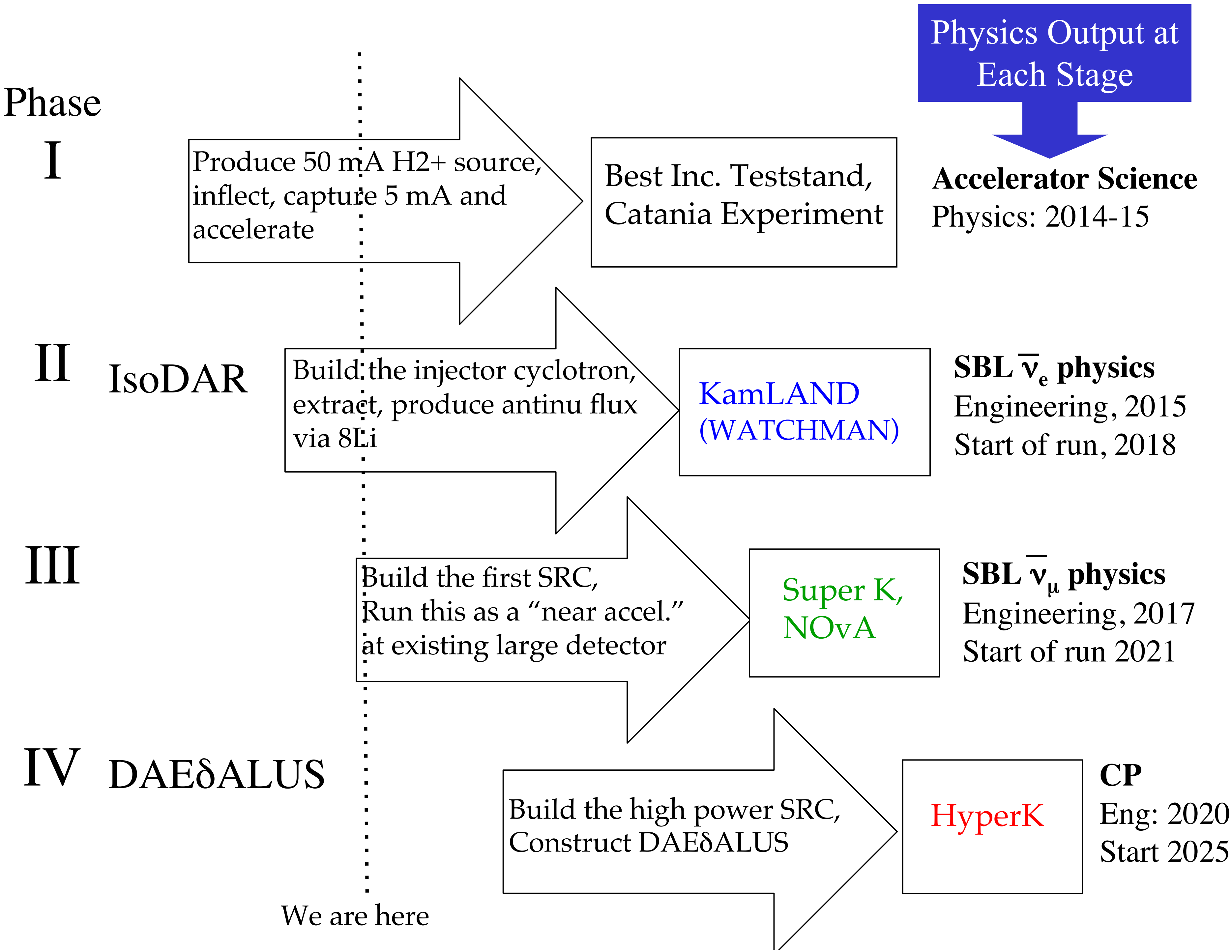
15 m total

Multimegawat Daeδalus Cyclotron for Neutrino Physics

arXiv:1207.4895

Superconducting Ring Cyclotron (SRC)

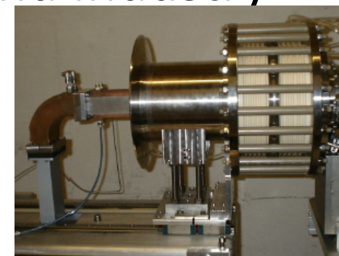
"Isochronous cyclotron" where mag. field changes with radius, but RF does not change with time. This can accelerate many bunches at once.



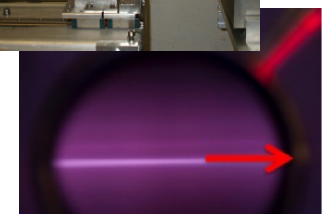
Physics Output at Each Stage
Phase
I
Produce 50 mA H2+ source, inflect, capture 5 mA and accelerate
Best Inc. Teststand, Catania Experiment
Accelerator Science
Physics: 2014-15
II
IsoDAR
Build the injector cyclotron, extract, produce antinu flux via 8Li
KamLAND (WATCHMAN)
SBL $\bar{\nu}_e$ physics
Engineering, 2015
Start of run, 2018
III
Build the first SRC, Run this as a “near accel.” at existing large detector
Super K, NOvA
SBL $\bar{\nu}_\mu$ physics
Engineering, 2017
Start of run 2021
IV
DAEδALUS
Build the high power SRC, Construct DAEδALUS
HyperK
CP
Eng: 2020
Start 2025
We are here

DAEδDALUS Cyclotron Accomplishments and Status

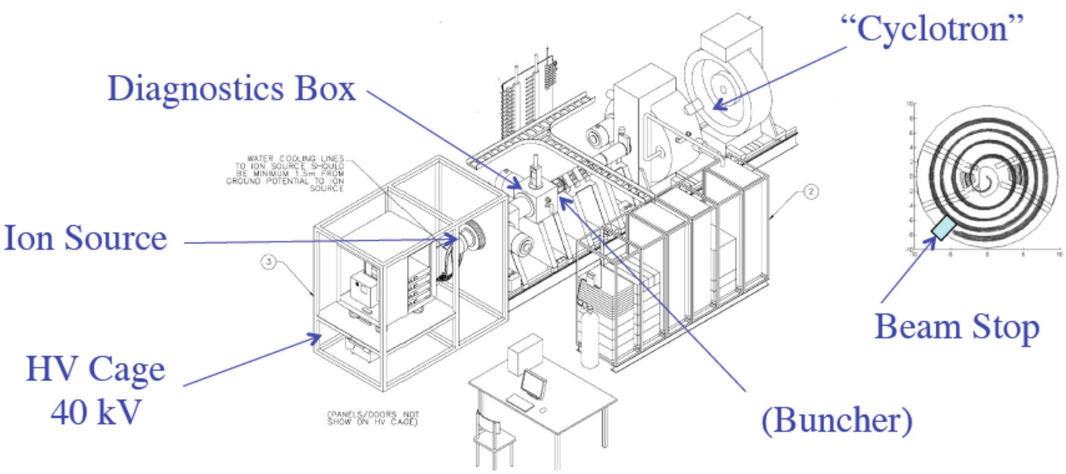
International Partnership Between Universities, Labs, and Industry

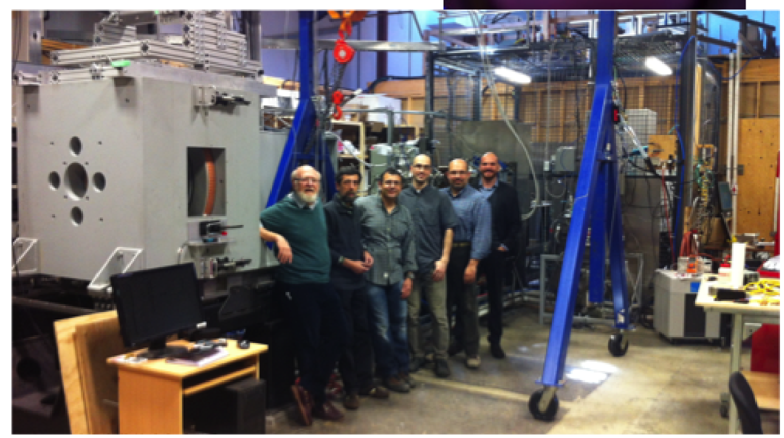


- Ion source developed by collaborators at INFN Catania
  - Reached adequate intensities for the system

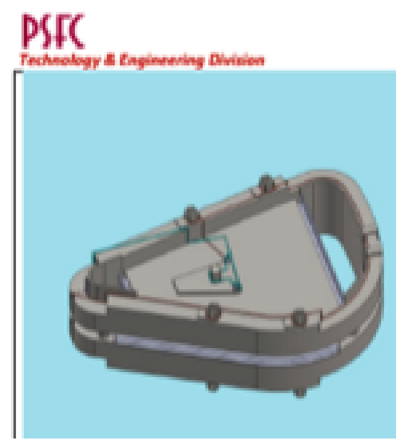


- Ion Source Beam and capture currently being characterized at Best Cyclotrons, Inc, Vancouver with INFN-Catania and MIT





- Engineering study of SRC magnet completed
  - Engineering design, Assembly plan, Structural analysis, Cryo system design (see arXiv:1209.4886)



The DAEδDALUS Experiment

Search for CP Violation using $\bar{\nu}_e$ Appearance with Pion Decay-at-Rest Neutrino Beams

Use L/E Dependence of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ to Measure δ_{CP}

$$P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) = \left(\sin^2\theta_{23}\sin^2 2\theta_{13}\right)\left(\sin^2\Delta_{31}\right)$$
$$\mp \underline{\sin\delta}\left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)\left(\sin^2\Delta_{31}\sin\Delta_{21}\right)$$
$$+ \underline{\cos\delta}\left(\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12}\right)\left(\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}\right)$$
$$+\left(\cos^2\theta_{23}\sin^2 2\theta_{12}\right)\left(\sin^2\Delta_{21}\right).$$

We want to see if δ is nonzero

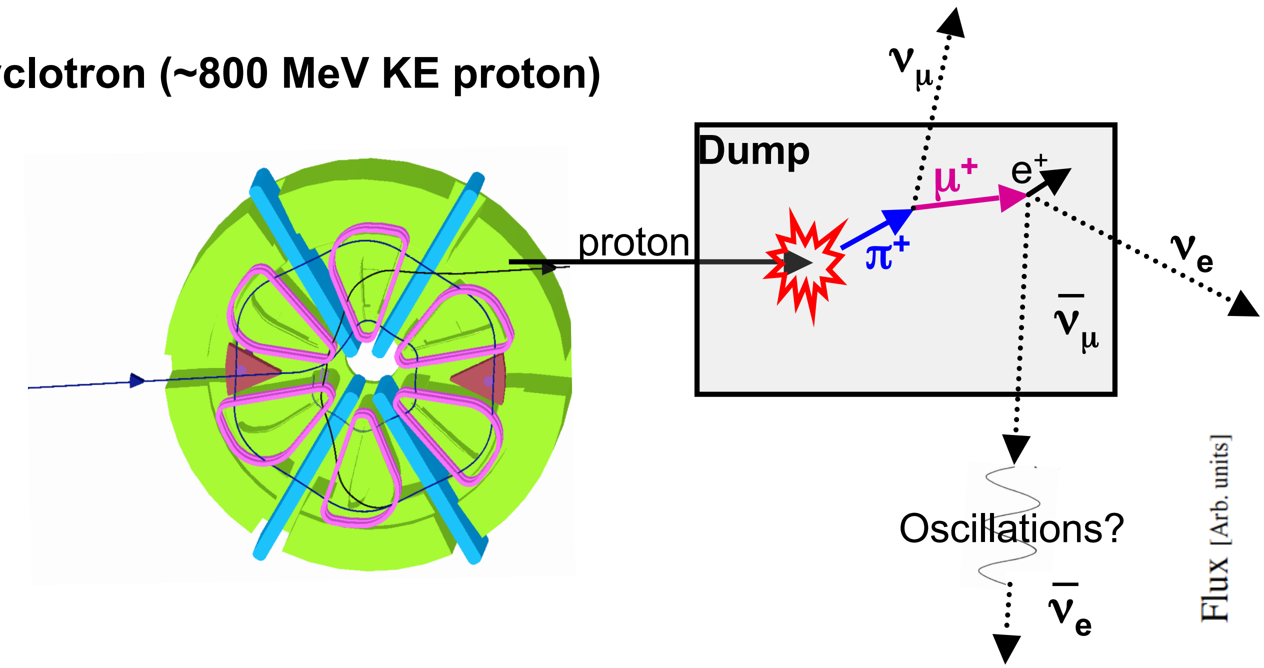
terms depending on mixing angles

terms depending on mass splittings

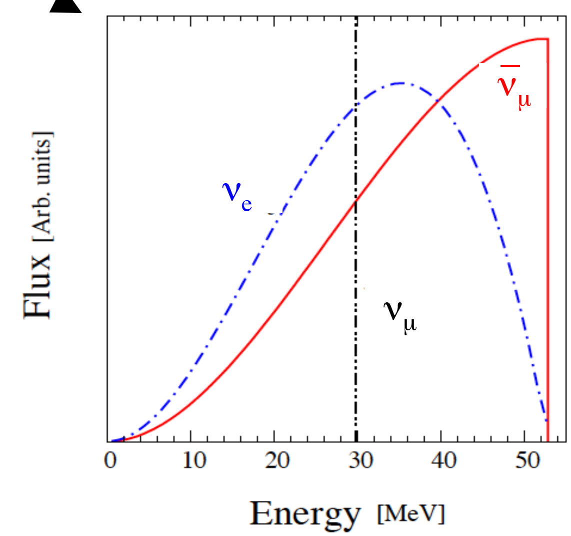
$$\Delta_{ij} = \Delta m^2_{ij} L / 4E_\nu$$

Use Multiple Neutrino Sources at Different Distances to Map Out $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Rate

Cyclotron (~800 MeV KE proton)

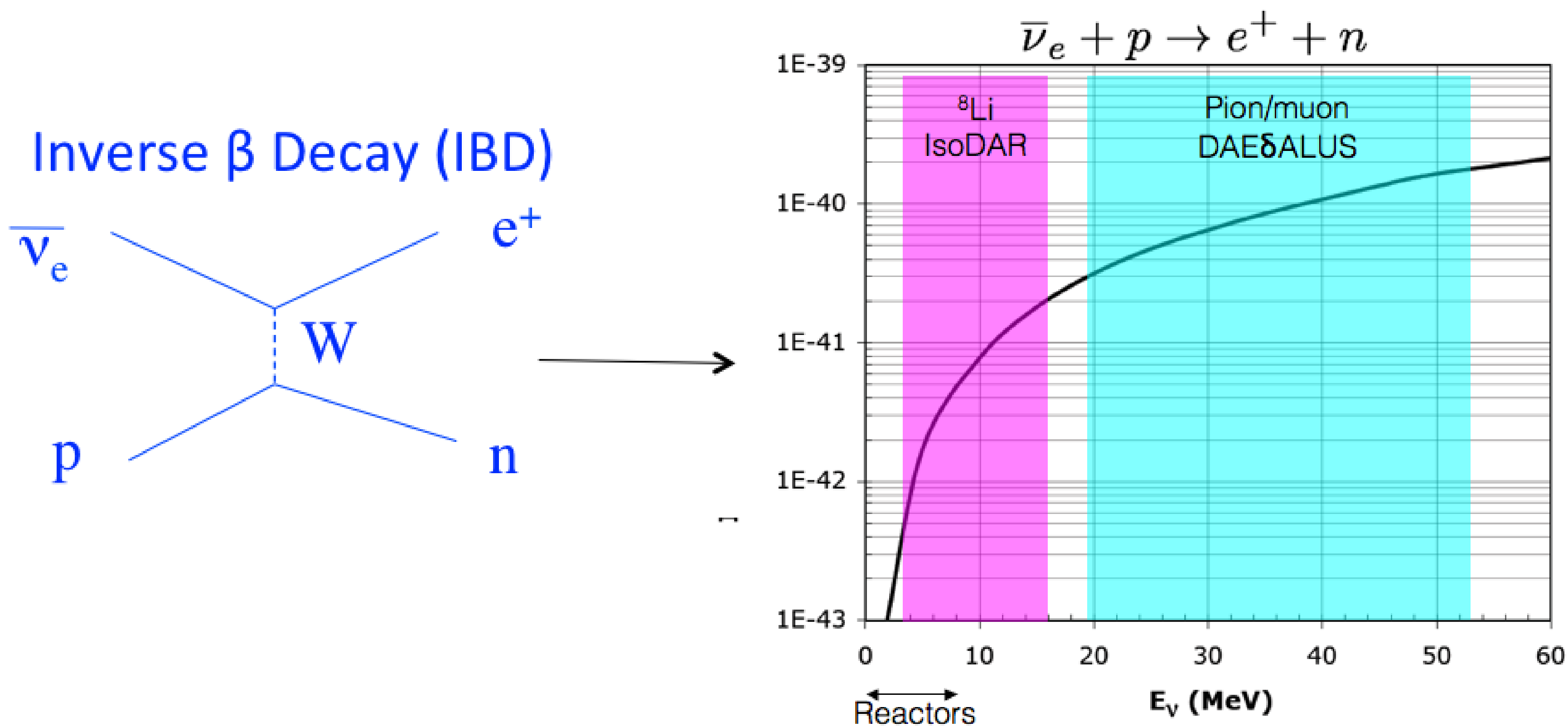


Each source produces a pure π/μ decay-at -rest beam at a different distances to the detector



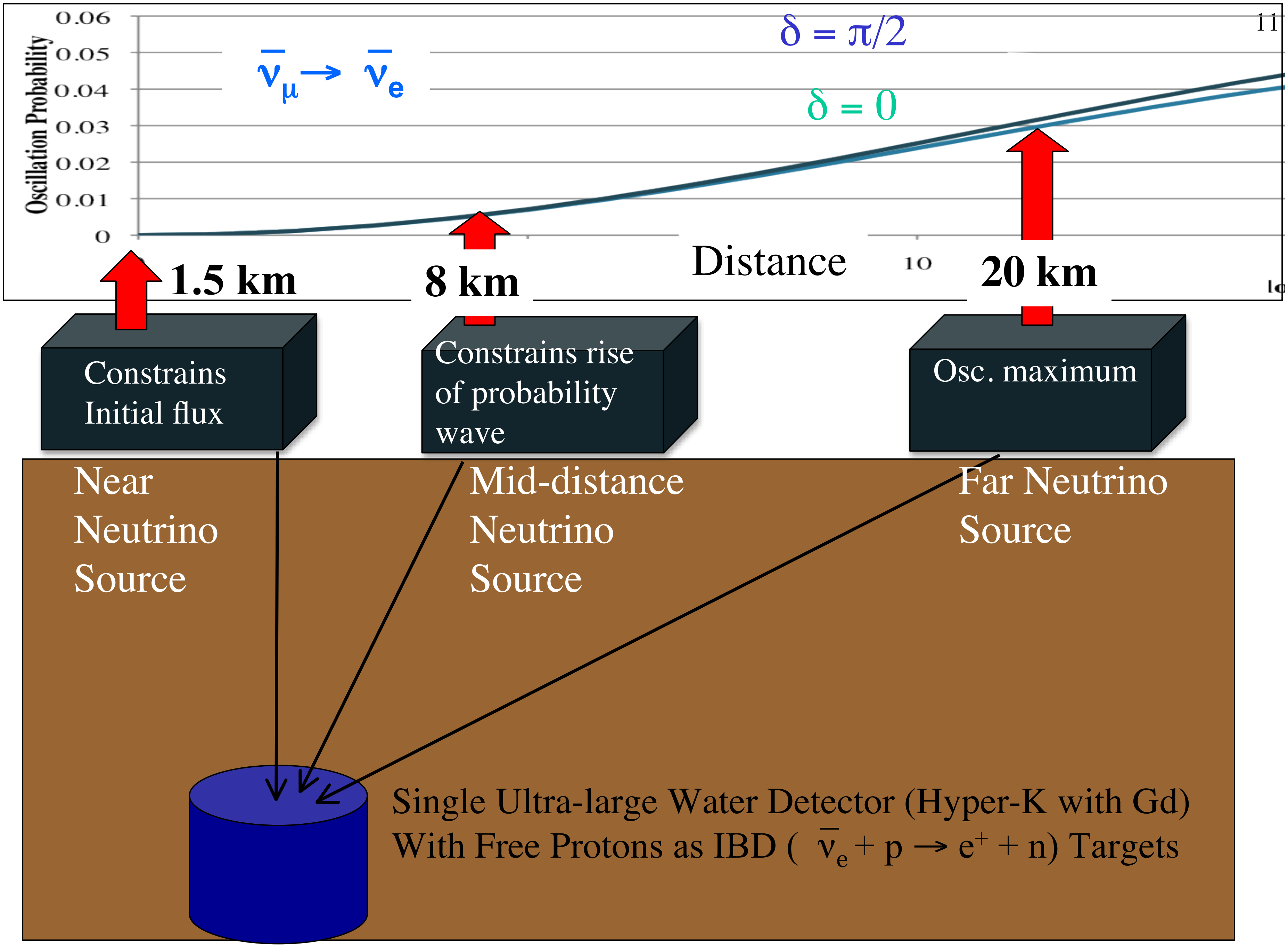
Very small $\bar{\nu}_e$ contamination in the beam so ideal to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

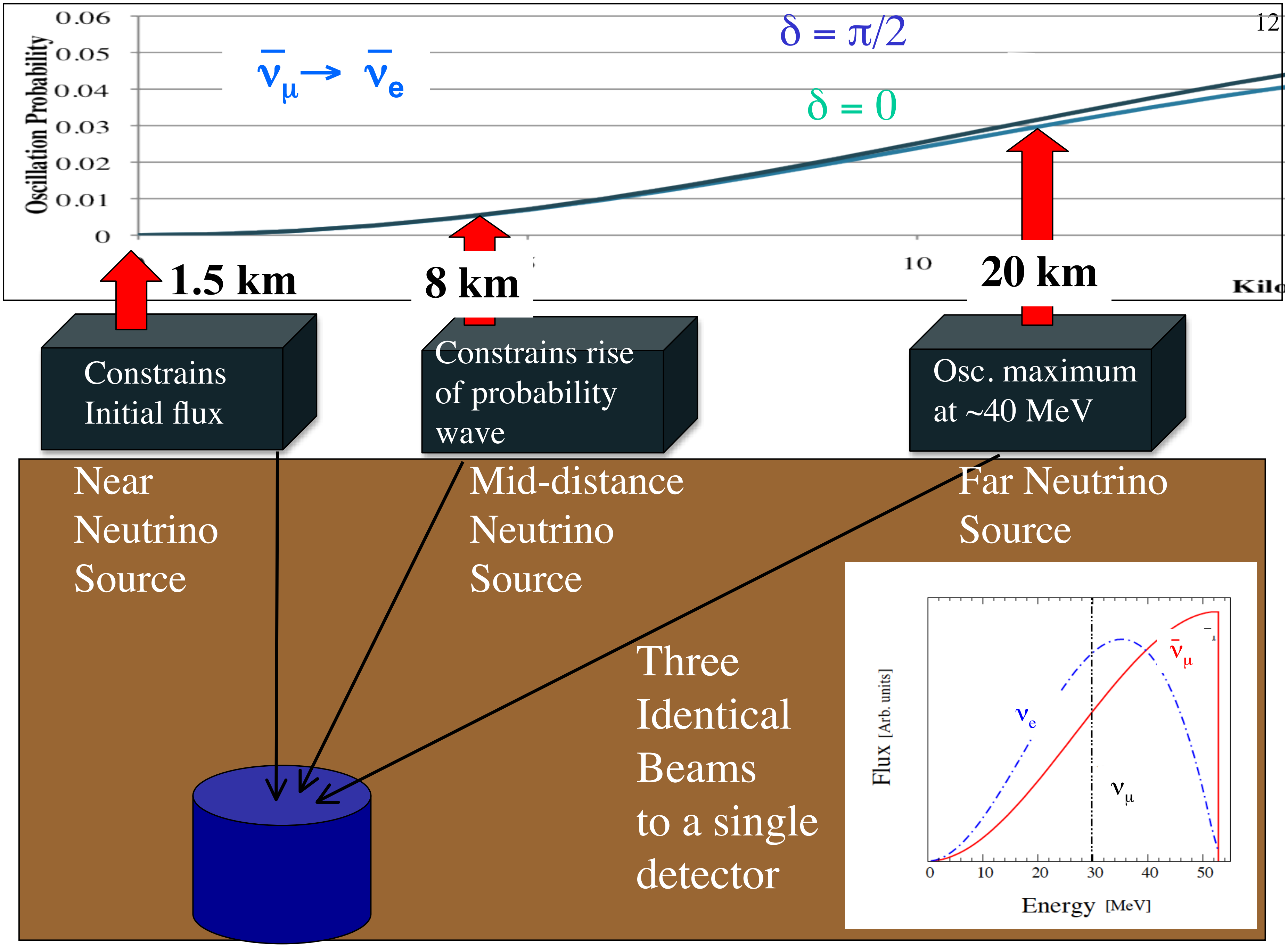
Detect $\overline{\nu}_e$ Events using Inverse Beta Decay (IBD)



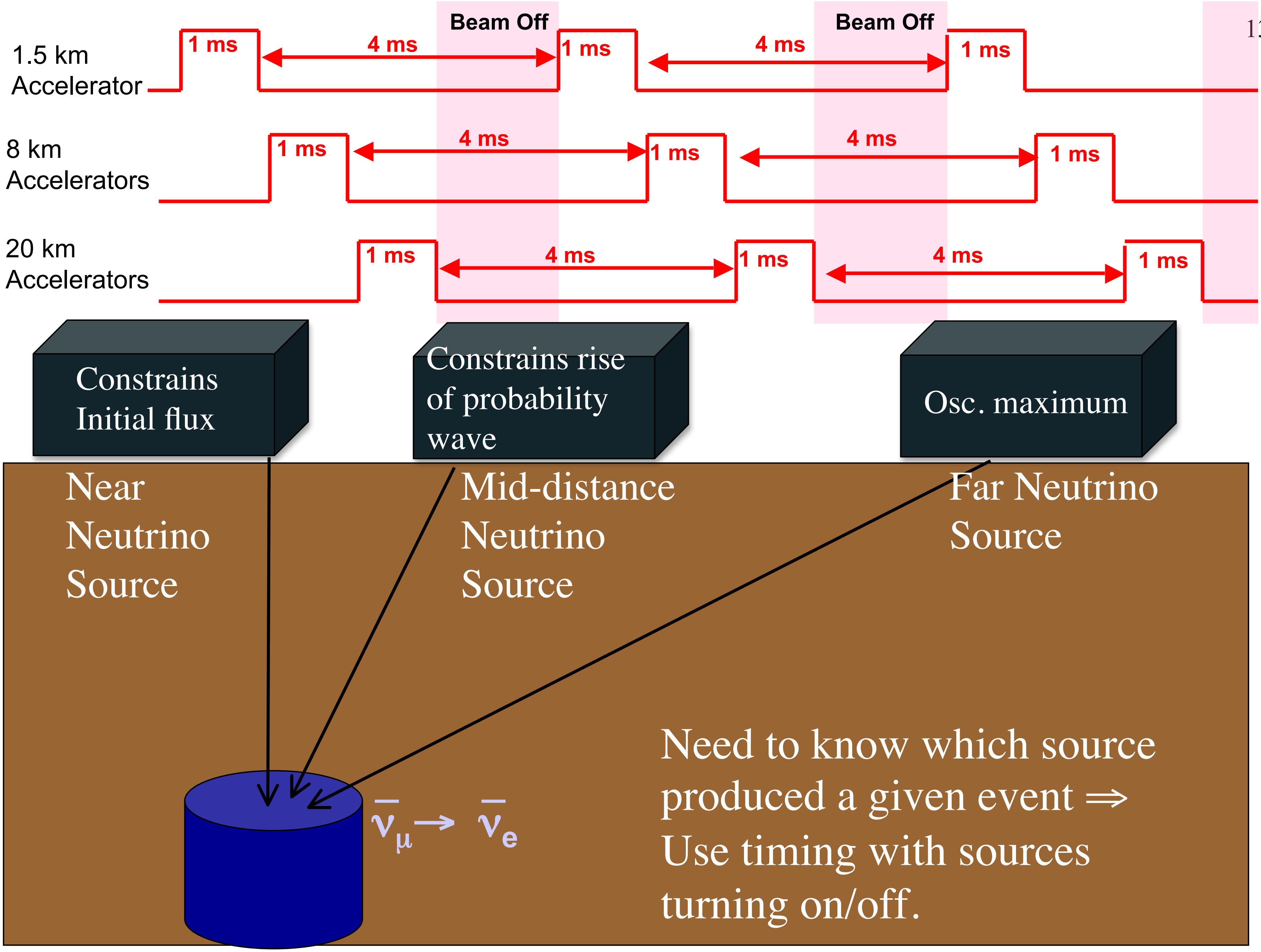
- Prompt positron followed by delayed coincidence from n capture
  $\Rightarrow$ For water detector need Gd doping
- Antineutrino energy well measured
  $\Rightarrow$ $E_{\bar{\nu}e} = E_{prompt} + 0.78$ MeV

- IBD Cross section known very accurately
- Very small systematic uncertainty for a neutrino oscillation analysis


Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\delta = \pi/2$
$\delta = 0$
Distance
10
1.5 km
8 km
20 km
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
Single Ultra-large Water Detector (Hyper-K with Gd)
With Free Protons as IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$) Targets



12
Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
10
Kilo
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\delta = \pi/2$
$\delta = 0$
1.5 km
8 km
20 km
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum at ~40 MeV
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
Three Identical Beams to a single detector
Flux [Arb. units]
Energy [MeV]
0
10
20
30
40
50
ν_e
$\bar{\nu}_\mu$
ν_μ



Beam Off
Beam Off
1.5 km
Accelerator
1 ms
4 ms
1 ms
4 ms
1 ms
8 km
Accelerators
1 ms
4 ms
1 ms
4 ms
1 ms
20 km
Accelerators
1 ms
4 ms
1 ms
4 ms
1 ms
Constrains Initial flux
Constrains rise of probability wave
Osc. maximum
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Need to know which source produced a given event ⇒ Use timing with sources turning on/off.

DAEδALUS Measurement Strategy

Using the **near** neutrino source
measure **absolute flux normalization** with ν_e-e events to ~1%,
Also, measure the (ν_eO) event rate.

↓

At far and mid-distance neutrino source,
Compare predicted to measured ν_eO event rates.
to get the **relative flux normalizations between 3 sites**

↓

For all three neutrino sources,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with δ as a free parameter

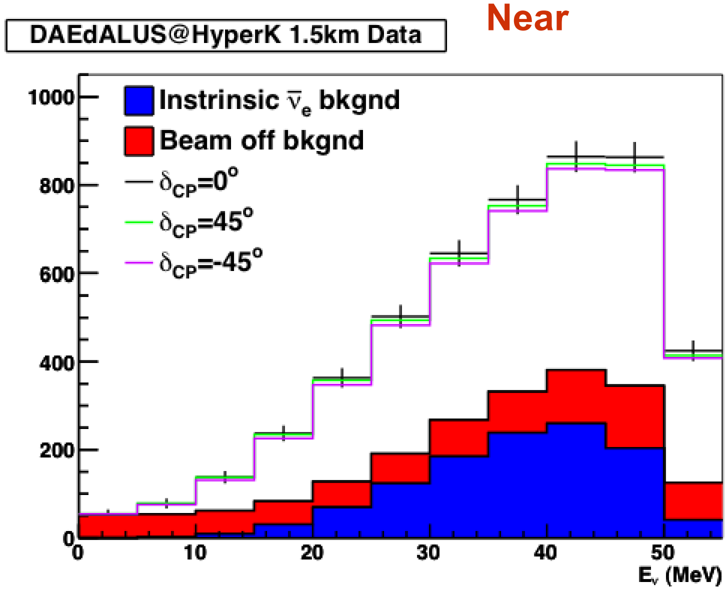
DAEδALUS at Hyper-K Event Statistics for 10 yrs

	Event Type	1.5 km	8 km	20 km
	IBD Oscillation Events ($E_{vis} > 20$ MeV)			
Oscillation Signal Events	$\delta_{CP} = 0^0$, Normal Hierarchy	2660	4456	4417
	” , Inverted Hierarchy	1838	3268	4338
	$\delta_{CP} = 90^0$, Normal Hierarchy	2301	4322	5506
	” , Inverted Hierarchy	2301	4328	5556
	$\delta_{CP} = 180^0$, Normal Hierarchy	1838	3263	4295
	” , Inverted Hierarchy	2660	4462	4460
	$\delta_{CP} = 270^0$, Normal Hierarchy	2197	3397	3206
	” , Inverted Hierarchy	2197	3402	3242
Beam $\bar{\nu}_e$ Bkgnd	IBD from Intrinsic $\bar{\nu}_e$ ($E_{vis} > 20$ MeV)	1119	79	31
Non-Beam Background	IBD Non-Beam ($E_{vis} > 20$ MeV)			
	atmospheric $\nu_\mu p$ “invisible muons”	505	505	505
	atmospheric IBD	103	103	103
	diffuse SN neutrinos	43	43	43
Absolute Norm	$\nu - e$ Elastic ($E_{vis} > 10$ MeV)	40025	2813	1123
Relative Norm	$\nu_e -$oxygen ($E_{vis} > 20$ MeV)	188939	13281	5305

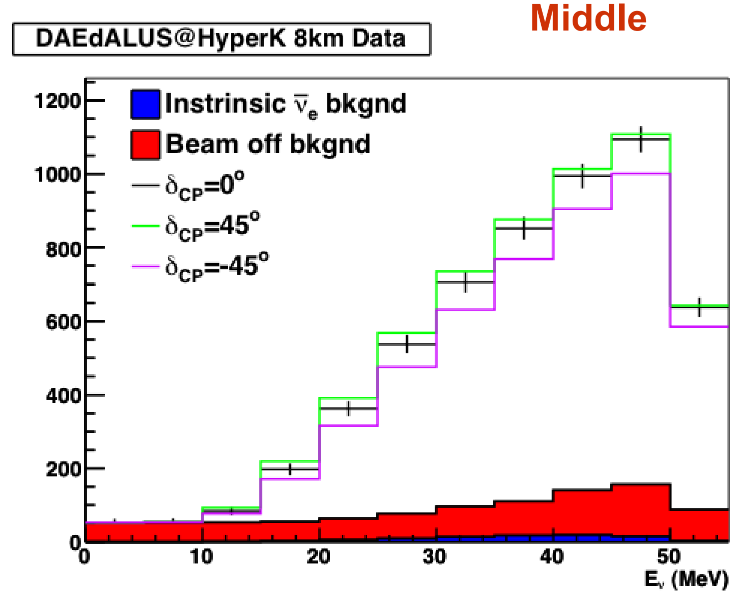
$\sin^2 2\theta_{13} = 0.10$

DAEδALUS at Hyper-K Event vs Energy for 10 yrs

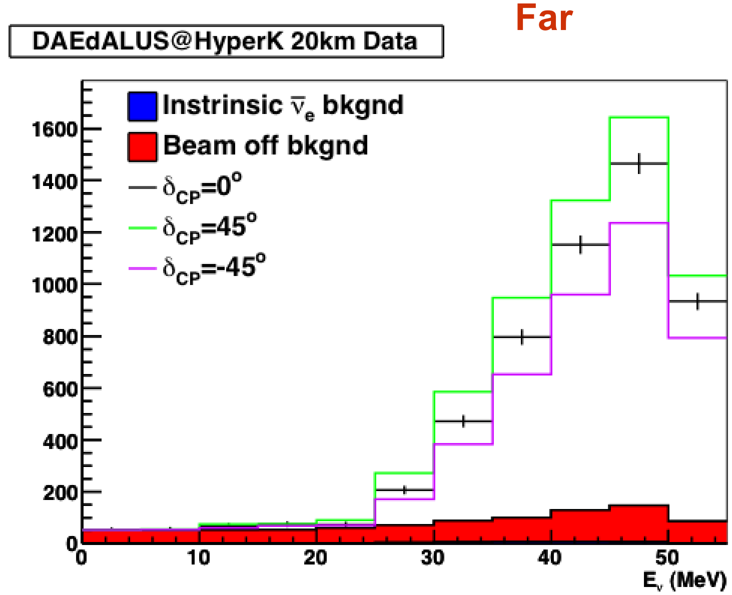
Near



Middle



Far



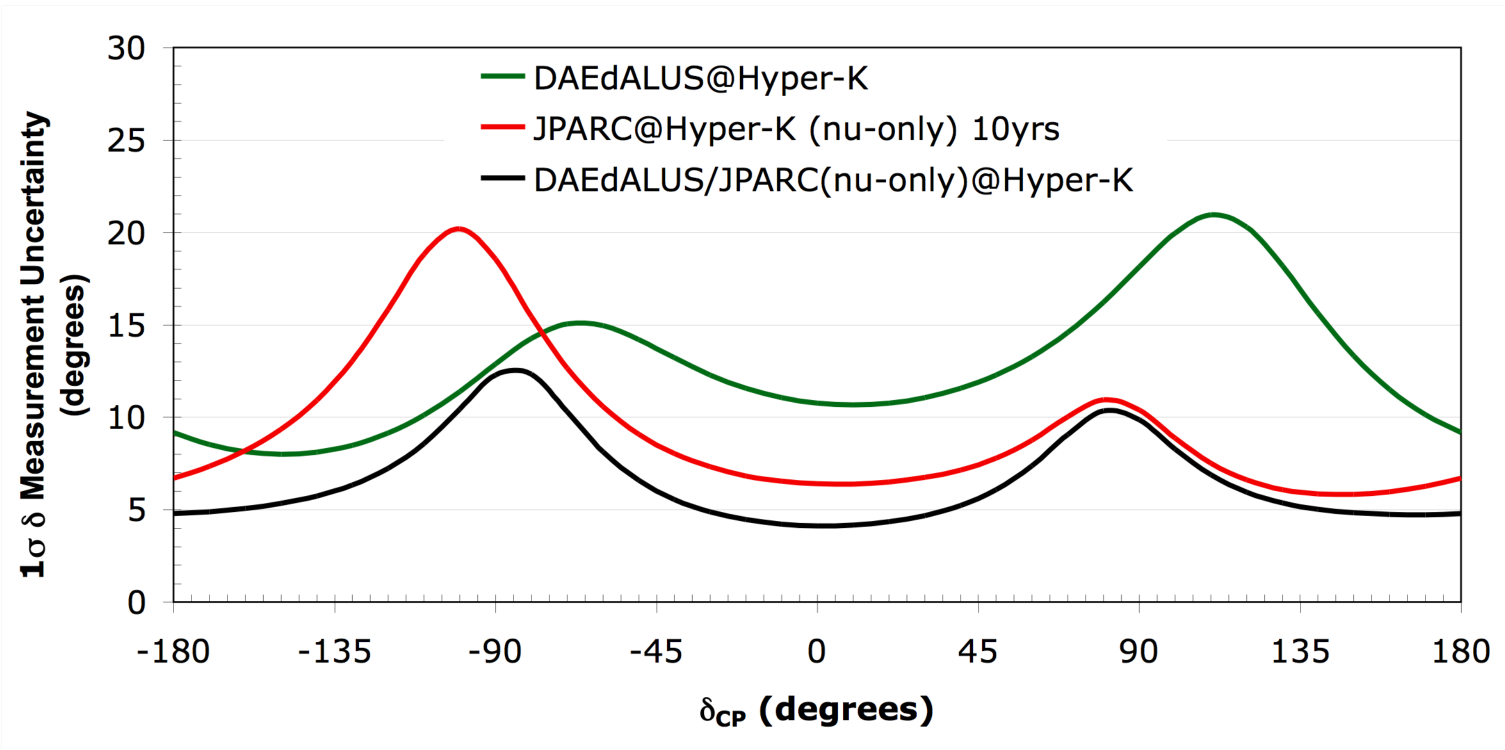
$\sin^2 2\theta_{13} = 0.10$

Configurations Considered for δ_{CP} Sensitivity Studies

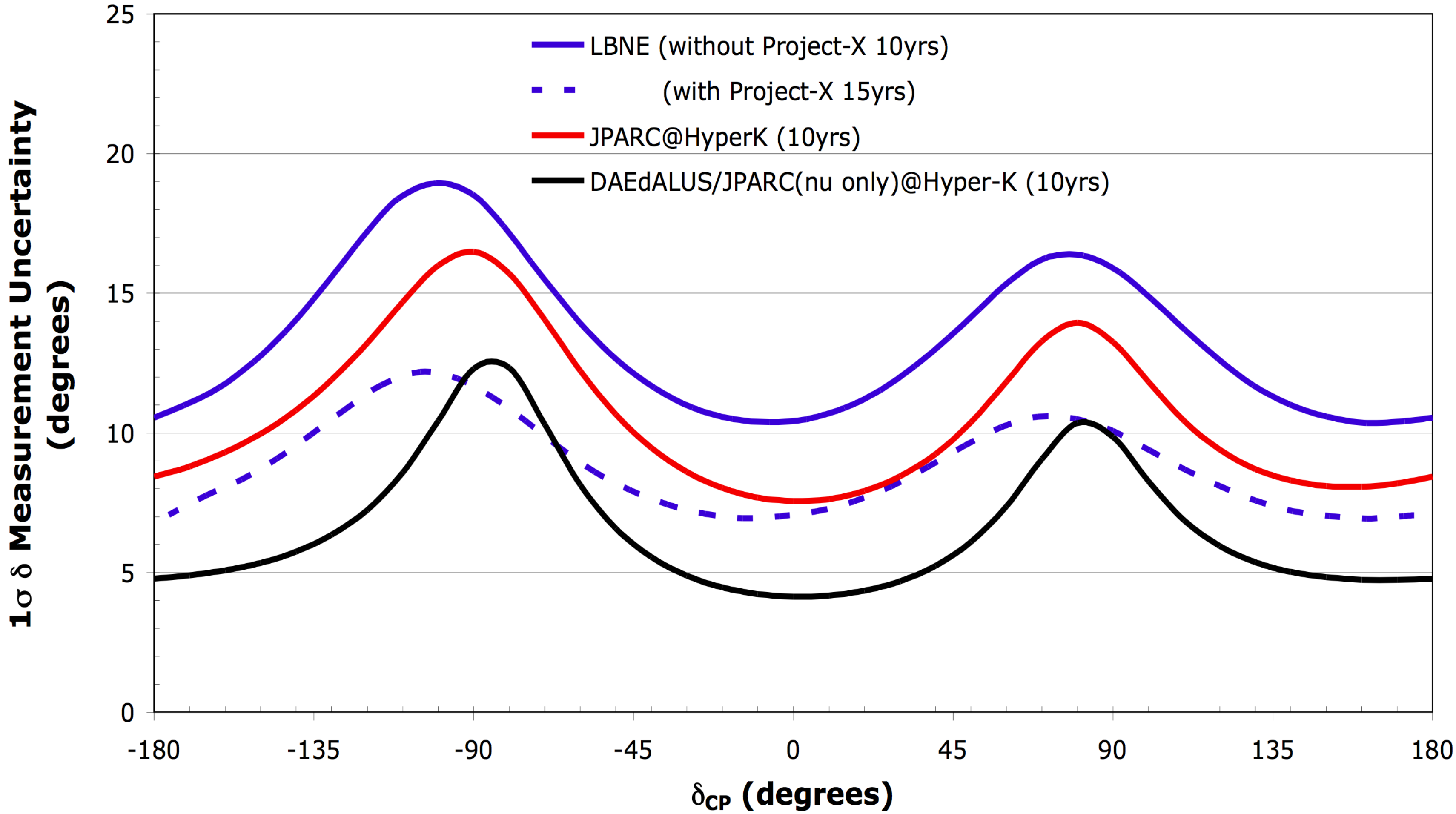
Configuration Name	Source(s)	Average Long Baseline Beam Power	Detector	Fiducial Volume	Run Length
DAEδALUS@Hyper-K	DAEδALUS only	N/A	Hyper-K	560 kt	10 years
DAEδALUS/JPARC (nu only)@Hyper-K	DAEδALUS & JPARC	750 kW	Hyper-K	560 kt	10yrs $\bar{\nu}$ DAEδALUS + 10yrs ν-only JPARC
JPARC@Hyper-K	JPARC	750 kW	Hyper-K	560 kt	3 years ν + 7 years $\bar{\nu}$ [106]
LBNE	FNAL	850 kW	LBNE	35 kt	5 years ν 5 years $\bar{\nu}$ [100]

CP Violation Sensitivity

- Daeδalus has good CP sensitivity as a stand-alone experiment.
  - Small cross section, flux, and efficiency uncertainties
- Daeδalus can also be combined with Hyper-K ν-only data to give enhanced δ_{CP} sensitivity
  - Long baseline experiments have difficulty obtaining good statistics for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ which Daeδalus can provide
  - Daeδalus has no matter effects so can help remove ambiguities.

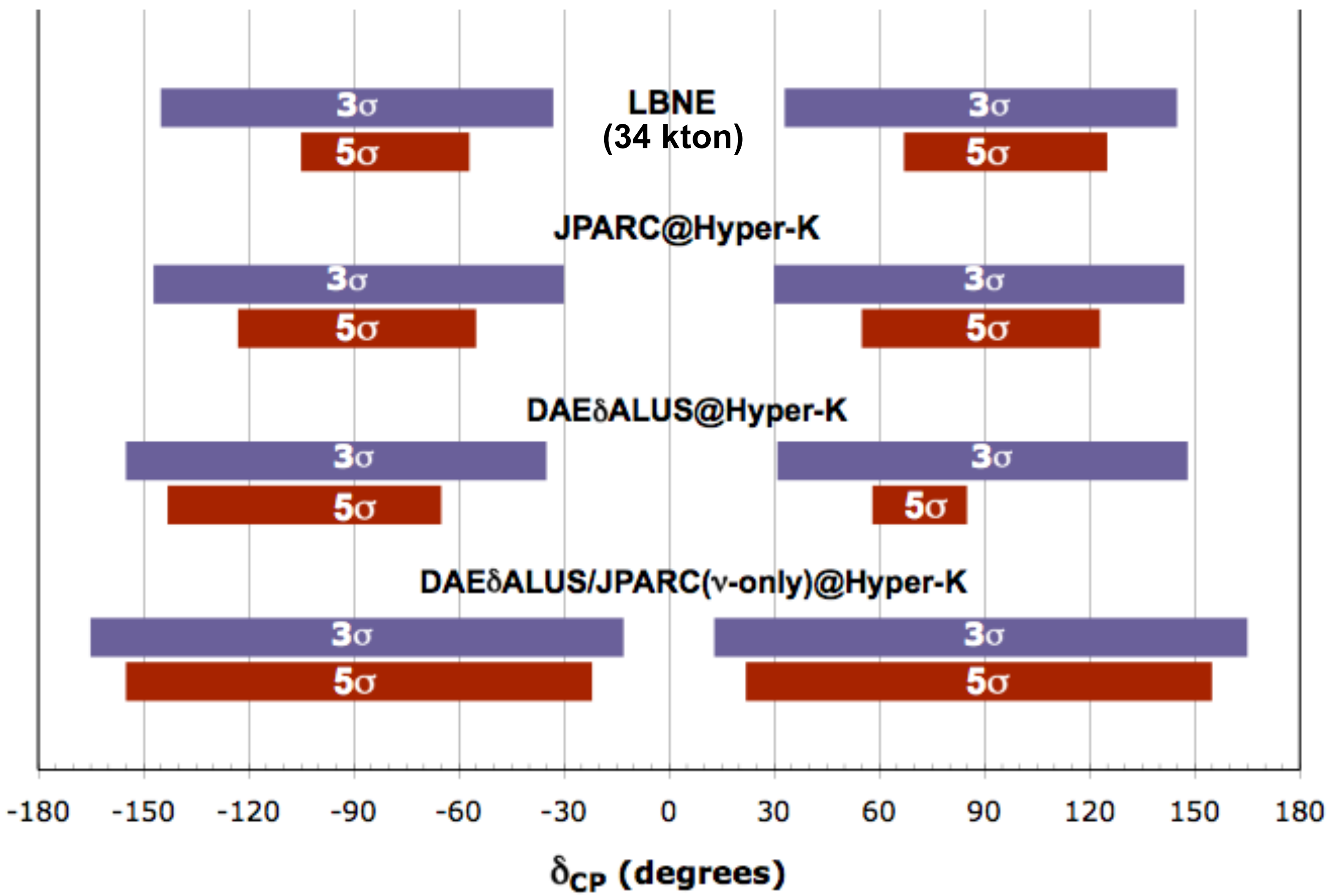


δ_{CP} Sensitivity Compared to Others

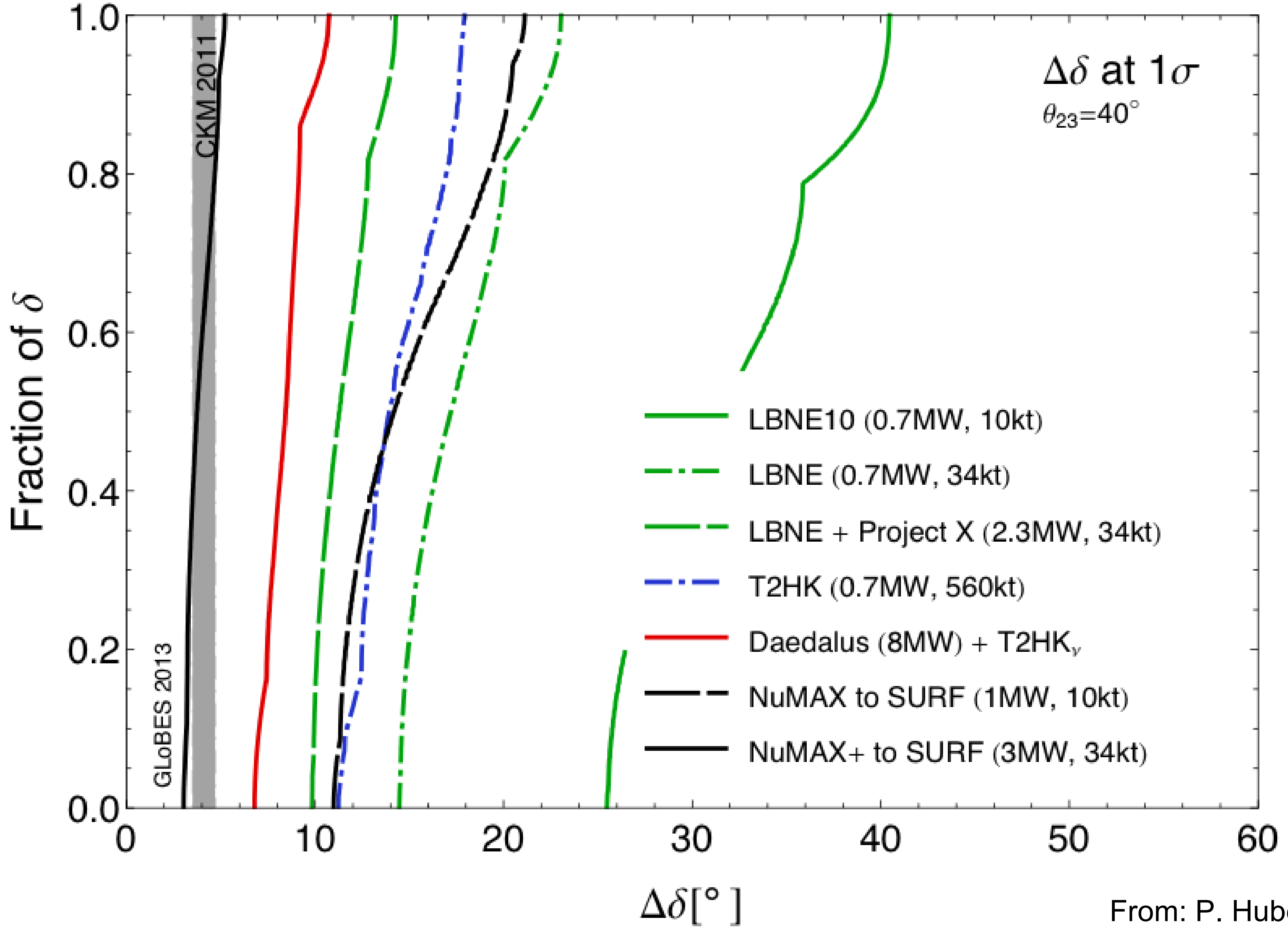


δ_{CP} Discovery Potential

(exclude 0^0 and 180^0 with σ significance in 10yrs)



Comparison of δ_{CP} Measurement Uncertianties



From: P. Huber
Globes 2013

DAEδALUS Top Level Cost Estimate

- $130M near accelerator plus $320M for 2nd and 3rd sites.
  - Includes various contingencies from 20% to 50%.
  - Assumes component costs drop by 50% after prod. of 1st item.
  - Does not include site specific cost (buildings)
- The cyclotron magnet is the cost driver.
  - For this we have: Engineering Study for Daedalus Sector Magnet; Minervini, et al., arXiv:1209.4886
- The RF is based on the PSI design and scaled from those costs.
- The strong similarity to RIKEN cyclotron allows cost cross check.
- All targets are ~1 MW (similar to existing targets), note each cyclotron can have more than one target to maintain the power level on each.

Final Comments

- High-power (~1MW) class cyclotrons are becoming a reality
  - For physics, they can provide high intensity neutrino sources
  - Important industrial interest for medical isotope production
  - Other applications in connection with accelerator driven reactors (ADS)

- IsoDAR using the Phase I DAEδALUS injector cyclotron can make a definitive search for sterile neutrinos at KamLAND

- DAEδALUS is another method to probe for CP violation in the ν-sector
  - Can provide high statistics $\bar{\nu}_e$ appearance data with no matter effects and reduced systematic uncertainties
  - Can give enhanced sensitivity when combined with Hyper-K long baseline ν_e appearance data

Backup

Method Uses $\Delta\chi^2$ with Pull Terms (Inspired by previous Hyper-K studies)

same

ν run

$$\chi^2 = \sum_i^{for\ \nu} \Big[N^i - (1+f^{\nu}_{\rm norm}) \Big\{ n^i_{\nu_\mu \to \nu_e, QE} + (1+f^{\nu}_{nQE}) n^i_{\nu_\mu \to \nu_e, nQE} + n^i_{\bar{\nu}_\mu \to \bar{\nu}_e} + (1+f^{\nu}_{\nu_\mu})(n^i_{\nu_\mu} + n^i_{\bar{\nu}_\mu}) + (1+f^{\nu}_{\nu_e})(n^i_{\nu_e} + n^i_{\bar{\nu}_e}) \Big\} \Big]^2 / N^i$$

antiν run

wrong sign

$$+ \sum_i^{for\ \bar{\nu}} \Big[N^i - (1+f^{\bar{\nu}}_{\rm norm}) \Big\{ n^i_{\bar{\nu}_\mu \to \bar{\nu}_e, QE} + (1+f^{\bar{\nu}}_{nQE}) n^i_{\bar{\nu}_\mu \to \bar{\nu}_e, nQE} + (1+f^{\bar{\nu}}_{\bar{\nu}_\mu}) n^i_{\bar{\nu}_\mu} + (1+f^{\bar{\nu}}_{\bar{\nu}_e}) n^i_{\bar{\nu}_e} \Big\} + (1+f^{\bar{\nu}}_{\rm WS}) \Big[n^i_{\nu_\mu \to \nu_e, QE} + (1+f^{\nu}_{nQE}) n^i_{\nu_\mu \to \nu_e, nQE} + (1+f^{\bar{\nu}}_{\nu_\mu}) n^i_{\nu_\mu} + (1+f^{\bar{\nu}}_{\nu_e}) n^i_{\nu_e} \Big] \Big]^2 / N^i$$

$$+ \sum_{\rm syst.\ par} \frac{f^2}{\sigma^2}$$

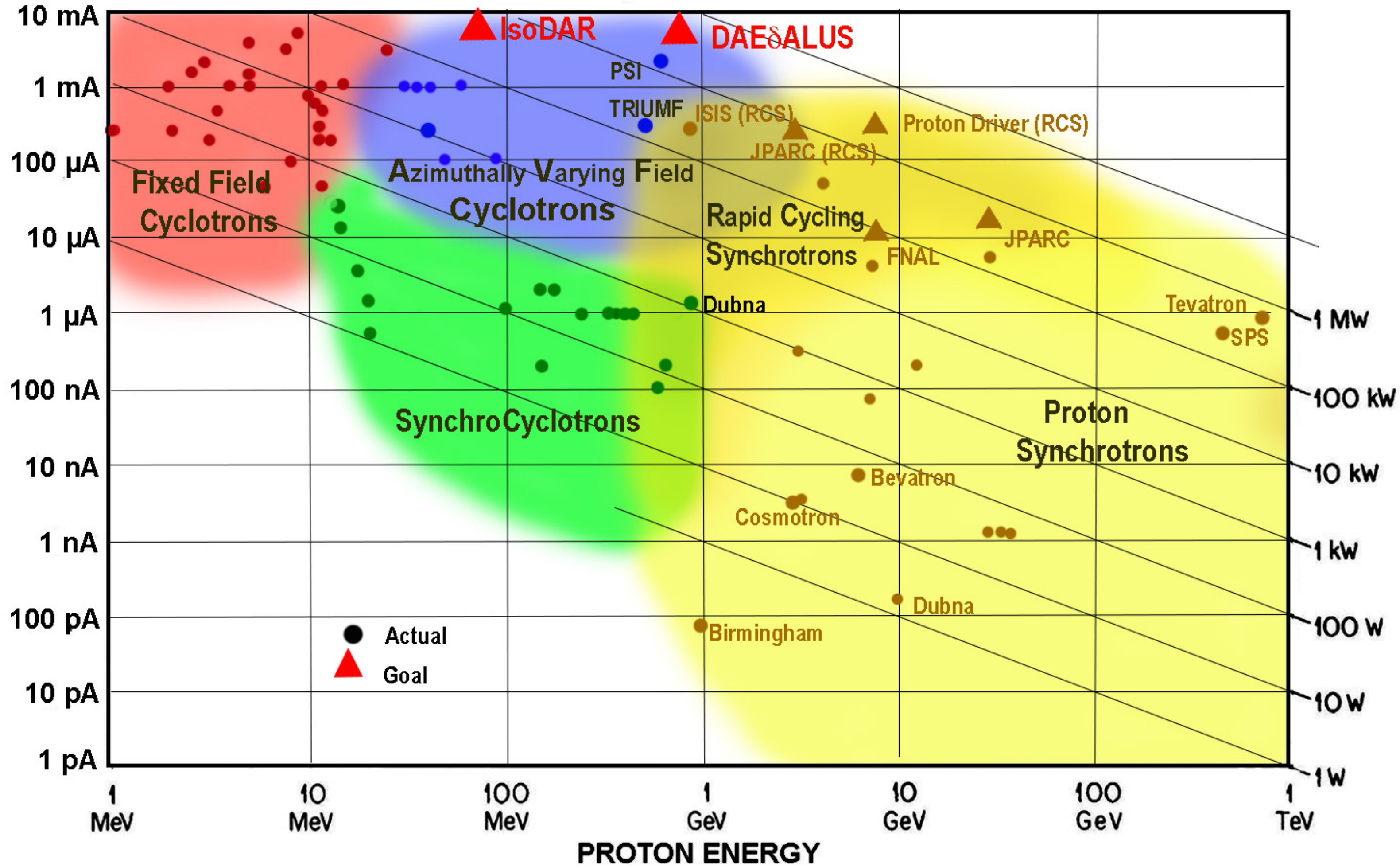
Assumptions for studies:

$\Delta m^2 = 2.4 \pm 0.05 \times 10^{-3}\ \mathrm{eV}^2$ Systematic $\sigma = 5\%$

$\sin^2 2\theta_{13} = 0.10 \pm 0.005$

$\sin^2 \theta_{23} = 0.57 \pm 0.01$

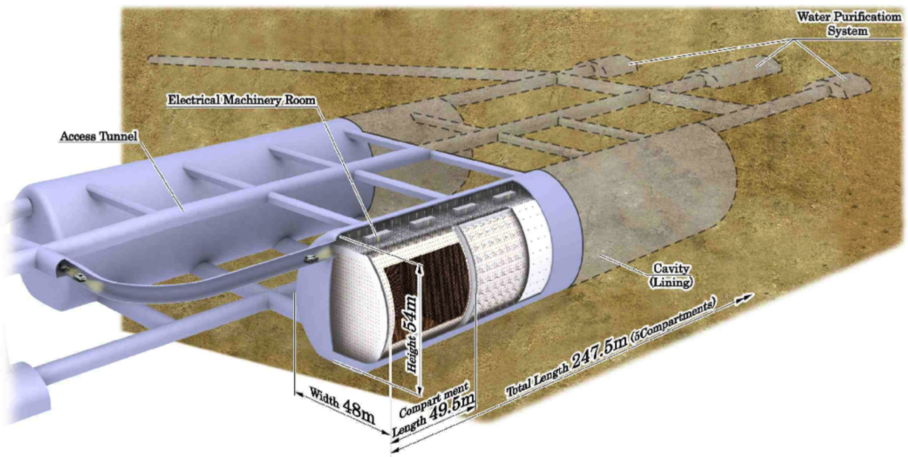
Accelerator Technologies

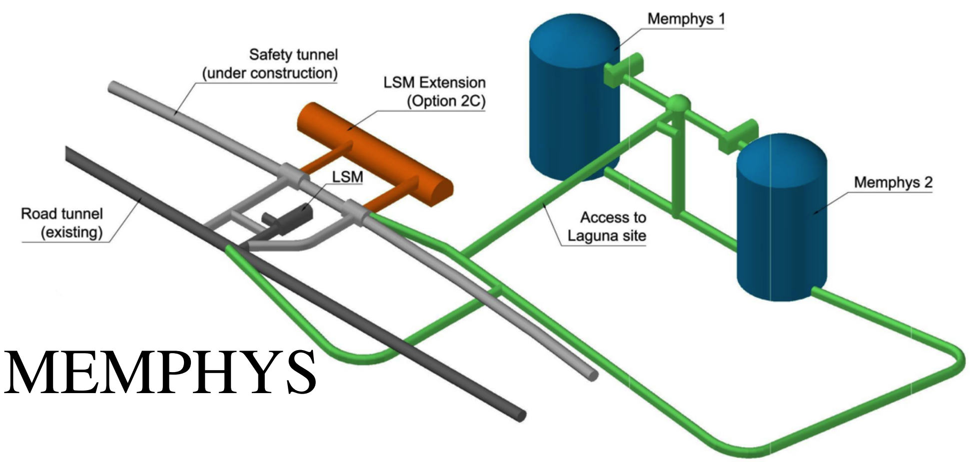


Where can DAEδALUS run?

Hyper-K (or initially, Super-K)

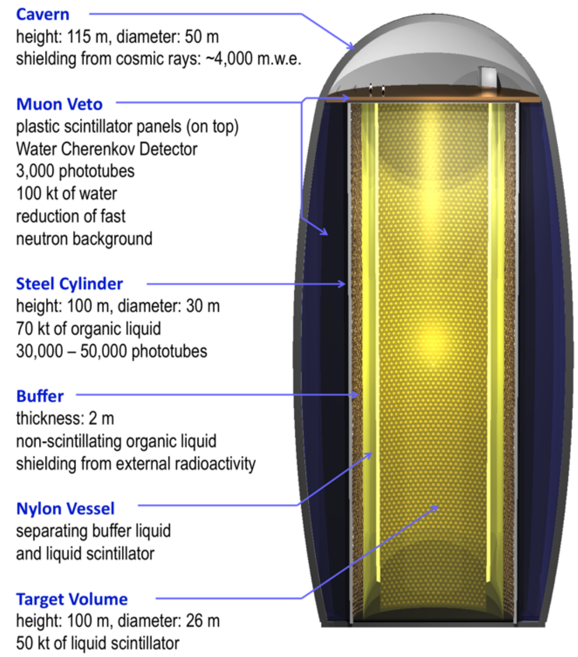
(Focus for current studies)





MEMPHYS

LENA - Scintillator Dectector



Detector needs to have free protons to capture neutrons from IBD ⇒ liquid argon is not an option