DAEδALUS

A Path to Measuring δ_{CP} Using Cyclotron Decay-at-Rest Neutrino Sources

Snowmass 2013

Matt Toups, MIT

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ Oscillations at $2\pi E/L \sim \left|\Delta m^2_{13}\right|$ Are Sensitive to δ_{CP}

in a vacuum…

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

We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

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

The Traditional Approach To $\overset{(-)}{\nu}_e$ Appearance:

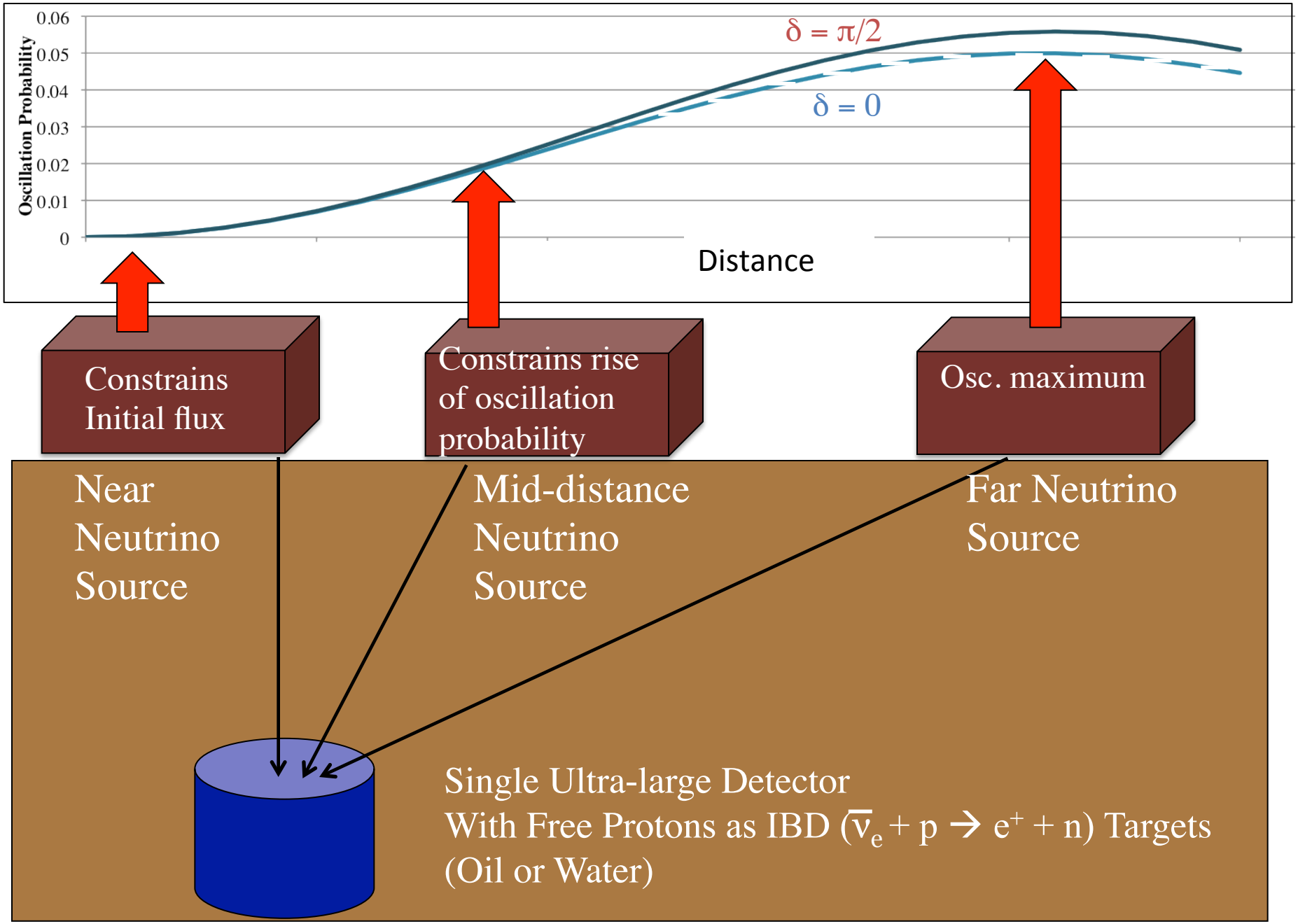
Single neutrino source

Multiple neutrino detectors at different baselines

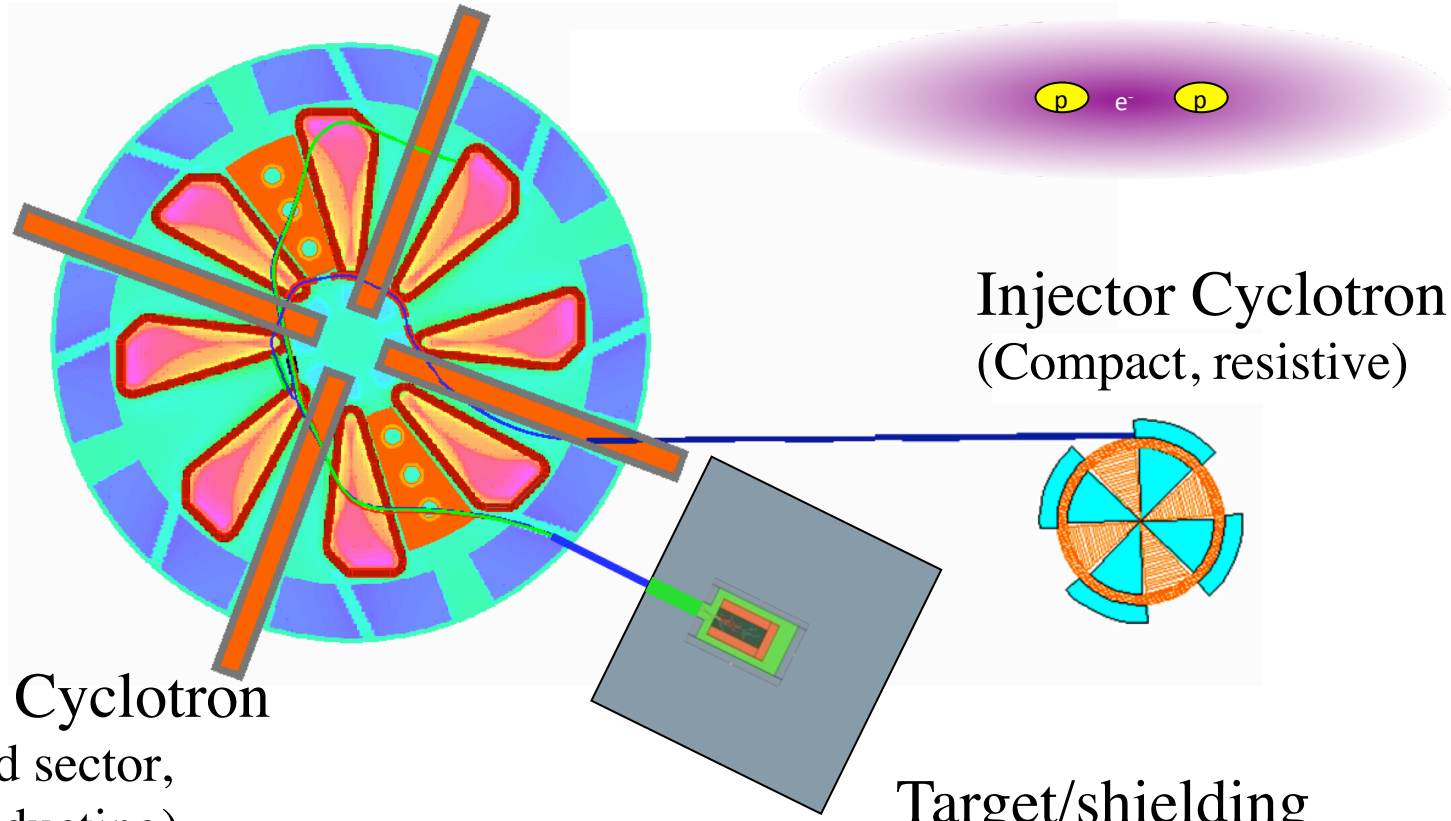
The DAEδALUS Approach To $\bar{\nu}_e$ Appearance:

Multiple neutrino sources at different baselines

Single neutrino detector


Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
δ = π/2
δ = 0
Distance
Constrains Initial flux
Constrains rise of oscillation probability
Osc. maximum
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
Single Ultra-large Detector
With Free Protons as IBD ($\bar{\nu}_e + p \rightarrow e^+ + n$) Targets
(Oil or Water)

We use multiple "Accelerator Units" to produce our DAR beam,
Constructed out of Cyclotrons,
Which accelerate H_2^+ to 800 MeV/amu



Injector Cyclotron
(Compact, resistive)

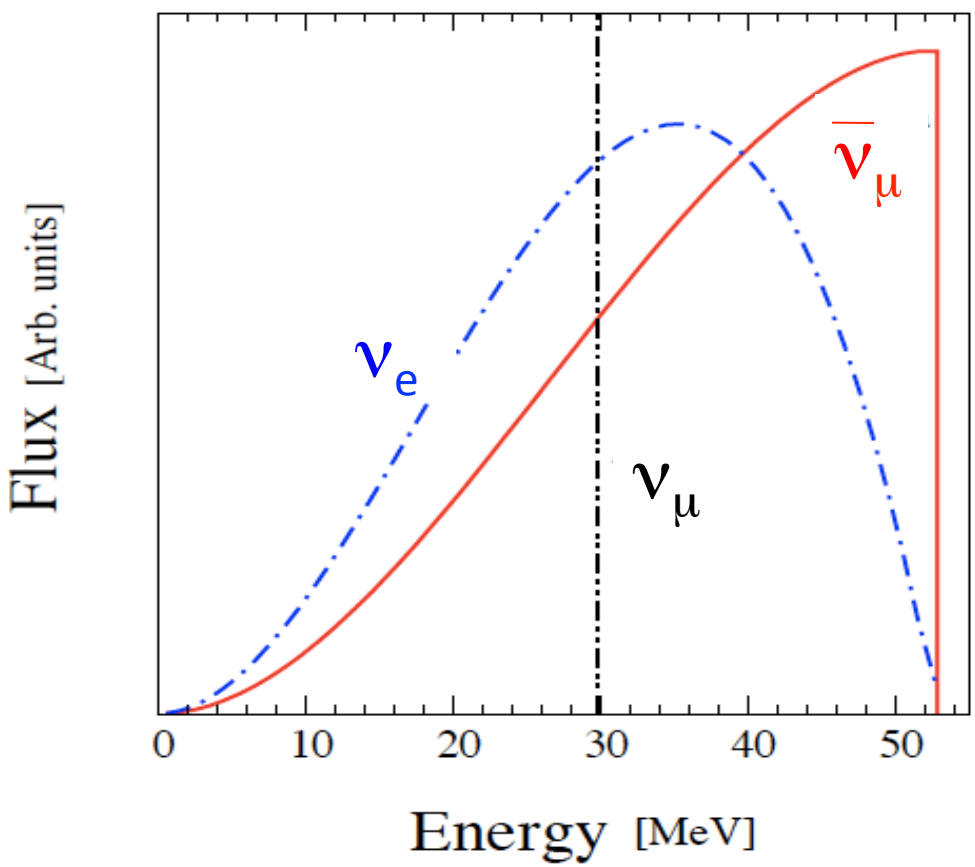
Primary Cyclotron
(Separated sector,
super-conducting)

Target/shielding

The DAEδALUS Neutrino Source

π^+ decay-at-rest (DAR) beam:

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

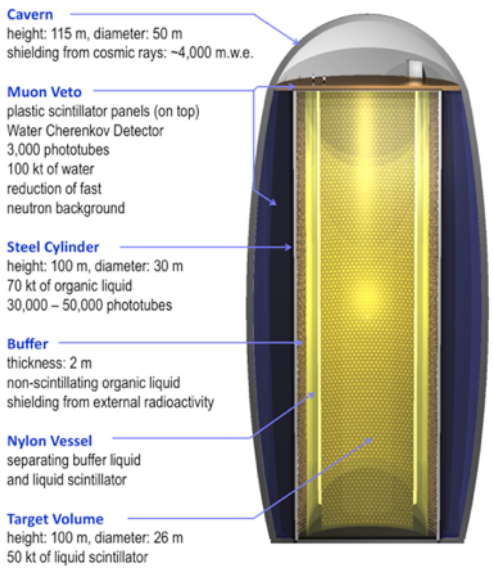


Shape driven by nature!

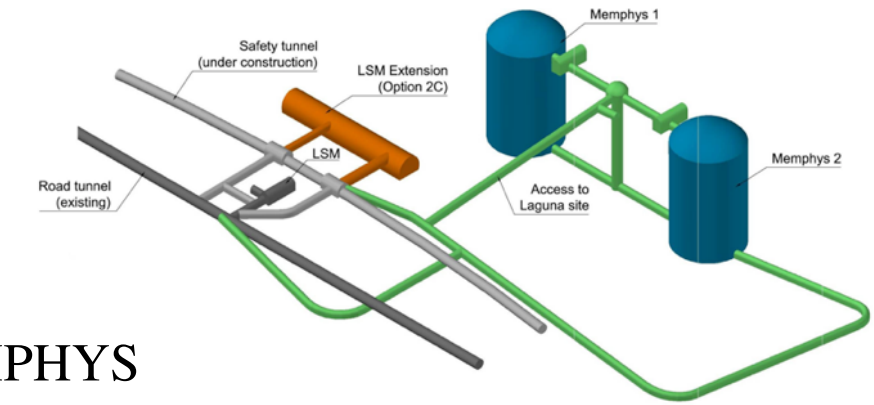
Only the normalization varies from beam to beam

A great place to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

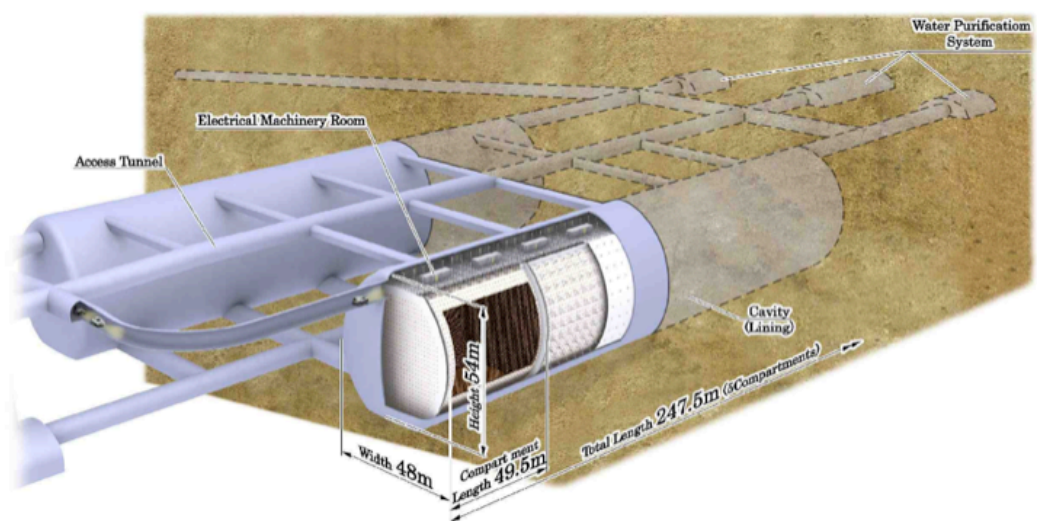
Where can DAEδALUS run?



LENA



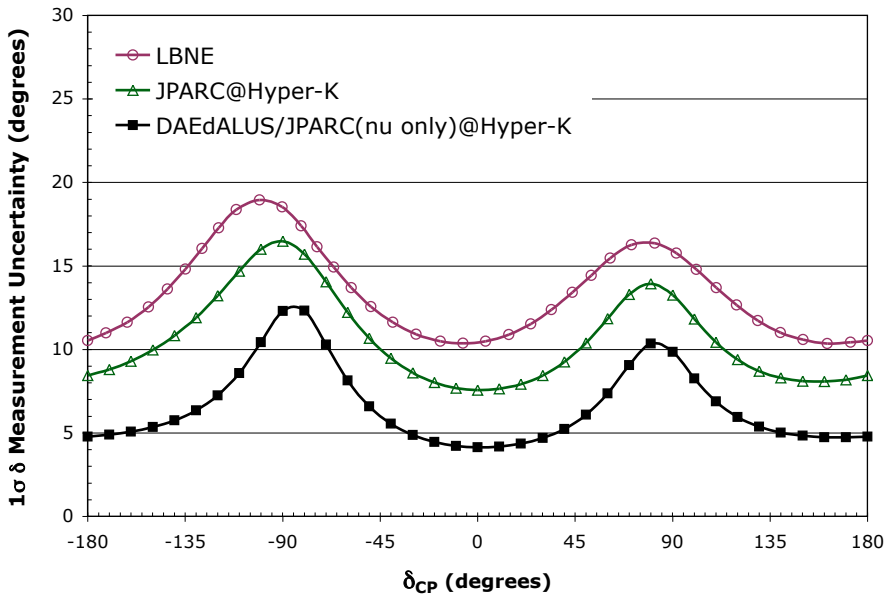
MEMPHYS

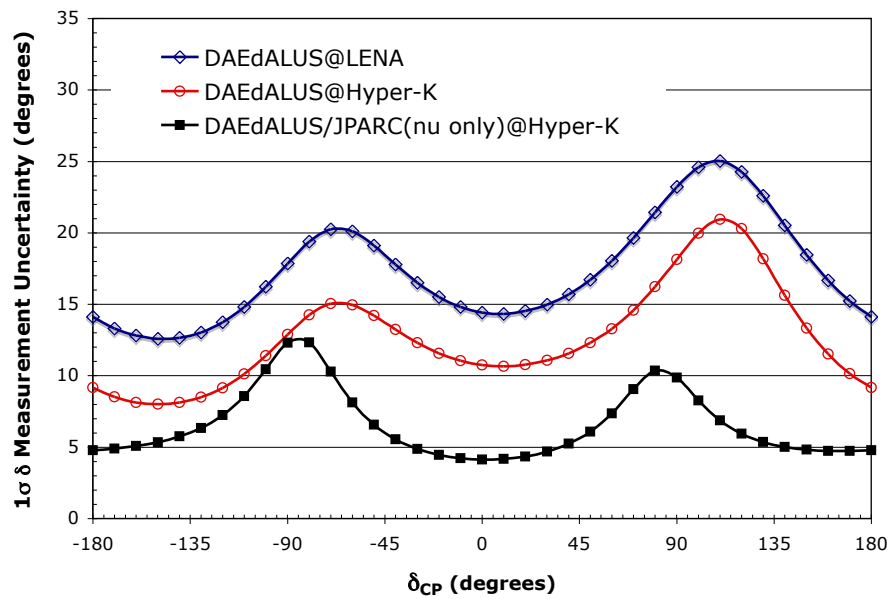


Hyper-K (or initially, Super-K)

Focus of this talk

Sensitivity to δ_{CP} to 5°

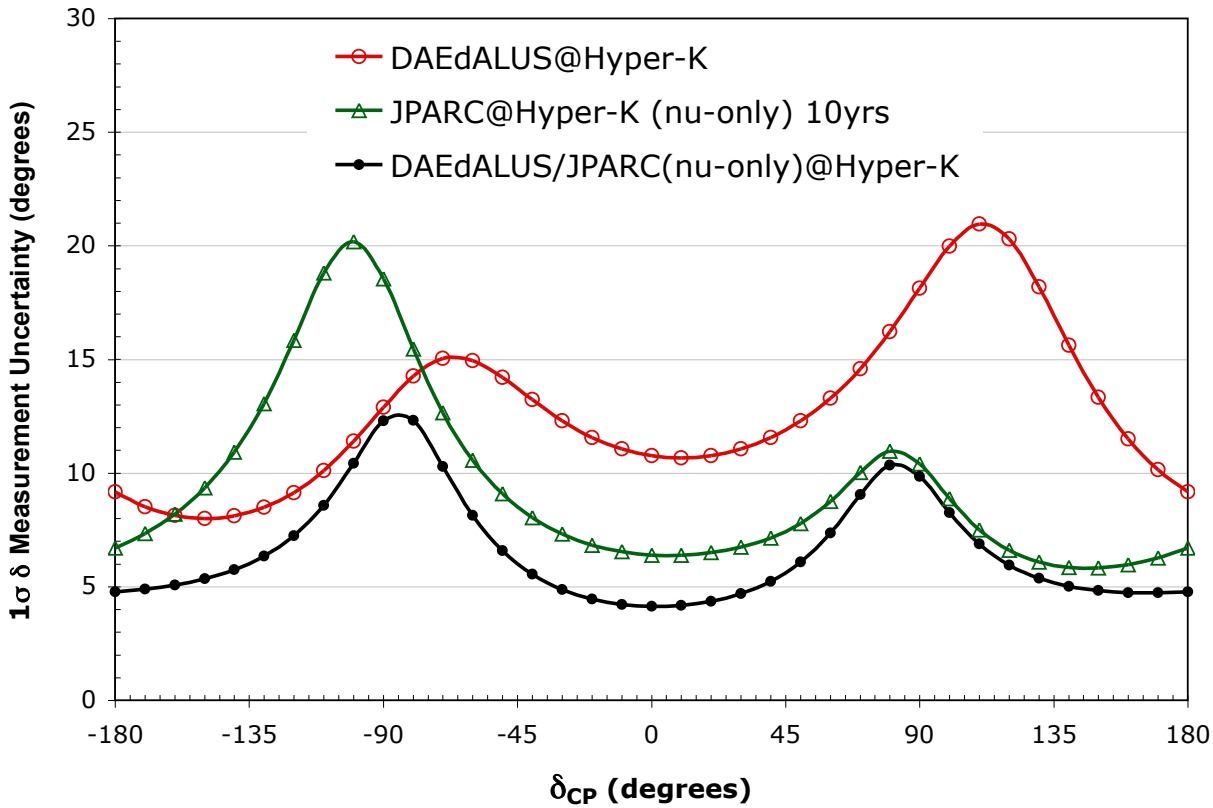




Configuration Name	Source(s)	Average Long Baseline Beam Power	Detector	Fiducial Volume	Run Length
DAEδALUS@LENA	DAEδALUS only	N/A	LENA	50 kt	10 years
DAEδALUS@Hyper-K	DAEδALUS only	N/A	Hyper-K	560 kt	10 years
DAEδALUS/JPARC (nu only)@Hyper-K	DAEδALUS & JPARC	750 kW	Hyper-K	560 kt	10 years
JPARC@Hyper-K	JPARC	750 kW	Hyper-K	560 kt	3 years ν + 7 years $\bar{\nu}$
LBNE	FNAL	850 kW	LBNE	35 kt	5 years ν 5 years $\bar{\nu}$

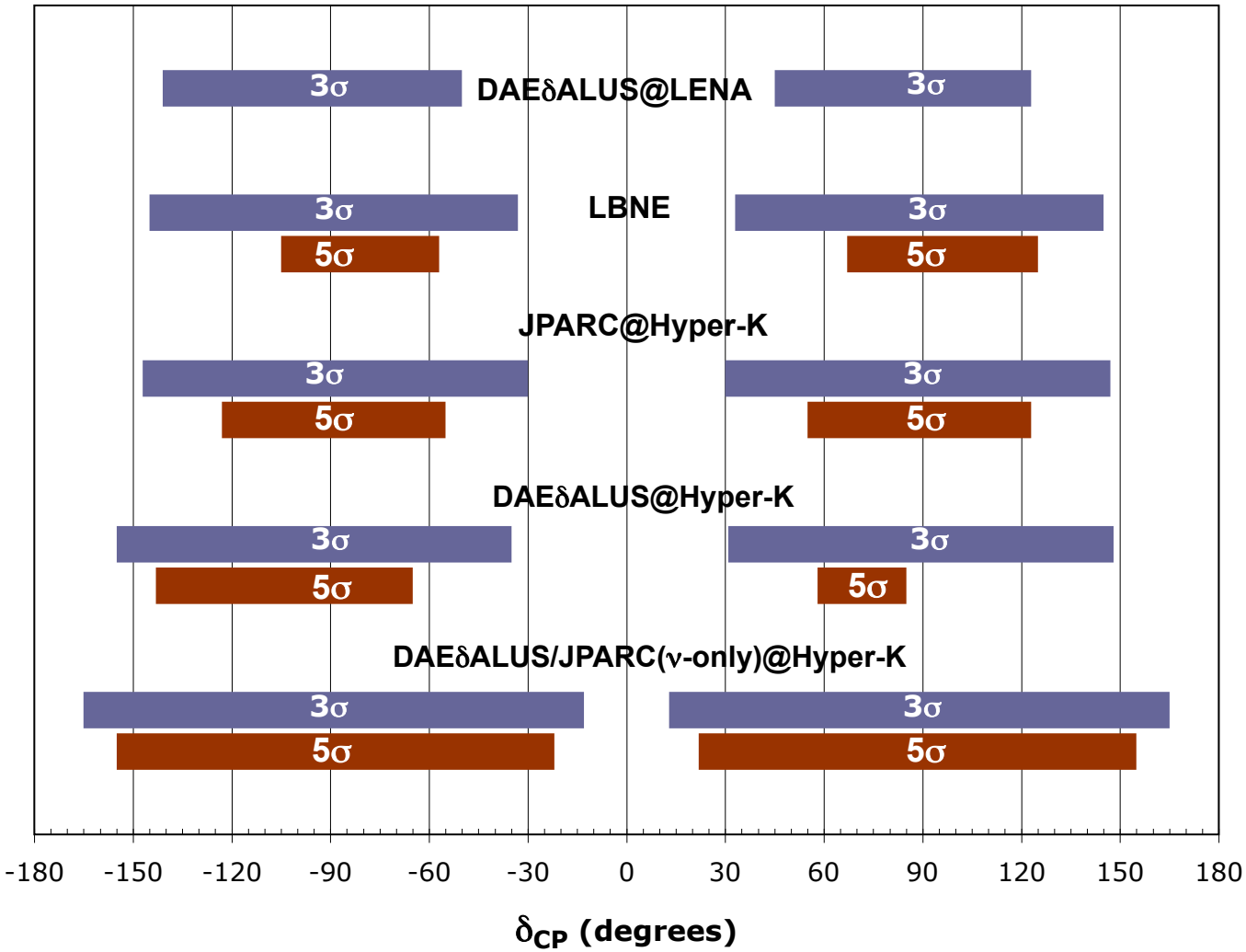
arXiv:1307.6465

DAEδALUS/JPARC@Hyper-K Complementarity



arXiv:1307.6465

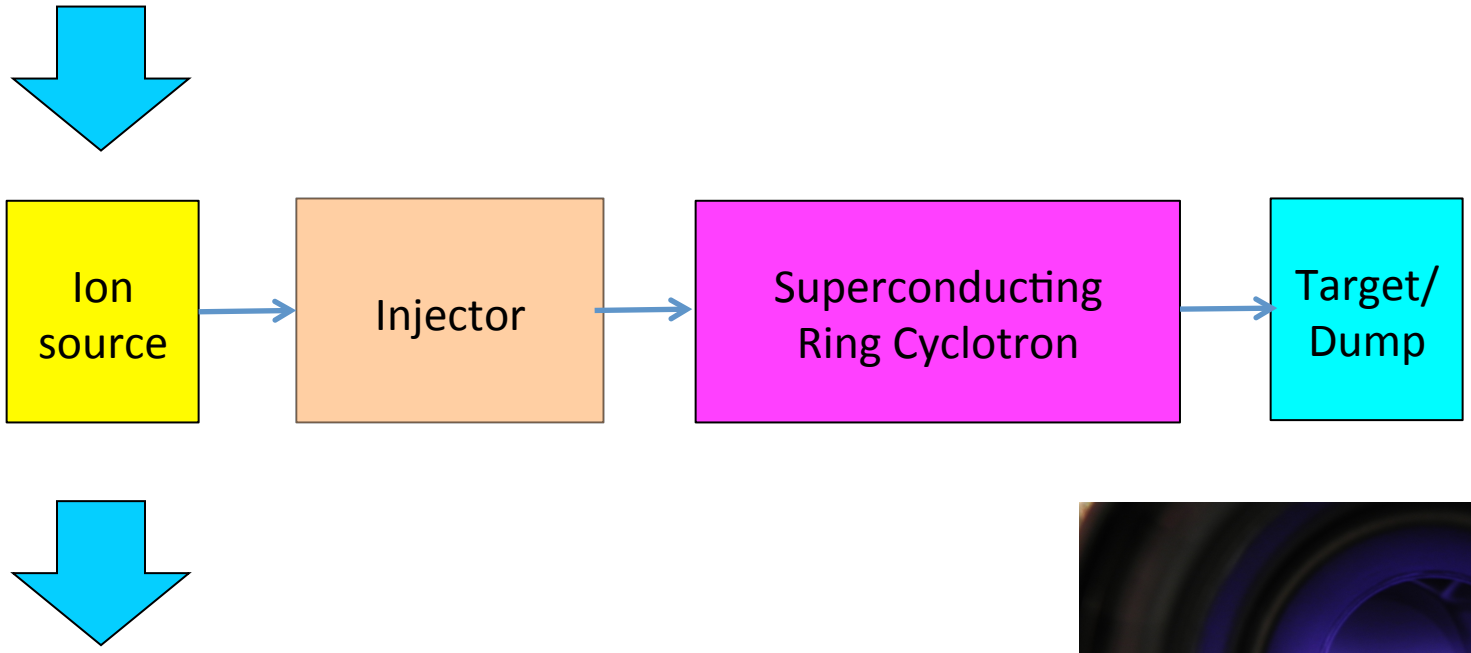
δ_{CP} Discovery Potential



arXiv:1307.6465

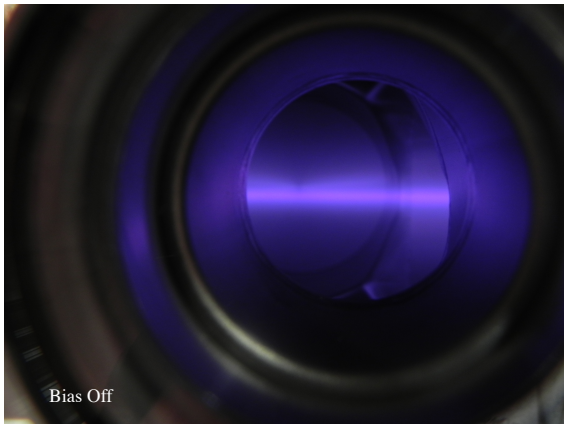
A Phased Approach to DAEδALUS

Phase I



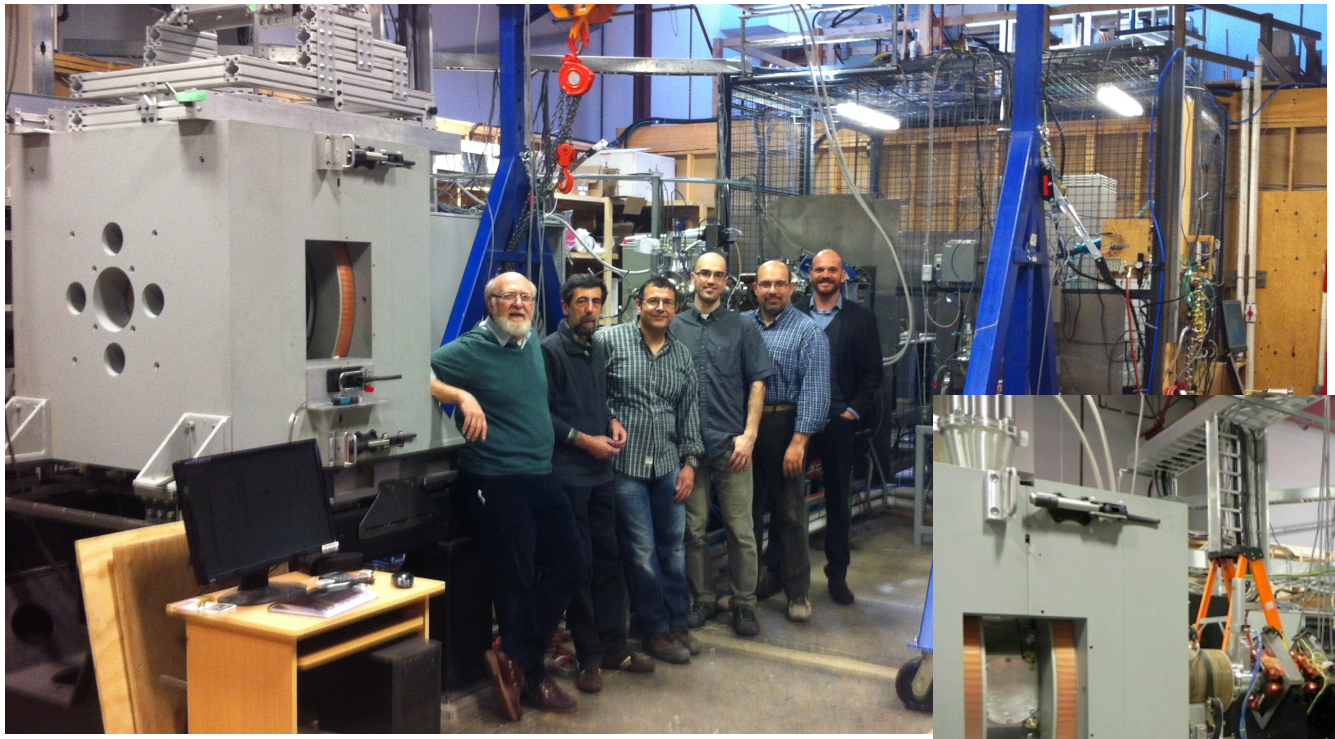
x 3 sites

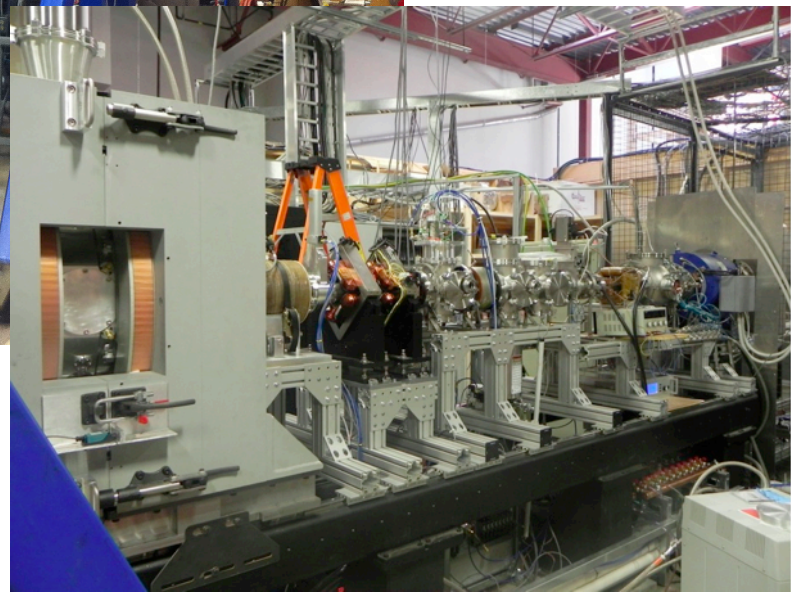
Tests of Versatile Ion Source (VIS)*
at Best Cyclotrons, Inc.



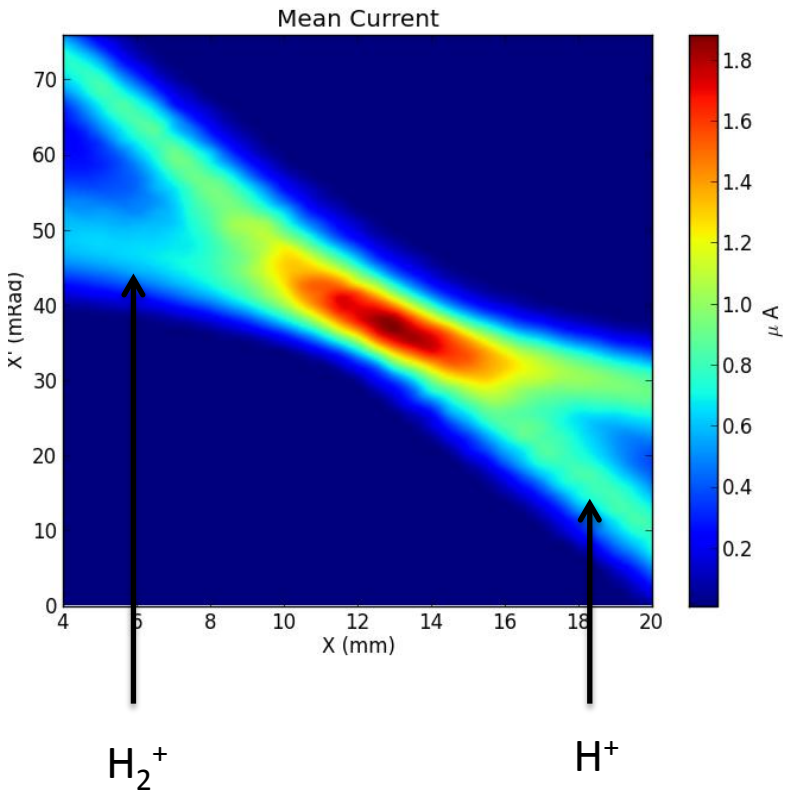
*S. Gammino et al., "Tests of the Versatile Ion Source (VIS) for high power proton beam production", ECRIS'10, Grenoble, France

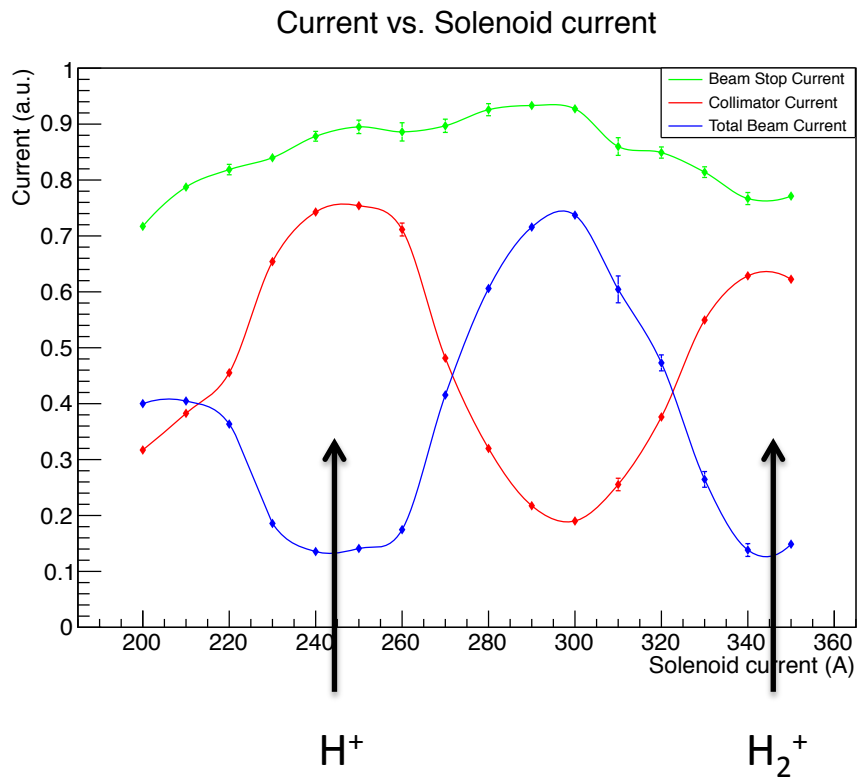
International Partnership Between Universities, Labs, and Industry



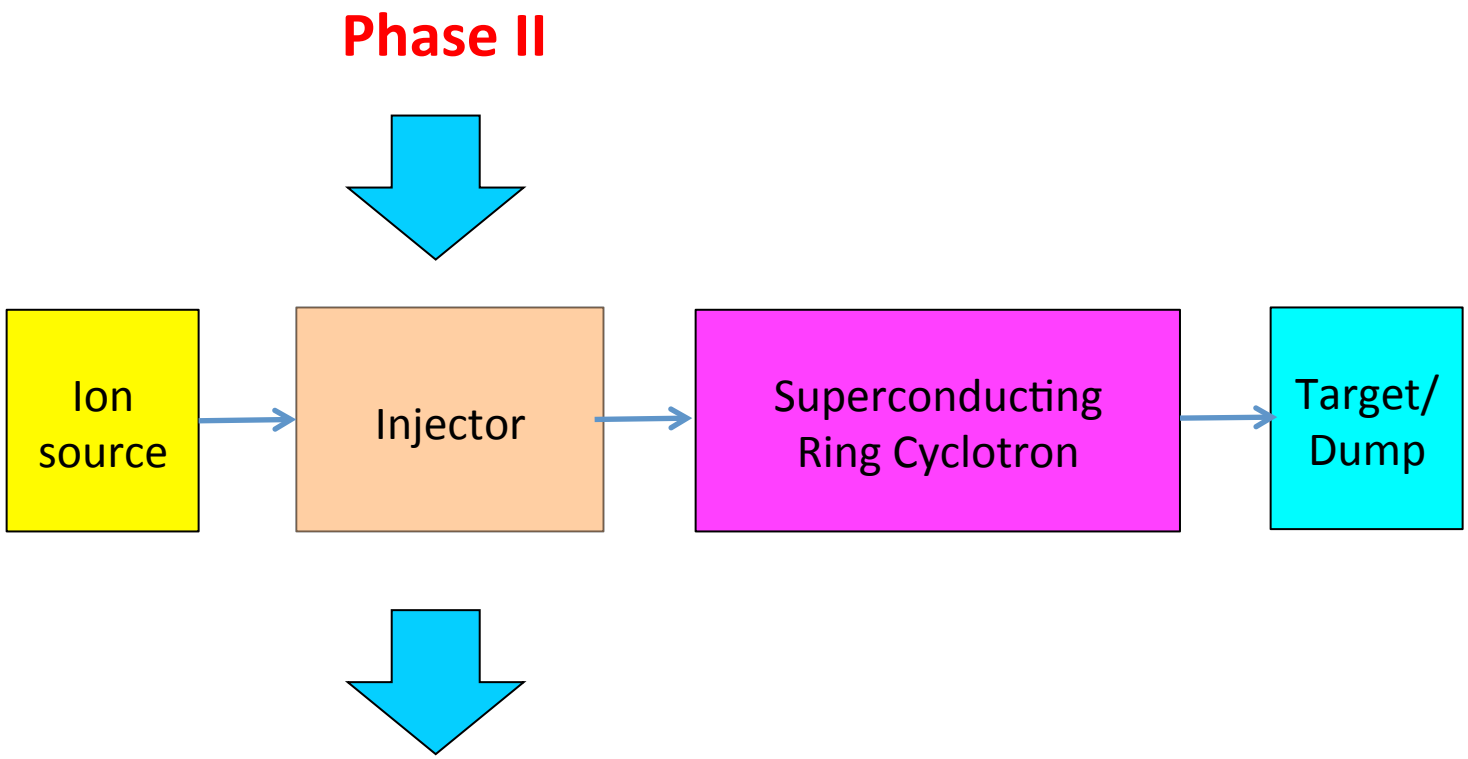


Beam Characterization Ongoing





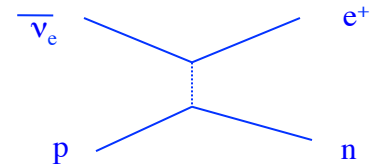
A Phased Approach to DAEδALUS



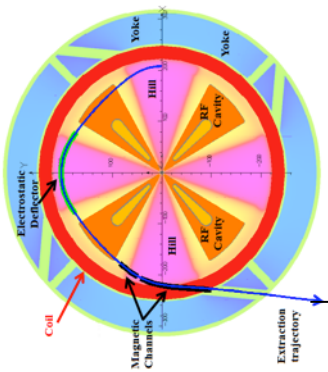
IsoDAR*: A sterile neutrino experiment

* *PRL 109, 141802 (2012)*

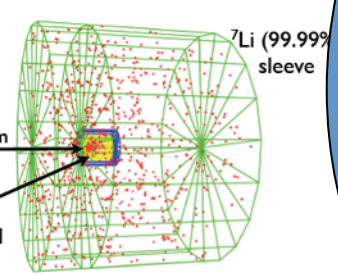
Proton beam → Be → n → captures on ^{7}Li → ^{8}Li → $\bar{\nu}_e$



Accelerates 5mA H_2^+
to 60 MeV/amu

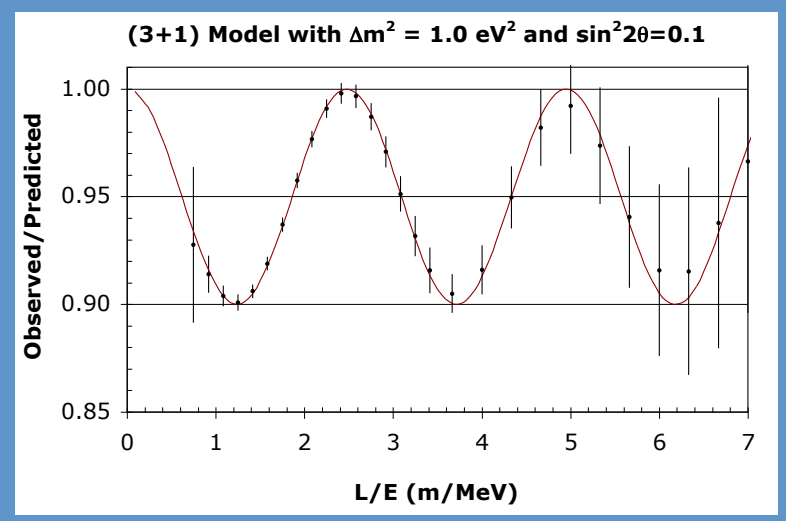


$^8\text{Li} \rightarrow {}^8\text{Be} + e^- + \bar{\nu}_e$



Not to scale

1 kton LS detector

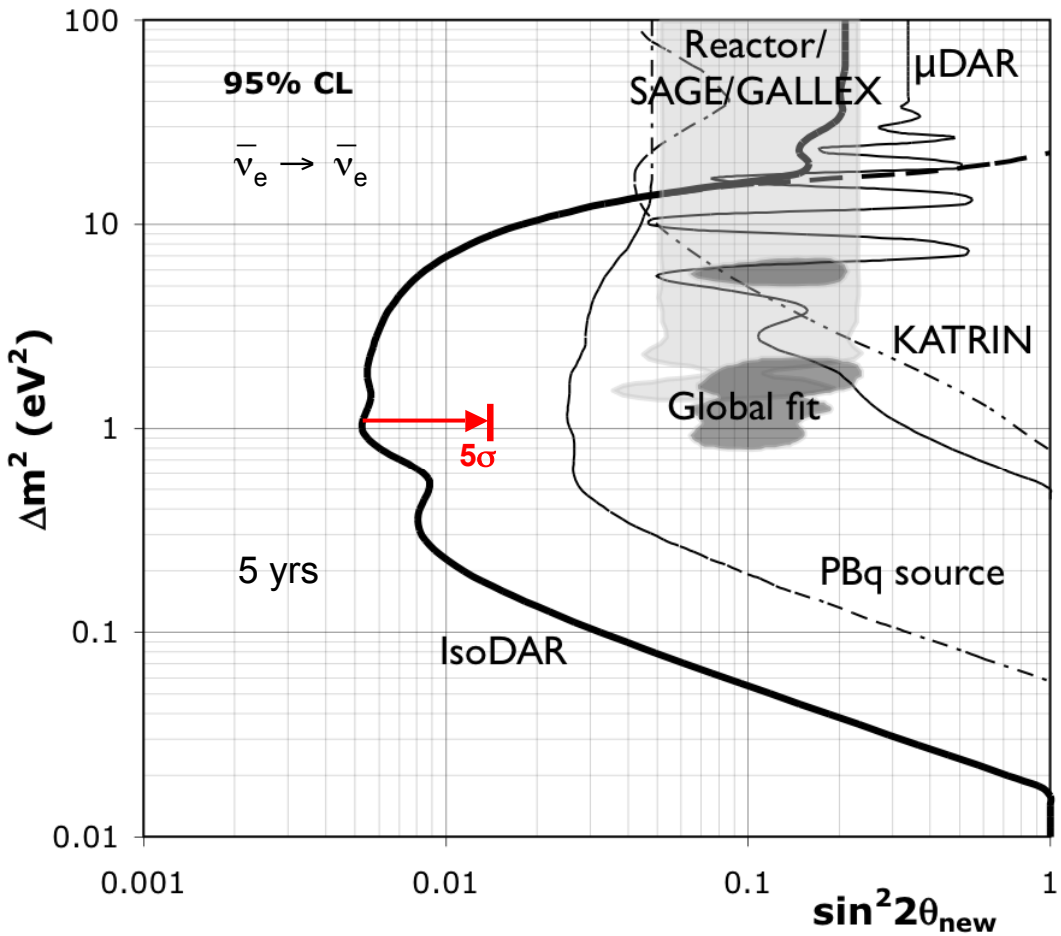


16.5 m

Potential location: KamLAND

IsoDAR $\bar{\nu}_e$ Disappearance Oscillation Sensitivity (3+1)

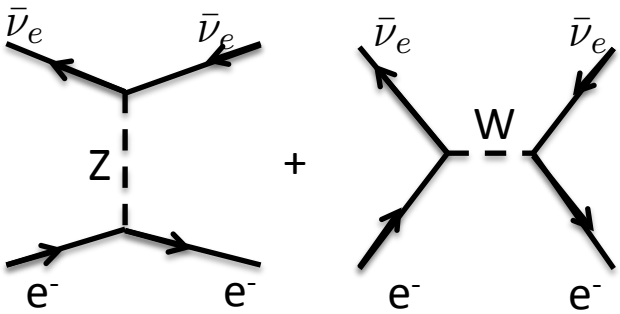
820,000 IBD events in 5 years of running



➢ Global fit can be ruled out at > 5σ in 4 months of running!

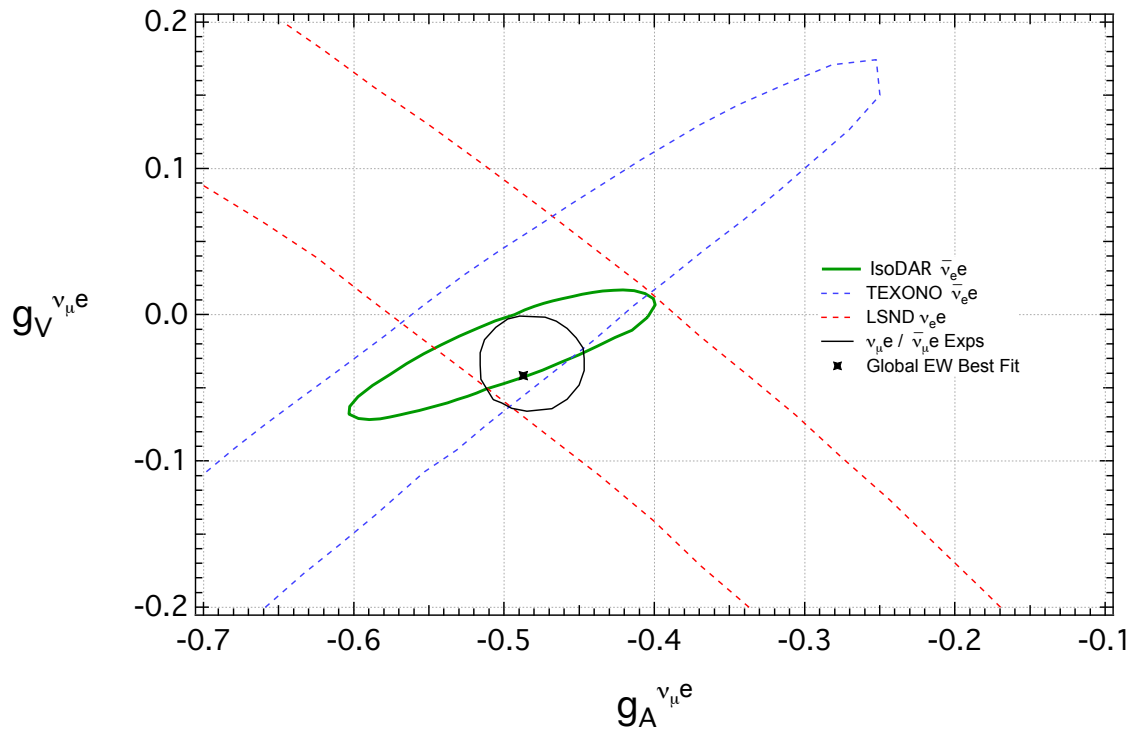
Precision $\bar{\nu}_e e$ Electroweak Measurements

7,200 $\nu_e e$ events in 5 years of running



$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_R^2 + g_L^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_R g_L \frac{m_e T}{E_\nu^2}\right]$$

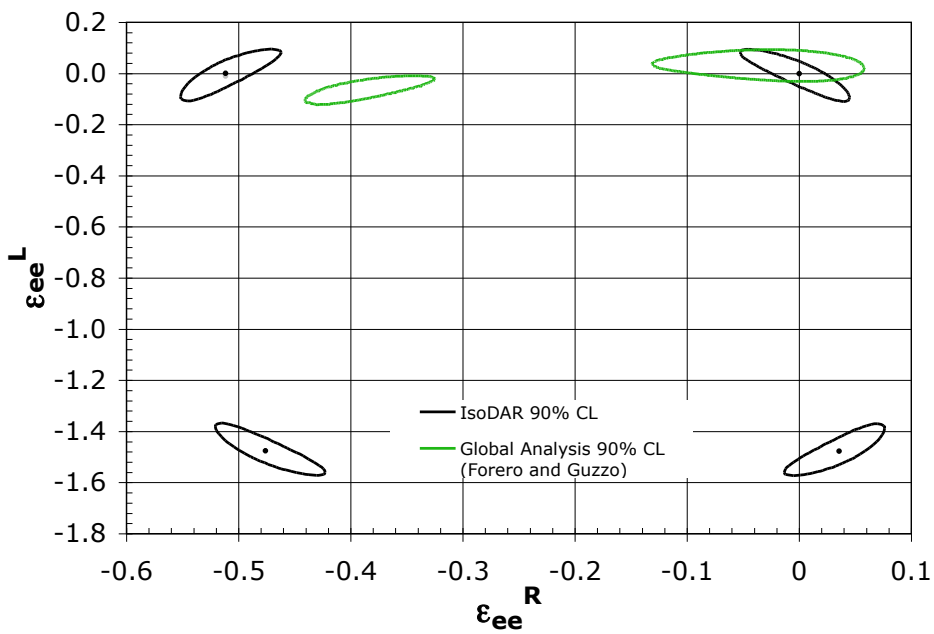
$$g_R = \tfrac{1}{2}(g_V - g_A)$$
$$g_L = \tfrac{1}{2}(g_V + g_A)$$

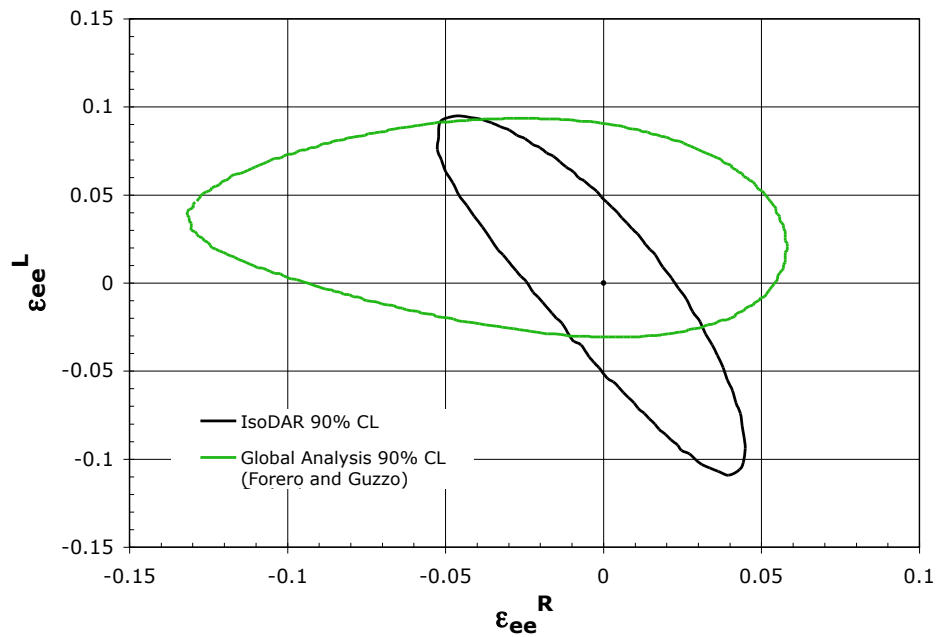


arXiv:1307.5081

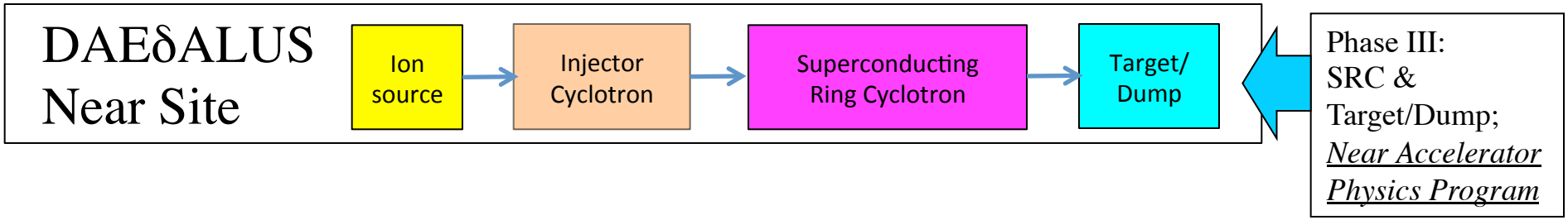
Non-standard Interactions

$$g_L \longrightarrow g_L + \epsilon_{ee}^{eL} \qquad g_R \longrightarrow g_R + \epsilon_{ee}^{eR}$$



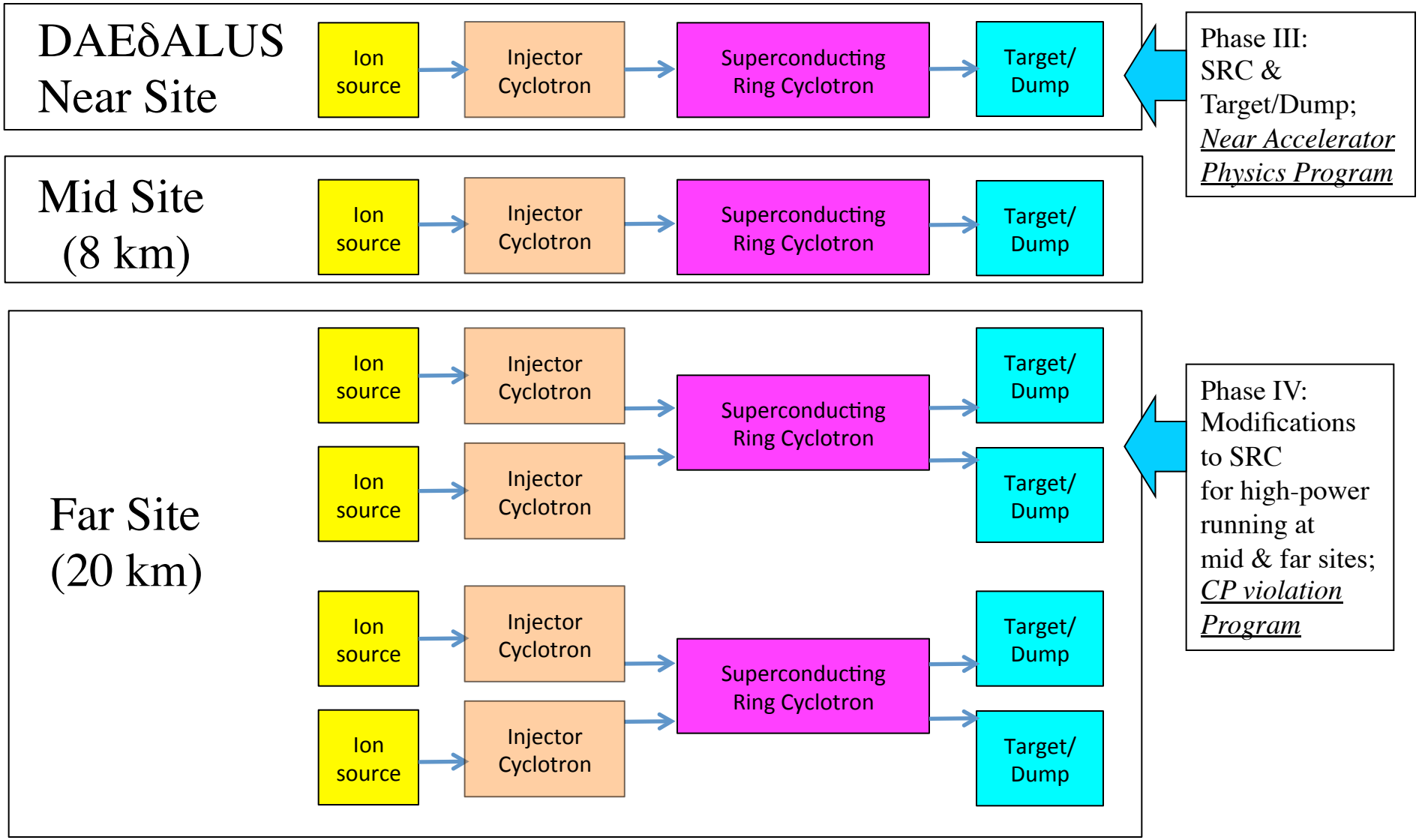


arXiv:1307.5081



Many exciting possibilities for a near accelerator physics program:

- Short-baseline neutrino oscillation waves in ultra-large liquid scintillator detectors
  Agarwalla, S. et. al. JHEP 12 (2011), 85
- Coherent neutrino scattering in dark matter detectors
  Anderson A., et. al. Phys. Rev. D 84, 013008 (2011)
- Active-to-sterile neutrino oscillations with neutral current coherent neutrino scattering
  Anderson, A. et. al. Phys. Rev. D 86, 013004 (2012)
- Measurement of the weak mixing angle with neutrino-electron scattering at low energy
  Agarwalla, S. and P. Huber JHEP 8 (2011), 59


DAEδALUS
Near Site
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Phase III:
SRC &
Target/Dump;
Near Accelerator Physics Program
Mid Site
(8 km)
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Far Site
(20 km)
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Ion source
Injector Cyclotron
Target/ Dump
Ion source
Injector Cyclotron
Superconducting Ring Cyclotron
Target/ Dump
Ion source
Injector Cyclotron
Target/ Dump
Phase IV:
Modifications
to SRC
for high-power
running at
mid & far sites;
CP violation Program

Conclusions

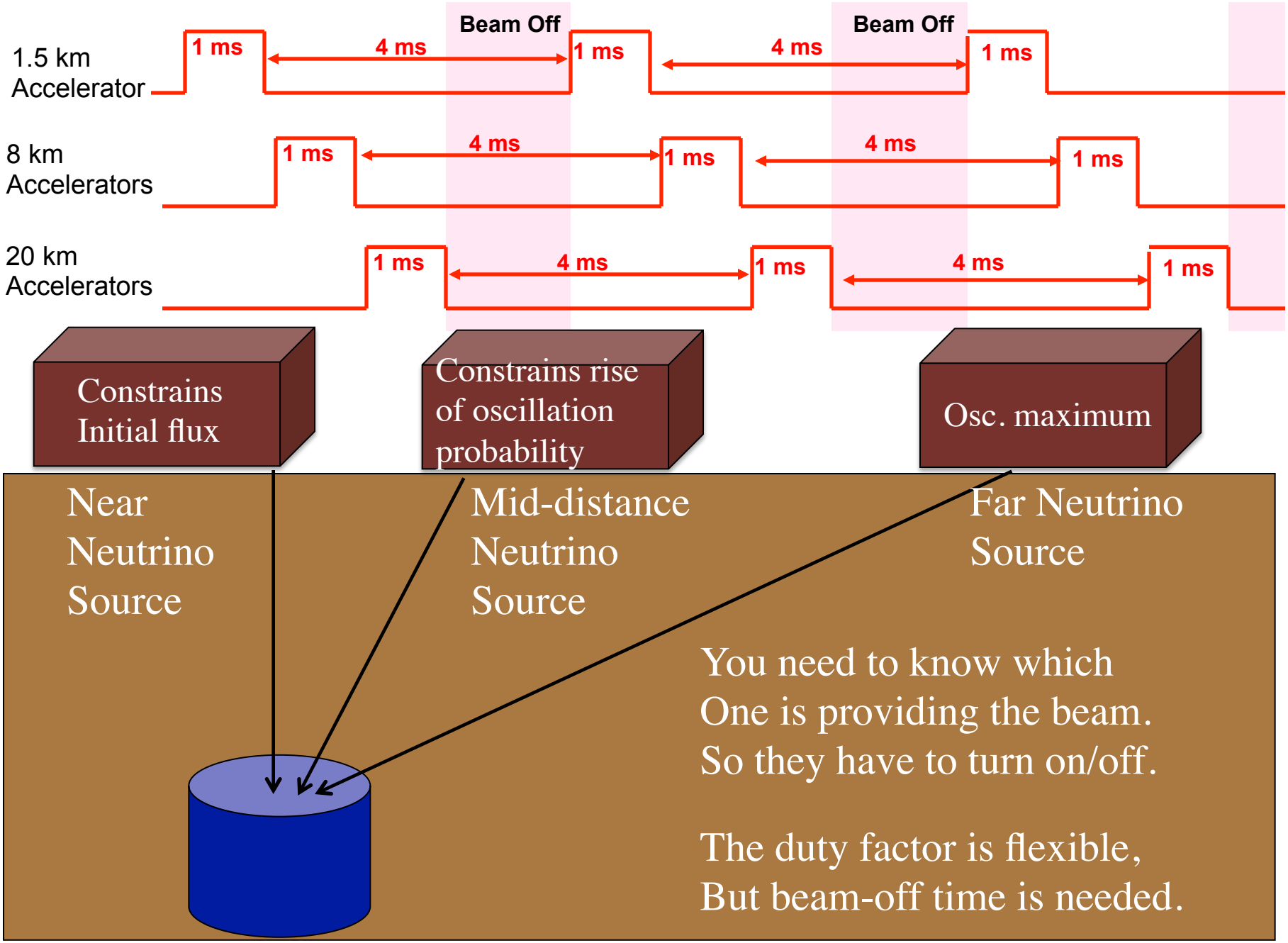
DAEδALUS

Has superb sensitivity to δ_{CP} extending down 5°

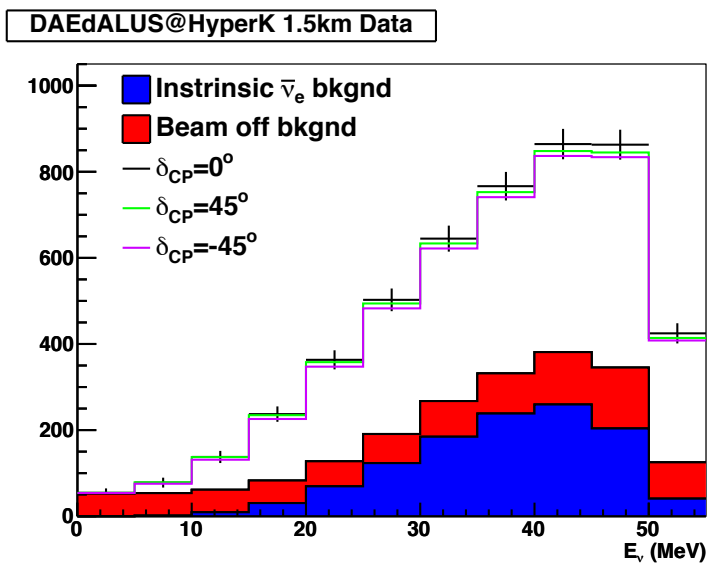
Is a phased program with strong physics along the way
(especially the IsoDAR sterile neutrino search!)

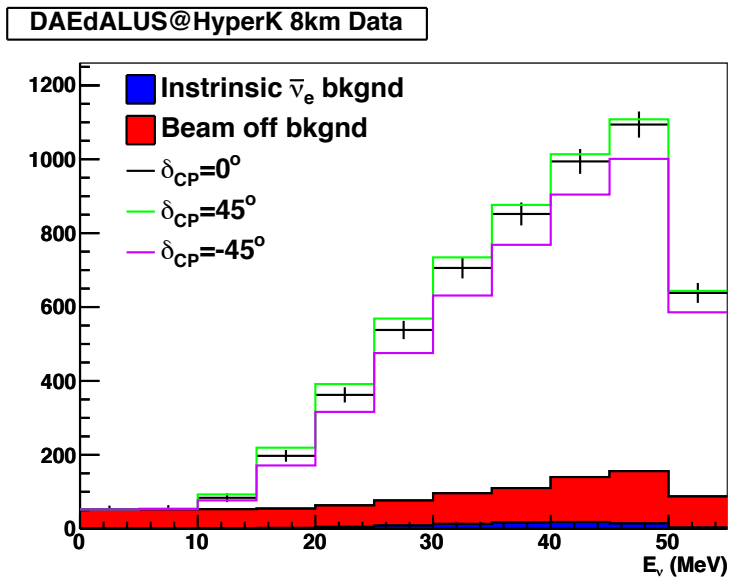
Being brought to you by an international collaboration
of accelerator and particle physicists,
with input from Industry

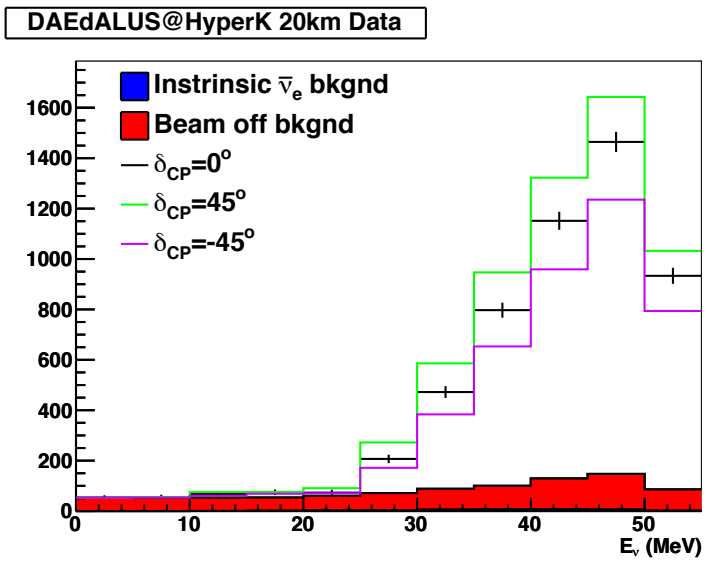
Backup


1.5 km Accelerator
8 km Accelerators
20 km Accelerators
Beam Off
Beam Off
1 ms
4 ms
1 ms
4 ms
1 ms
1 ms
4 ms
1 ms
4 ms
1 ms
1 ms
4 ms
1 ms
4 ms
1 ms
Constrains Initial flux
Constrains rise of oscillation probability
Osc. maximum
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
You need to know which One is providing the beam. So they have to turn on/off.
The duty factor is flexible, But beam-off time is needed.

DAEδALUS@Hyper-K Events



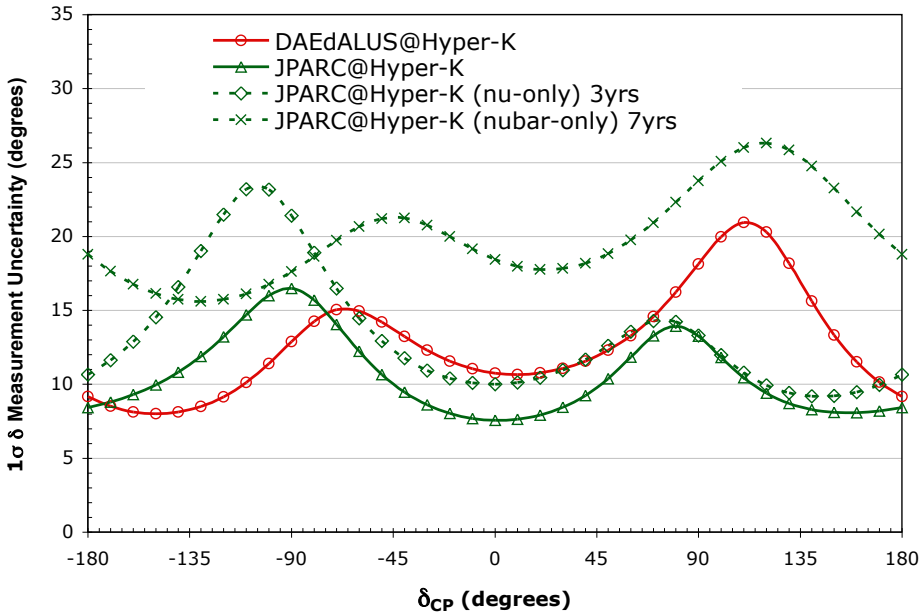


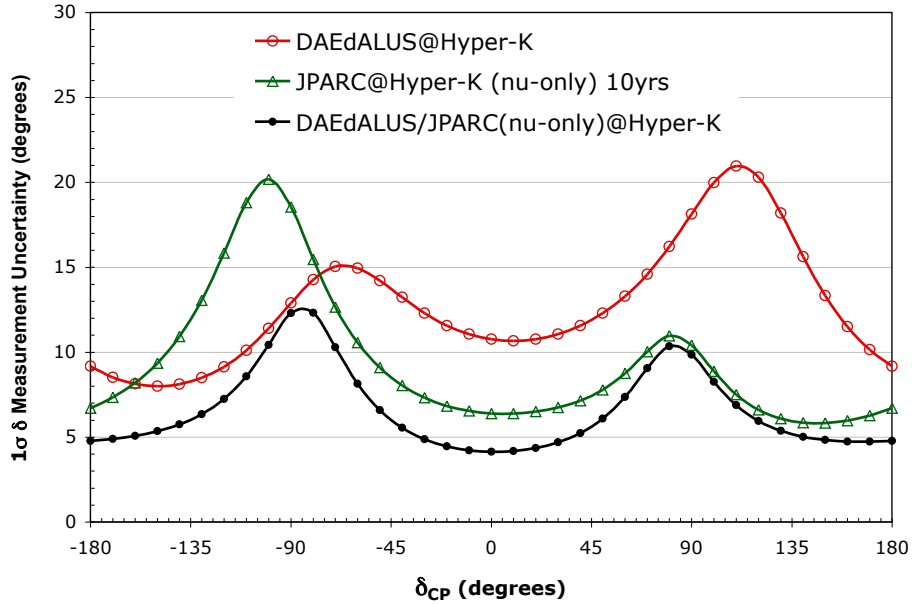


Event Type	1.5 km	8 km	20 km
IBD Oscillation Events ($E_{vis} > 20$ MeV)			
$\delta_{CP} = 0^0$, Normal Hierarchy	2660	4456	4417
" , Inverted Hierarchy	1838	3268	4338
$\delta_{CP} = 90^0$, Normal Hierarchy	2301	4322	5506
" , Inverted Hierarchy	2301	4328	5556
$\delta_{CP} = 180^0$, Normal Hierarchy	1838	3263	4295
" , Inverted Hierarchy	2660	4462	4460
$\delta_{CP} = 270^0$, Normal Hierarchy	2197	3397	3206
" , Inverted Hierarchy	2197	3402	3242
IBD from Intrinsic $\overline{\nu}_e$ ($E_{vis} > 20$ MeV)	1119	79	31
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
ν−e Elastic ($E_{vis} > 10$ MeV)	40025	2813	1123
ν_e−oxygen ($E_{vis} > 20$ MeV)	188939	13281	5305

arXiv:1307.6465

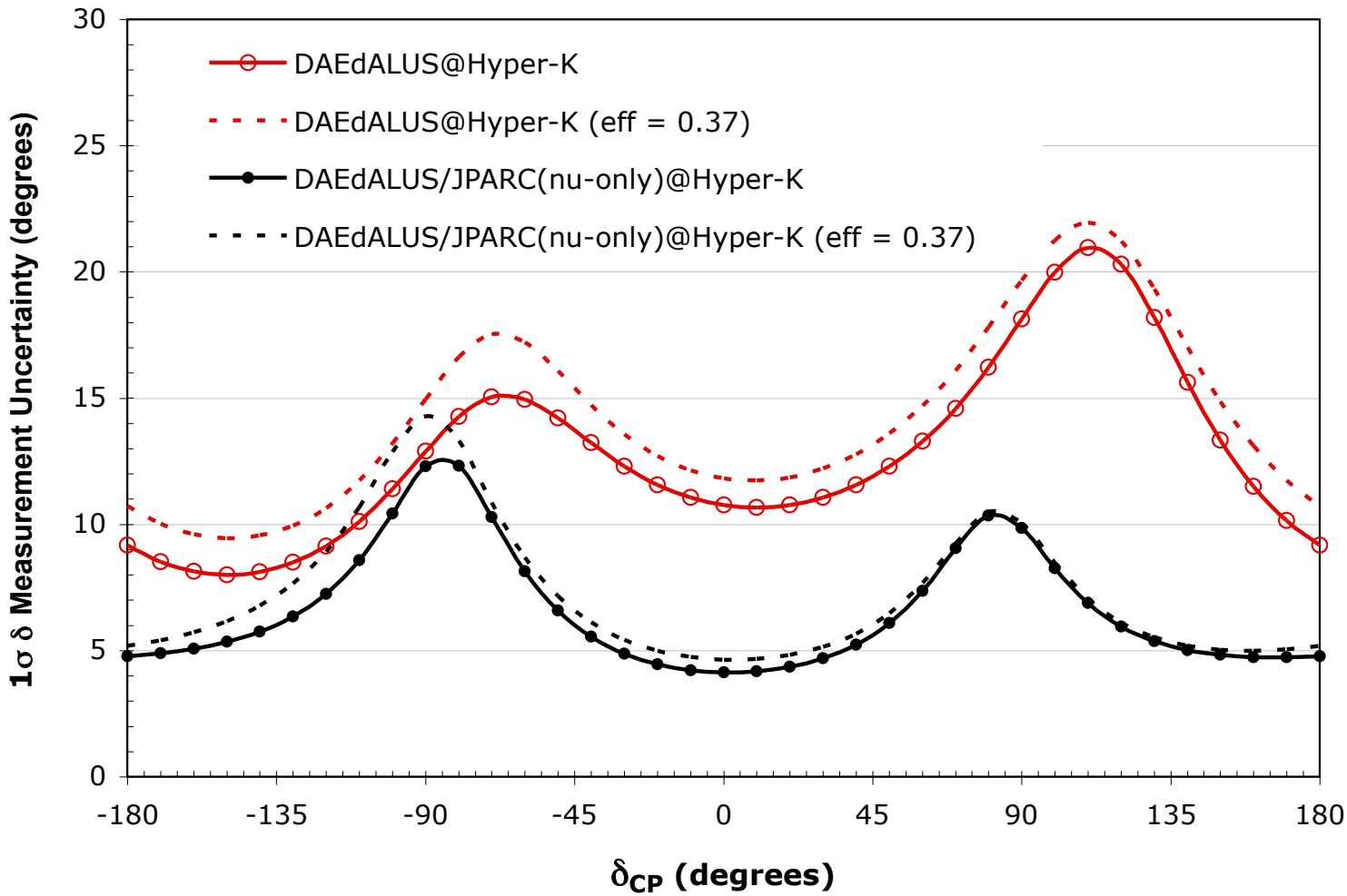
DAEδALUS/JPARC@Hyper-K Complementarity





arXiv:1307.6465

ε_{IBD} = 67% vs. ε_{IBD} = 37%



Our proposed 800 MeV super-conducting ring cyclotron is very similar to the existing Riken, Japan, cyclotron:

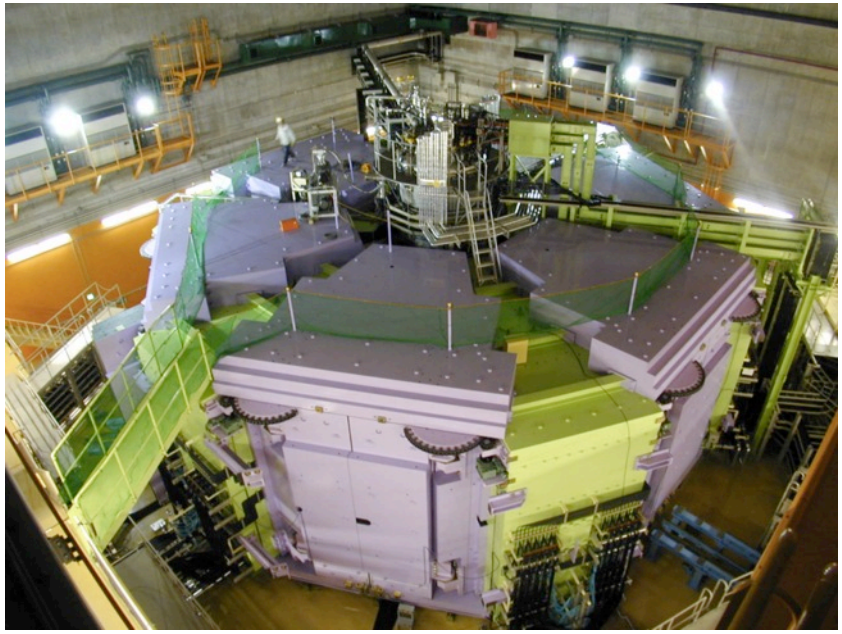


Table 5: Comparison of main parameters for DSRC with those for RIKEN-SRC

Basic Parameters	DSRC	RIKEN-SRC	Unit
Maximum field on the hill	6.05	3.8	T
Maximum field on the coil	6.18	4.2	T
Stored Energy	280	235	MJ
Coil size	30× 24 or 15× 48	21× 28	cm^2
Coil Circumference	9.8	10.86	m
Magnetomotive force	4.9	4	MAtot/sector
Current density	34	34	A/mm^2
Height	5.6	6.0	m
Length	6.9	7.2	m
Weight	$\leq$450	800	ton
Additional magnetic shield	0	3000	ton/total
Magnetic Forces			
Expansion	1.87 or 1.8	2.6	MN/m
Vertical	3.7	3.3	MN
Radial shifting	2.7	0.36	MN
Azimuthal shifting	0.2	0	MN
Force on the pole	tbd	630	MN
Main Coil			
Operational current	5000	5000	A
Layer × turn	31×16	22×18	
Cooling	Bath cooling	Bath cooling	
Maddock Stabilized Current	6345	6665	A
Other Components			
SC trim	no	4	sets
NC trim× turn	no	22	pairs
Stray field in the SRC valley region	0.01	0.04	T
Gap for thermal insulation	40	90@min.	mm
Extraction method	Stripper foil	Electrostatic channel	

Our first engineering design from MIT-PFSC Technology and Engineering Division:

arXiv.org > physics > arXiv:1209.4886 Search or

Physics > Accelerator Physics

Engineering Study of Sector Magnet for the Daedalus Experiment

Joseph Minervini, Mike Cheadle, Val Fishman, Craig Miller, Alexi Radovinsky, Brad Smith

(Submitted on 21 Sep 2012)

The Daedalus experiment seeks to evaluate neutrino scattering effects that go beyond the standard model. Modular accelerators are employed to produce 800 MeV proton beams at the megawatt power level directed toward a target, producing neutrinos. The Superconducting Ring Cyclotron (SRC) consists of identical sectors (currently 6) of superconducting dipole magnets with iron return frames. The Daedalus Collaboration has objectively concentrated designs for the magnet which satisfy several requirements, is the current best design that achieves the physics requirements of the experiment. The Technology and Engineering Division (T&ED) of the MIT Plasma Science and Fusion Center was awarded with a contract by the Daedalus team to further develop the magnet conceptual design. The resulting Engineering Study is reported here.

Winner of the 2013 IEEE Council on Superconductivity Award!

arXiv.org > physics > arXiv:1207.4895

Physics > Accelerator Physics

Design work
By A. Calanna

Abs[j], A. Adelmann[b,*], J.R. Alonso[c], W.A. Barletta[c], R. Barlow[h], L. Calabretta[f], A. Cala
npo[c], L. Celona[f], J.M. Conrad[c], S. Gammino[f], W. Kleeven[j], T. Koeth[a], M. Maggiore[e], H.
L.A.C. Piazza[e], M. Seidel[b], M. H. Shaevitz[d], L. Stingelin[b], J. J. Yang[c], J. Yeck[i]

nstitute for Research in Electronics and Applied Physics, University of Maryland, College Park, Marylan
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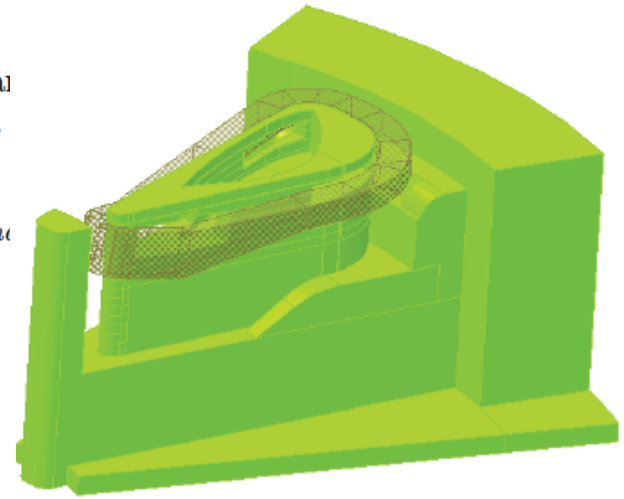
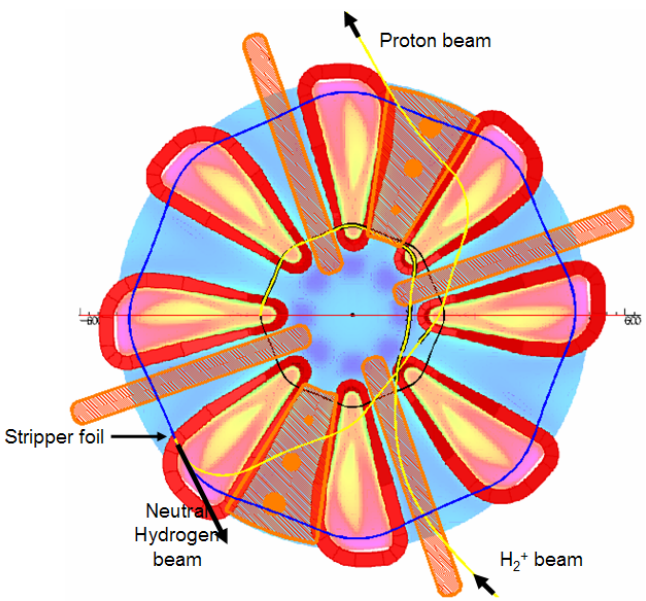
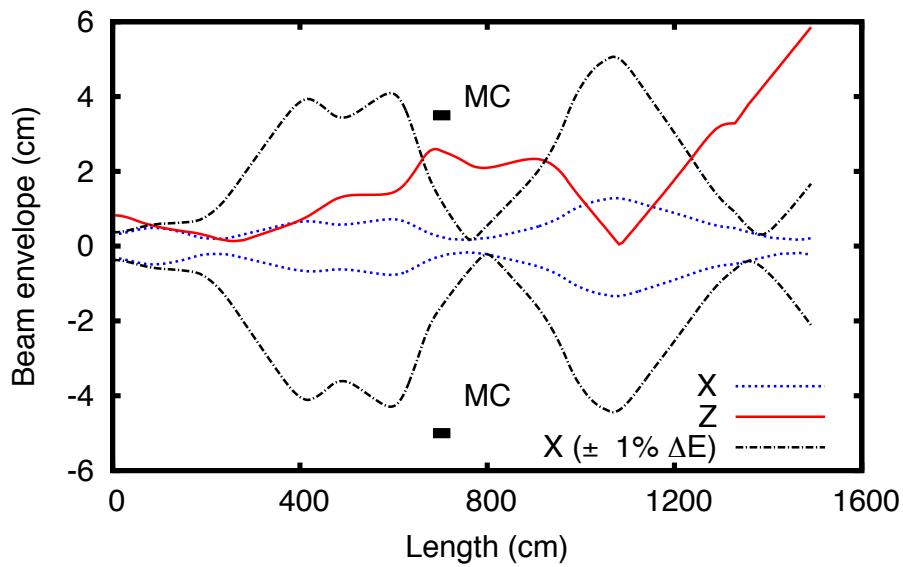
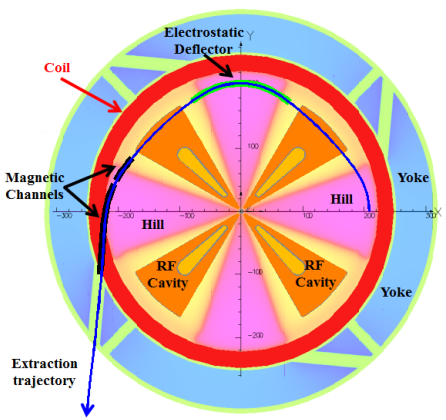


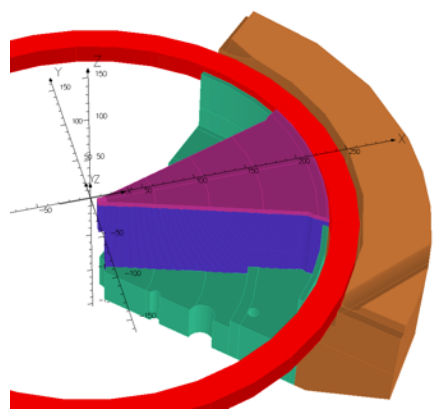




Injector Cyclotron

- Non-superconducting, single coil design
- Accelerates 5mA H_2^+ to 60 MeV/amu (600 kW proton beam)
- Beam dynamics simulated using OPAL code [Phys. Rev. ST Accel. Beams 13, 064201 (2010)]
  - Verified single turn extraction with 'classical' electrostatic septum





E_{max}	60 MeV/amu	E_{inj}	35 keV/amu
R_{ext}	1.99 m	R_{inj}	55 mm
$< B >$ @ R_{ext}	1.16 T	$< B >$ @ R_{inj}	0.97 T
Sectors	4	Hill width	28 - 40 deg
Valley gap	1800 mm	Pole gap	100 mm
Outer Diameter	6.2 m	Full height	2.7 m
Cavities	4	Cavity type	$\lambda/2$, double gap
Harmonic	6th	rf frequency	49.2 MHz
Acc. Voltage	70 - 240 kV	Power/cavity	310 kW
ΔE/turn	1.3 MeV	Turns	95
ΔR /turn @ R_{ext}	> 14 mm	ΔR/turn @ R_{inj}	> 56 mm
Coil size	200x250 mm^2	Current density	3.1 A/mm^2
Iron weight	450 tons	Vacuum	$< 10^{-7}$ mbar

Comparison of IsoDAR to alternative designs

Assessment

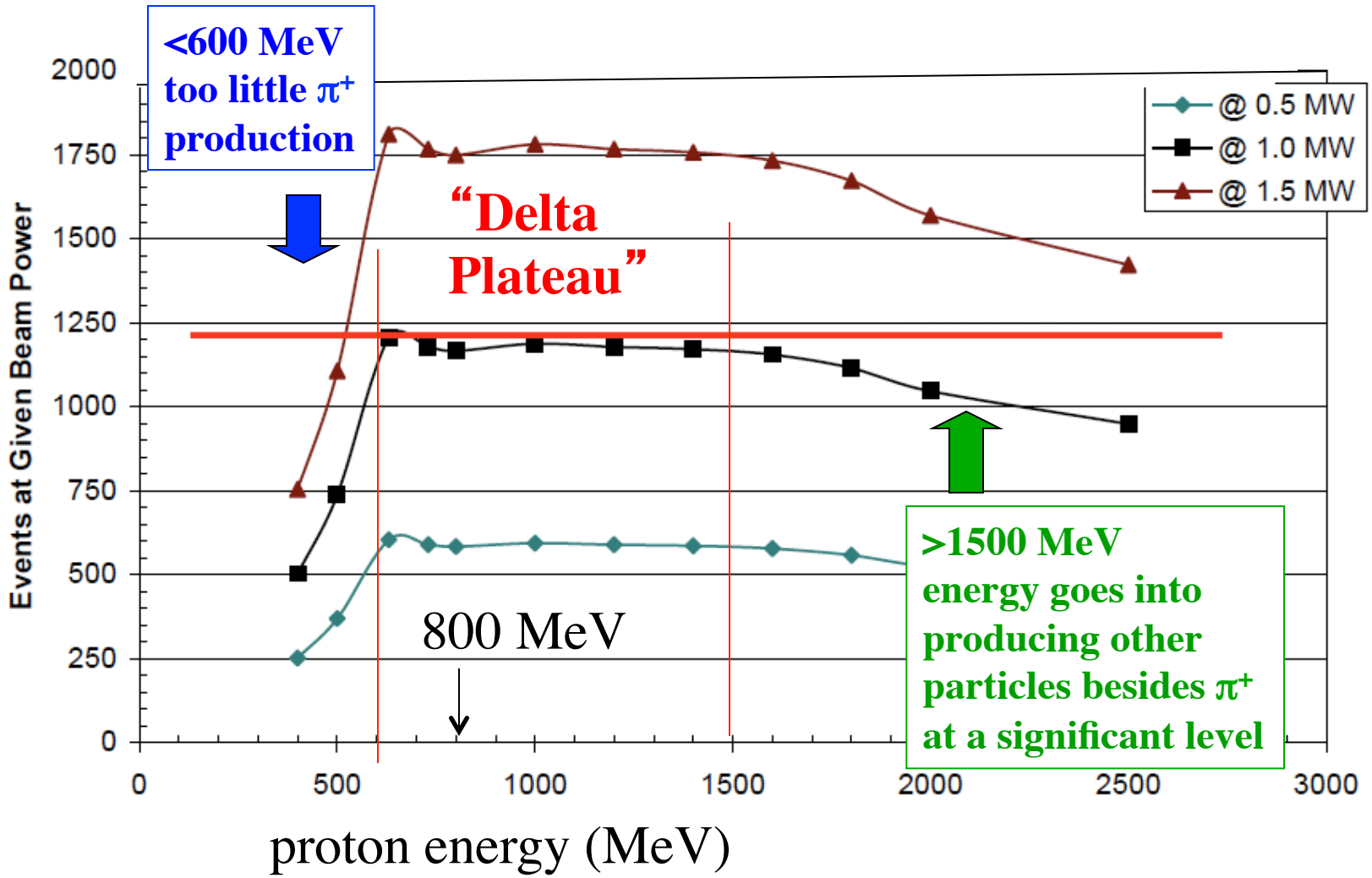
- Good
- Moderate
- Bad

	IsoDAR Base Design	RFQ/Separated Sector Cyclotron	LINAC, 30 MeV, 40 mA	Modified Beta Beam Design	New Detector at Existing Beam
1. Cost	Good	Moderate	Bad	Moderate	Bad
2. $\bar{\nu}_e$ rate	Good	Good	Good	Bad	Good
3. Backgrounds low	Good	Good	Good	Good	Moderate
4. Technical risk	Moderate	Moderate	Moderate	Moderate	Good
5. Compactness	Good	Moderate	Bad	Good	Moderate
6. Simplicity u'ground	Good	Moderate	Moderate	Bad	Moderate
7. Reliability	Good	Good	Good	Bad	Good
8. Value to other exps	Good	Good	Good	Bad	Bad
9. Value to Industry	Good	Moderate	Moderate	Bad	Bad

arXiv:1210.4454

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



Accelerator Collaborators and Participants*

- Collaboration Spokespersons:
  - Janet Conrad, MIT
  - Mike Shaevitz, Columbia
- Collaborating Laboratories (Support: Internal and MIT contracts)
  - Laboratori Nazionali del Sud (INFN-LNS), Catania, Italy
    - Luciano Calabretta, Alessandra Calanna, Daniela Campo, Luigi Celona, Santo Gammino, …
  - Paul Scherrer Institute, Villigen, Switzerland
    - Andreas Adelmann, Jianjun Yang, Marco Schippers, …
  - RIKEN, Wako, Saitama, Japan
    - Hiroki Okuno
- Industries (Support: Internal)
  - Best Cyclotron Systems, Vancouver BC
    - Bruce Milton, Todd Mawhinney, Francis Labecque, …
  - IBA, Louvain la Neuve, Belgium
    - Yves Jongen, Willem Kleeven, Michel Abs, …
  - AIMA, Nice, France
    - Pierre Mandrillon, Gerome Mandrillon
- Many Universities worldwide
  - See http://www.nevis.columbia.edu/daedalus/collab/index.html)

* Principle funding provided by NSF through MIT

Accelerator Physicists and Engineers Involved in the Cyclotron Development

Adriana Bungau, University of Huddersfield
Alessandra Calanna, MIT
Anna Kolana, University of Huddersfield/PSI
Andreas Adelmann, PSI
Bernard Gottschalk, Harvard University
Bill Barletta, MIT
Bruce Milton, Best, Inc.
Chris Tschalaer, MIT
Daniel Winklehner, Michigan State University
Daniela Campo, MIT
Eric Forton, IBA-Research
Francis Labrecque, Best, Inc.
Hiroki Okunu, RIKEN
Hywel Owen, University of Manchester
Jerome Mandrillon, AIMA
Jerry Nolen, Argonne National Laboratory
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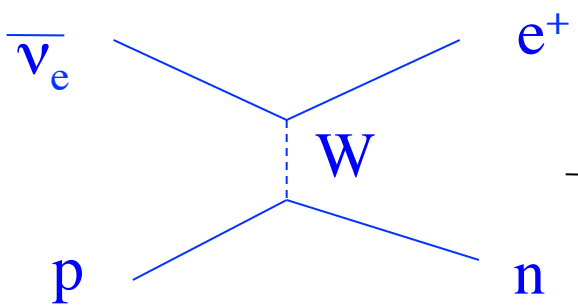
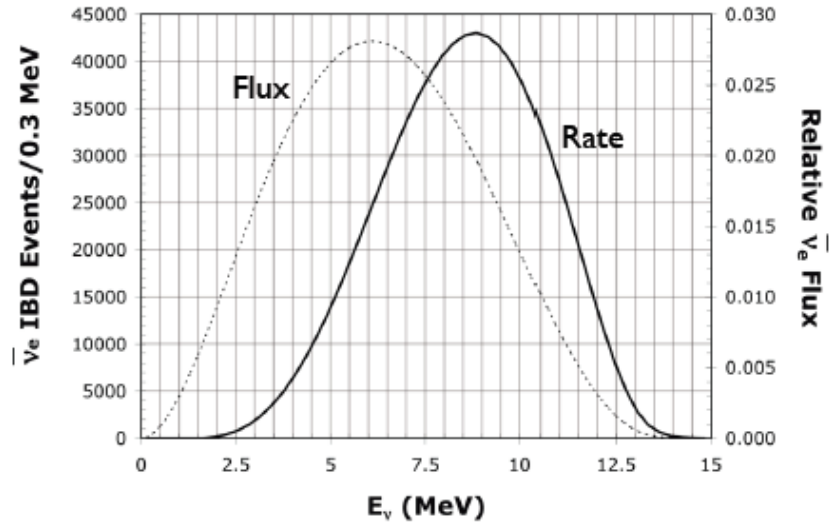
Santo Gammino, INFN-Catania
Sebastiano Albergo, CSFSM-Sicily, Italy
Tim Koeth, University of Maryland
Todd Mawhinney, Best, Inc.
Willem Kleeven, IBA-Research

Five Years of Running at KamLAND

Inverse β Decay (IBD)





Accelerator	60 MeV/amu of H_2^+
Current	10 mA of protons on target
Power	600 kW
Duty cycle	90%
Run period	5 years (4.5 years live time)
Target	^{9}Be surrounded by ^{7}Li (99.99%)
$\overline{\nu}$ source	^{8}Li β decay ($\langle E_\nu \rangle$=6.4 MeV)
$\overline{\nu}_e$/1000 protons	14.6
$\overline{\nu}_e$ flux	1.29×10^{23} $\overline{\nu}_e$
Detector	KamLAND
Fiducial mass	897 tons
Target face to detector center	16 m
Detection efficiency	92%
Vertex resolution	12 cm/$\sqrt{E}$ (MeV)
Energy resolution	6.4%/$\sqrt{E}$ (MeV)
Prompt energy threshold	3 MeV
IBD event total	8.2×10^5
$\overline{\nu}_e$-electron event total	7200

820,000 IBD events

- **Sterile neutrino search**

7,200 $\overline{\nu}_e$-electron events

- Measure $\sin^2\theta_W$ to 3.2%
- Probe weak couplings and nonstandard interactions (NSIs)

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Accelerator Science

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SYNOPSIS

Particle accelerator systems have been key drivers for a broad array of fundamental discoveries and transformational scientific advances since the early 20th century. Since their inception, they have also been core components of U.S. technological innovation and economic competitiveness.

The Accelerator Science program will support and foster research at universities that exploits the educational and discovery potential of basic accelerator physics research, and allows the development of transformational discoveries in this crosscutting academic discipline. In particular, this program seeks to support research with the potential to disrupt existing paradigms and advance accelerator science at a fundamental level, such as enabling discoveries that lead to novel, compact, powerful, and/or cost-effective accelerators. Key questions that this program will address include: what are the fundamental limitations affecting the acceleration, control, intensity, and quality of particle beams? What novel approaches can be employed to substantially increase accelerating gradients? How can developments in other fields lead to new approaches in accelerator science and beam physics?

The goal of this program is to seed and support fundamental accelerator science at universities as an academic discipline, providing the foundation in knowledge and workforce upon which major advances in accelerator-driven technologies will be based. An important component of the program will be the support and training of the next generation of accelerator scientists, including students, postdoctoral researchers, and junior faculty, who will lead innovations in the field and will form the backbone of the