# DAEδALUS

A Path to Measuring $\delta_{CP}$ Using Cyclotron Decay-at-Rest Neutrino Sources

NOW 2012

Matt Toups, MIT

## A two-part talk:

1. The experimental design for the flagship measurement:

   CP Violation

2. Implementing a phased approach with rich physics, highlighting:

   The IsoDAR sterile neutrino program (Phase II)

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

in a vacuum…

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

We want to see if δ is nonzero

terms depending on mixing angles

terms depending on mass splittings

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

# Use L/E Dependence Of $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ to Extract $\delta_{CP}$

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

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

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

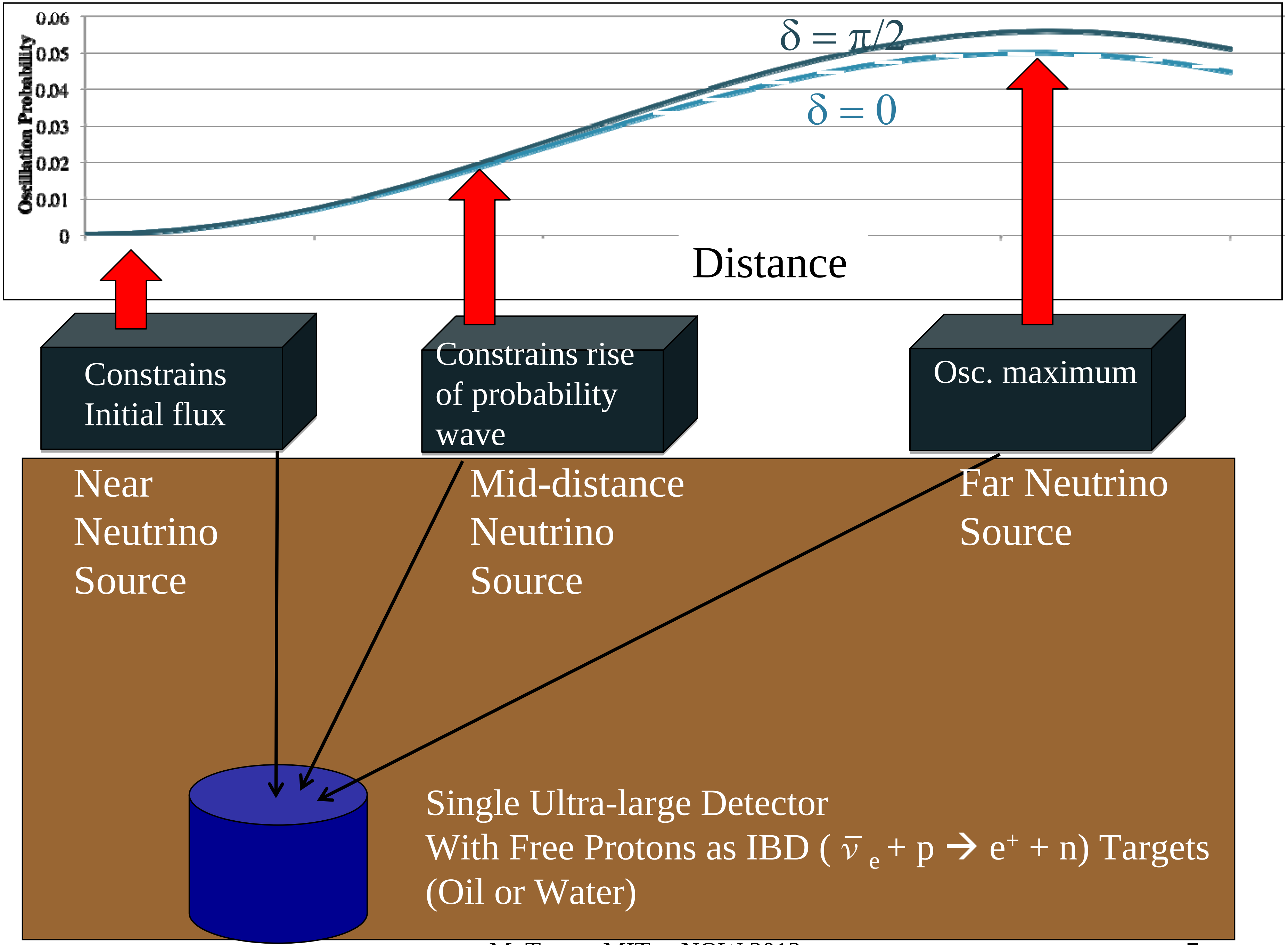
Single neutrino source

Multiple neutrino detectors at different baselines

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

Multiple neutrino sources at different baselines

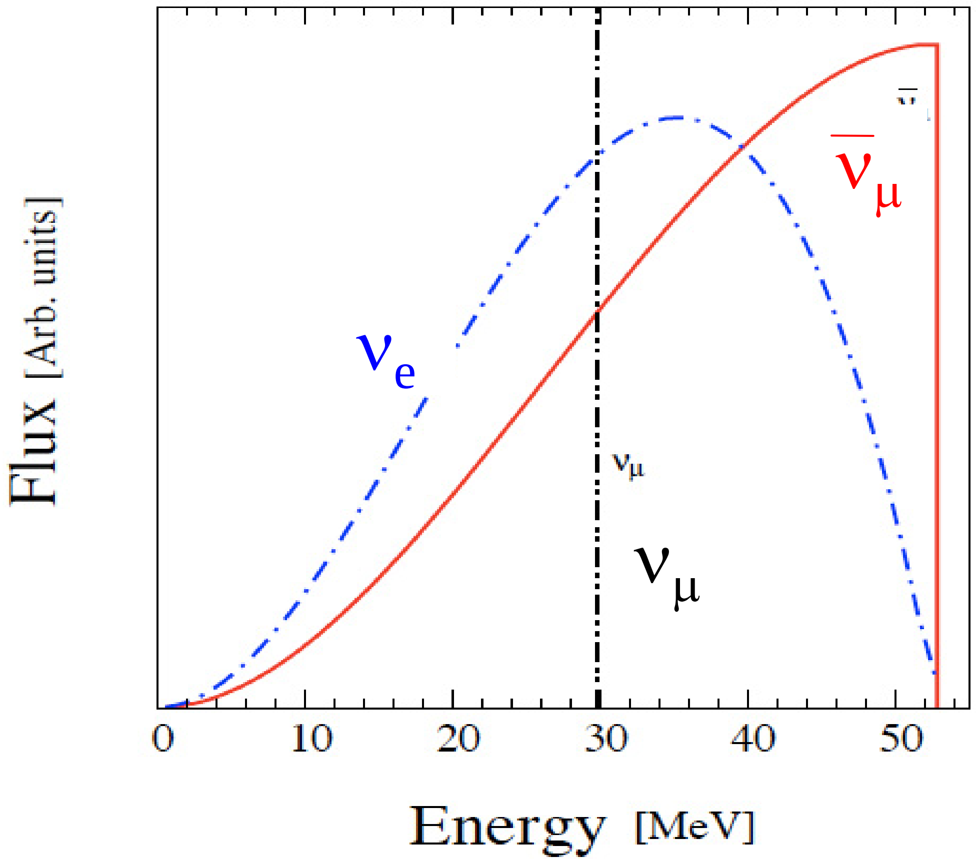
Single neutrino detector


0.06
0.05
0.04
0.03
0.02
0.01
0
Oscillation Probability
$\delta = \pi/2$
$\delta = 0$
Distance
Constrains Initial flux
Constrains rise of probability wave
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)

# The DAEδALUS Neutrino Source

## $\pi^+$ decay-at-rest (DAR) beam:

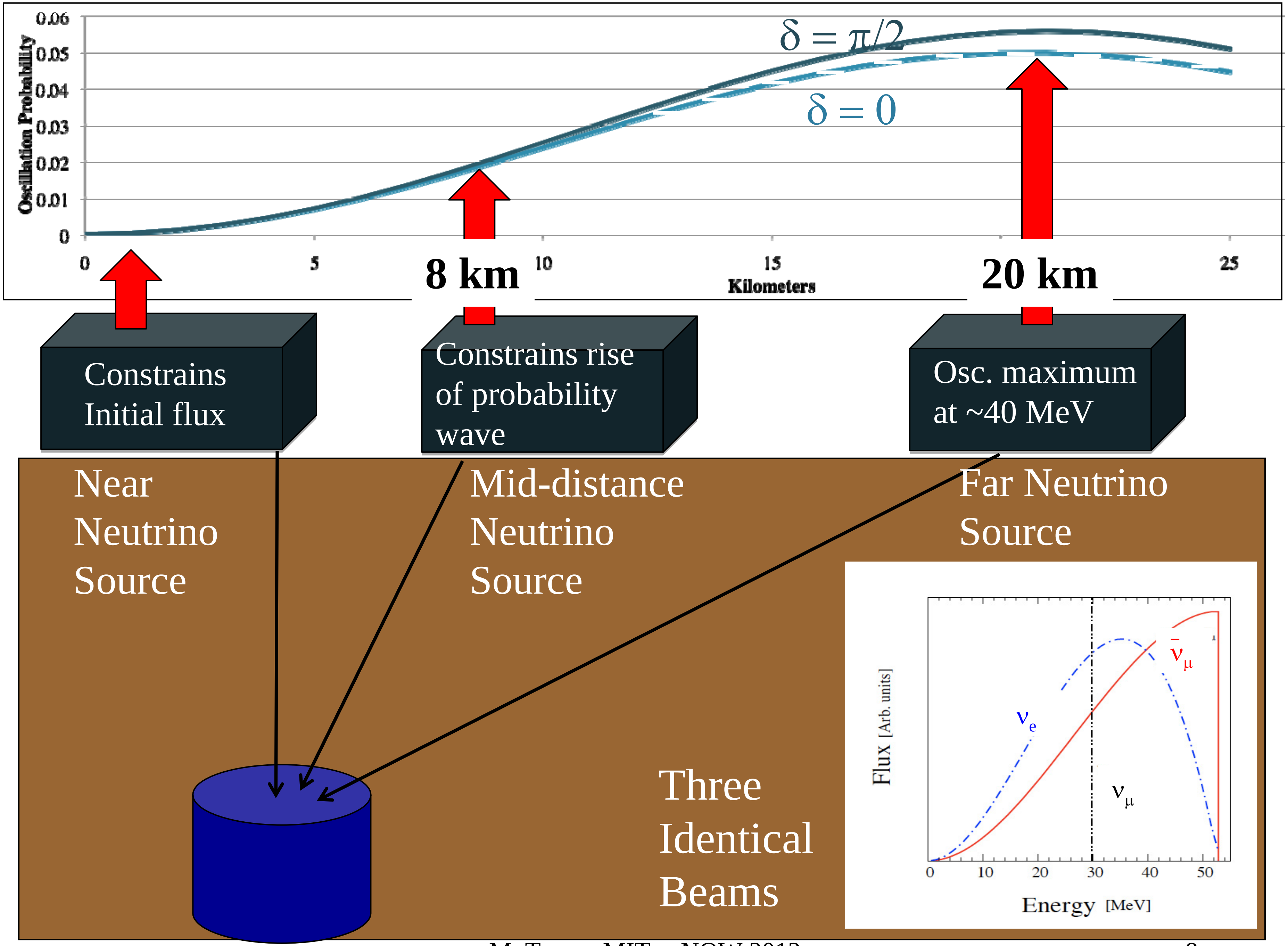
$$p + C \rightarrow \pi^+ \rightarrow \nu_\mu + \mu^+$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e,$$



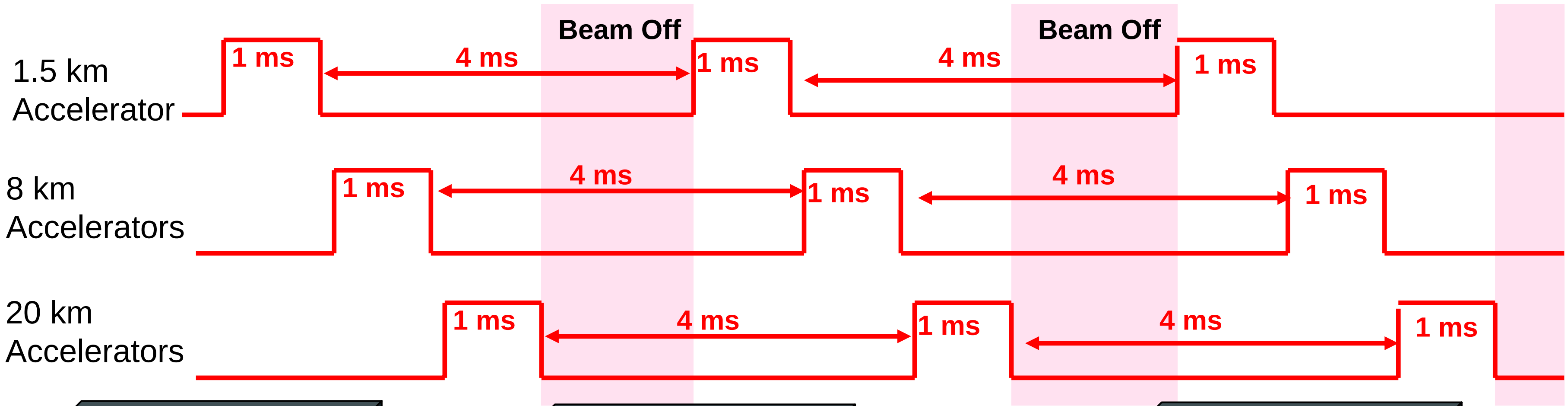

Shape driven by nature!

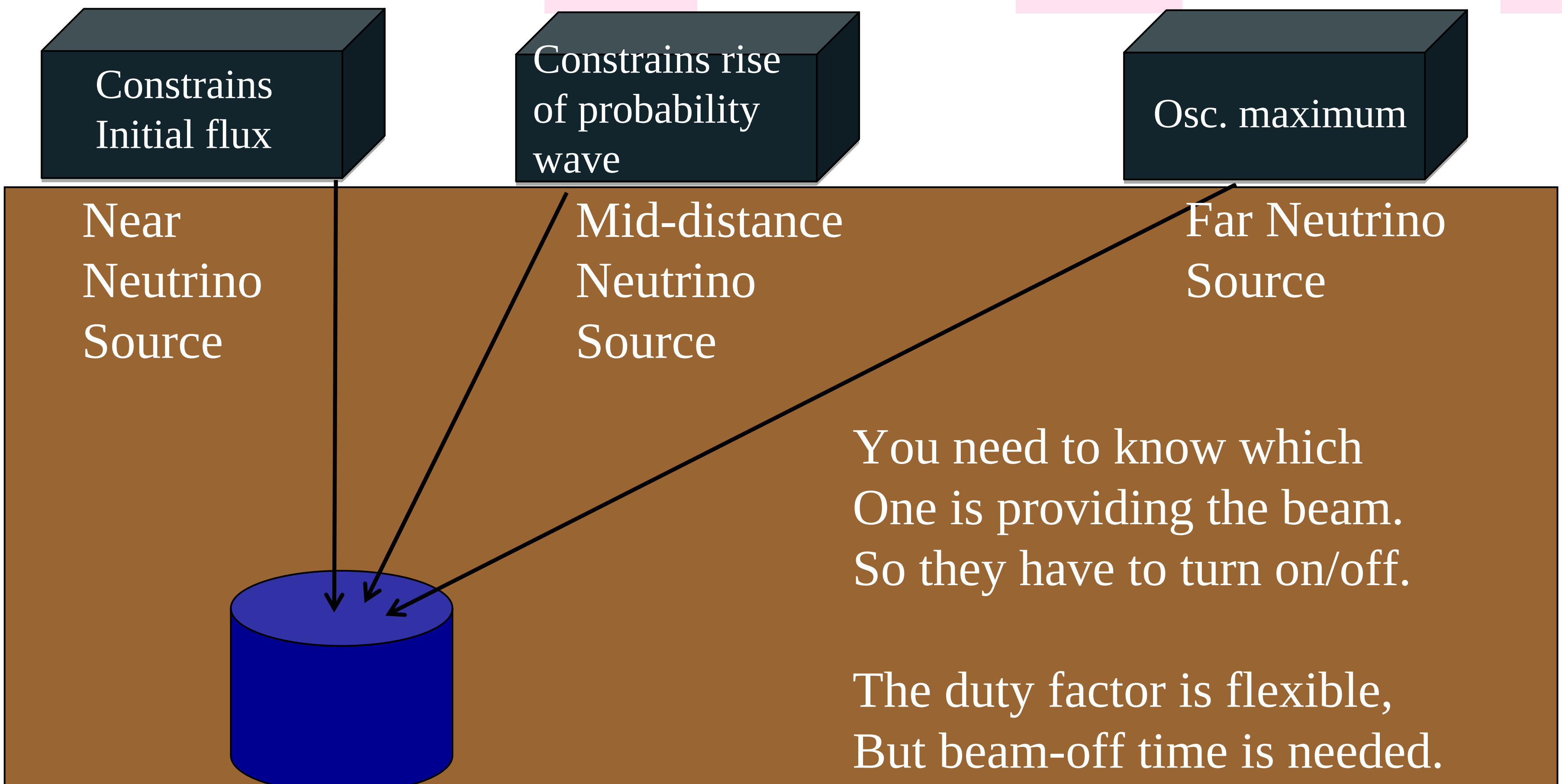
Only the normalization varies from beam to beam

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



Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
0
5
10
15
20
25
Kilometers
δ = π/2
δ = 0
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
Flux [Arb. units]
Energy [MeV]
ν̄μ
νe
νμ




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.

Measurement strategy:

Using the **near** neutrino source
measure **absolute flux normalization** with $\nu_e$-e events to ~1%,
Also, measure the $\nu_e$C event rate.

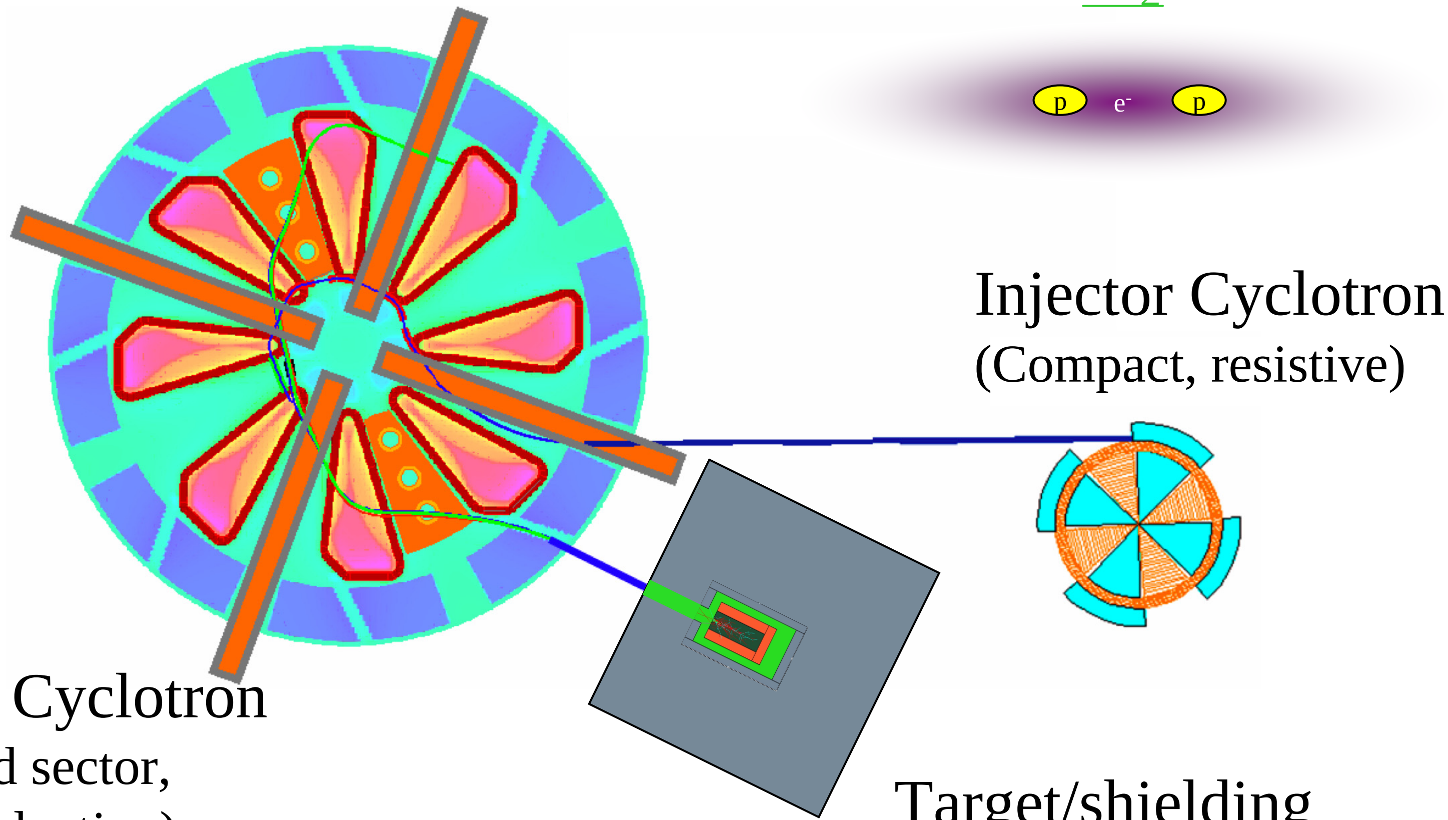
At far and mid-distance neutrino source,
Compare predicted to measured $\nu_e$C event rates
to get the **relative flux normalizations between 3 sites**

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

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 result is a decay-at-rest-flux

That can be used for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches arXiv.org > physics > arXiv:1207.4895

Physics > Accelerator Physics

# Multimegawatt DAE$\delta$ALUS Cyclotrons for Neutrino Physics

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

[a] *Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland, 20742*
[b] *Paul Scherrer Institut, CH-5234 Villigen, Switzerland*
[c] *Department of Physics, Massachusetts Institute of Technology*
[d] *Columbia University*
[e] *Istituto Nazionale di Fisica Nucleare - LNL*
[f] *Istituto Nazionale di Fisica Nucleare - LNS*
[g] *Riken*
[h] *Huddersfield University, Queensgate Campus, Huddersfield, HD1 3DH, UK*
[i] *IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706*
[j] *IBA-Research*

In this paper we address the most challenging questions regarding a cyclotron-based high-power proton driver in the megawatt range with a kinetic energy of 800 MeV. Aspects of important subsystems like the ion source and injection chain, the magnet design and radio frequency system will be addressed.

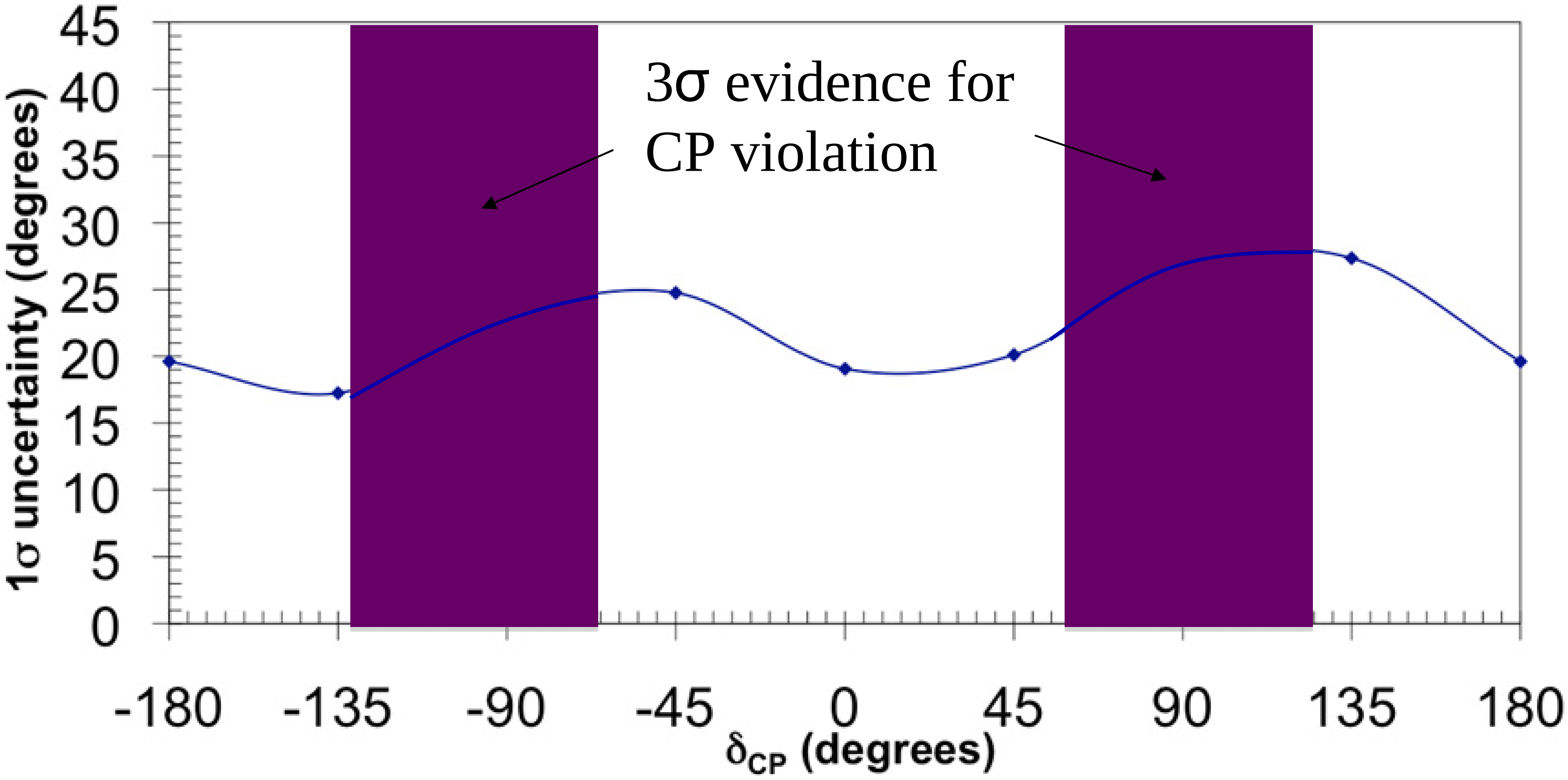
Precise beam dynamics simulations, including space charge and the $H_2^+$ stripping process, are the base for the characterization and quantification of the beam halo–one of the most limiting processes in high-power particle accelerators.

Submitted to NIM

Where can DAEδALUS run?

LENA is an outstanding possibility!

Coverage of CP violation parameter at LENA, 10 years




This gets even better if it can be played against a conventional beam!

## A two-part talk:

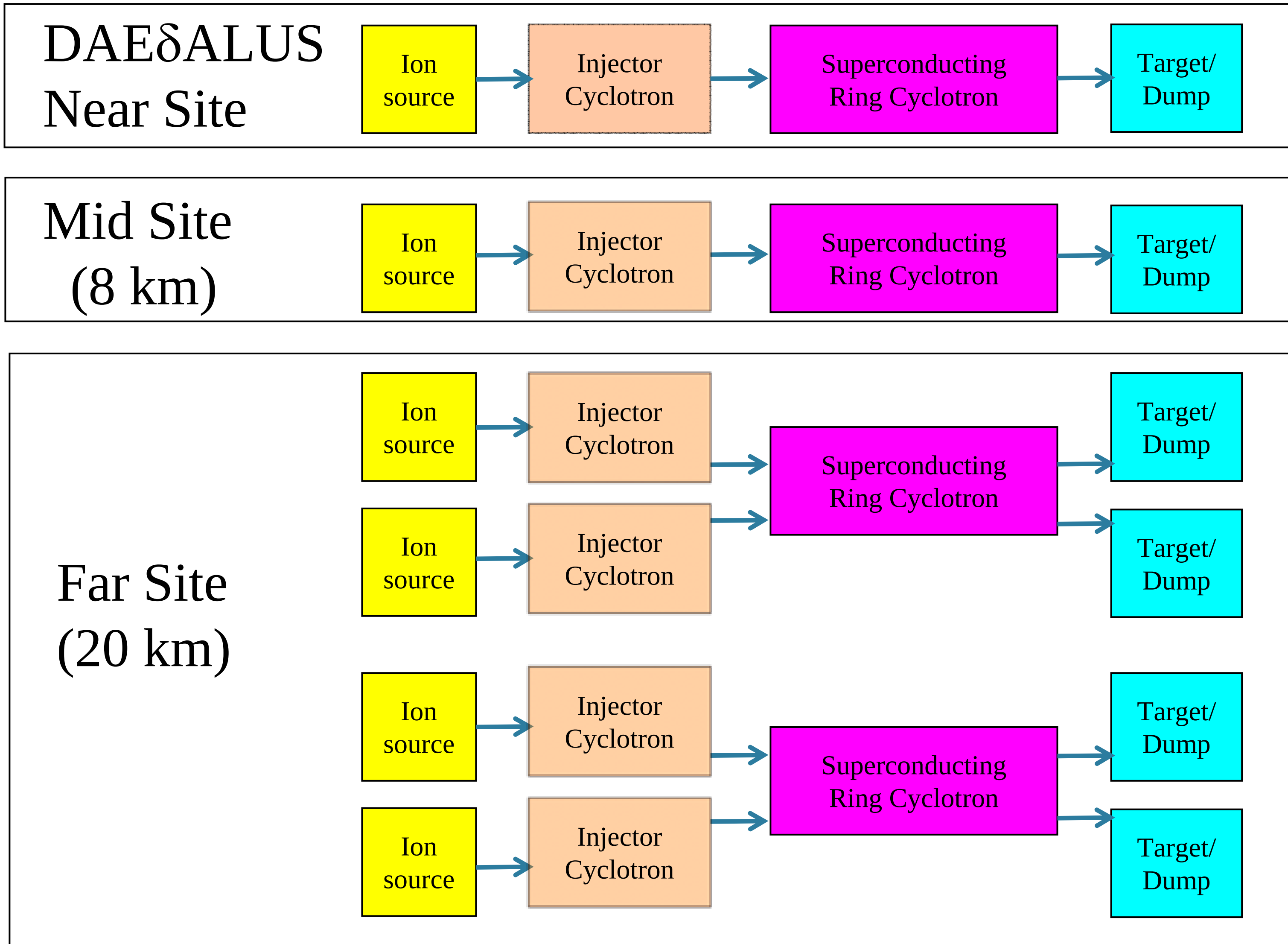
1. The experimental design for the flagship measurement:

CP Violation

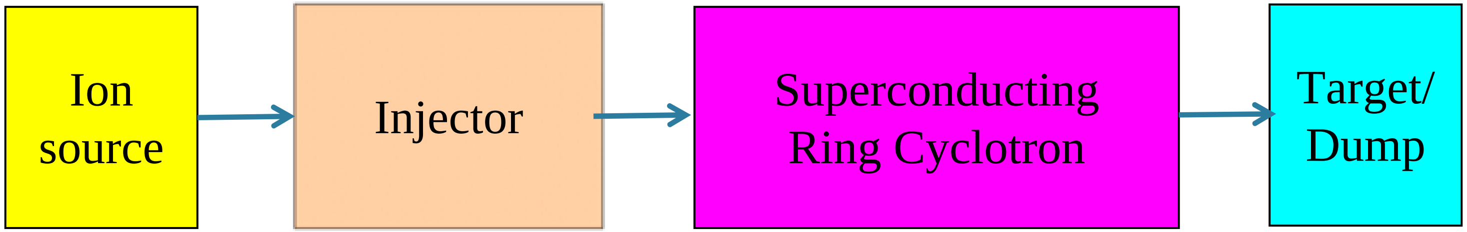
2. Implementing a phased approach with rich physics, highlighting:

The IsoDAR sterile neutrino program (Phase II)

# Design Principle: “Plug-and-play”

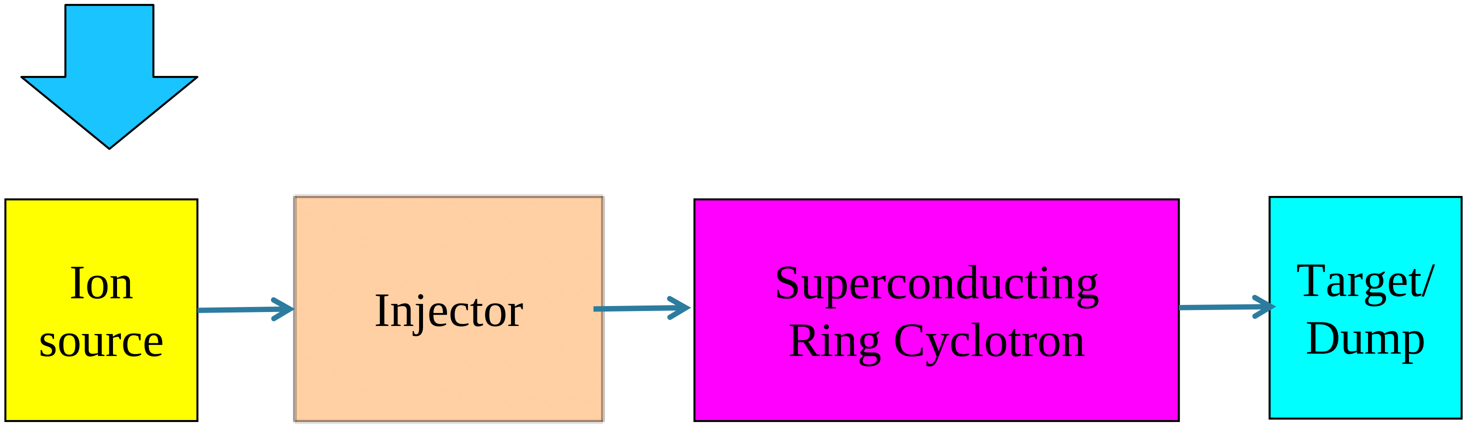


The “plug-and-play design” of what we are building

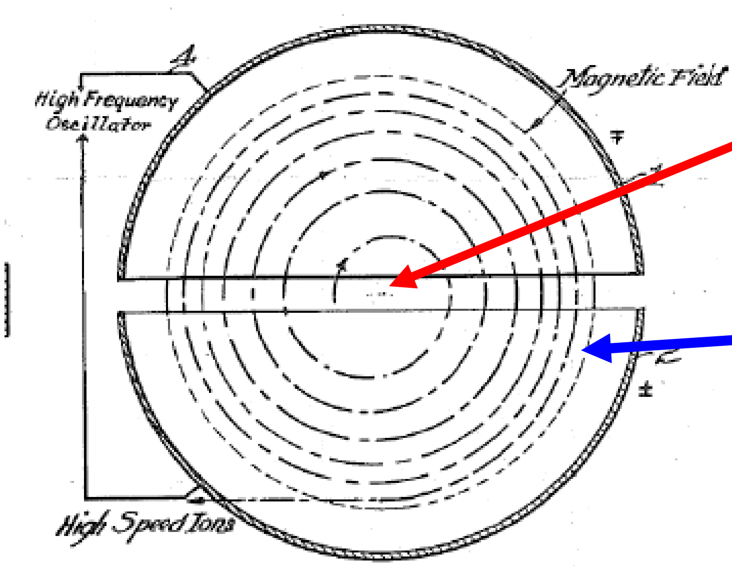



Leads to an obvious multiphase development plan

# Phase I: The Ion Source



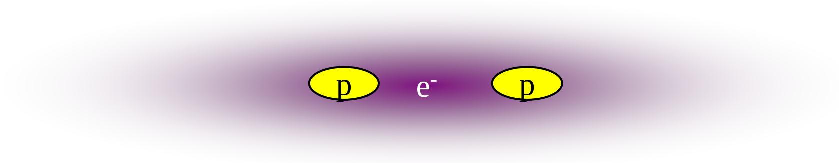
# The big issue… Space Charge Effects




If you inject a lot of charge here, it repels & beam "blows up"

As radii get closer together, bunches at different radii interact

To reduce the "space charge" at injection… we use $H_2^+$




2 protons per unit of +1 charge

Two options for extraction:

- Stripping foil
- "Classical" Electrostatic Septum

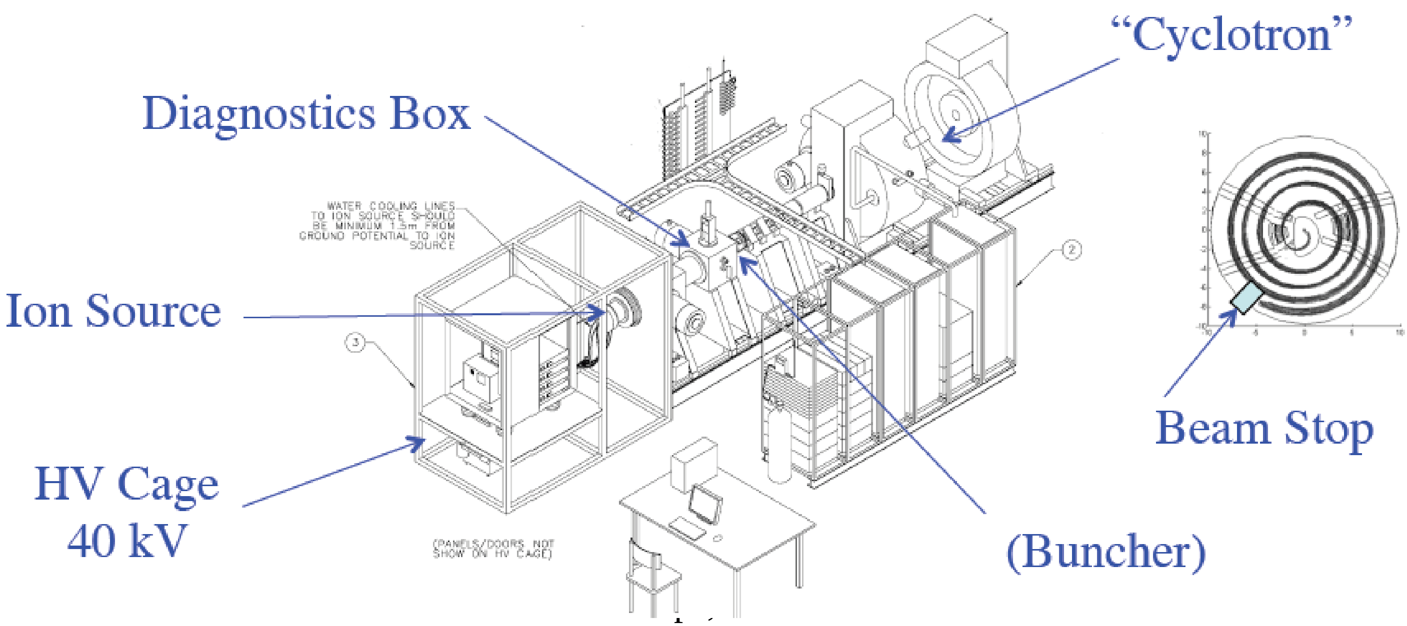
# Ion Source:

By our collaborators at INFN Catania.

→ Produces sufficient $H_2^+$!

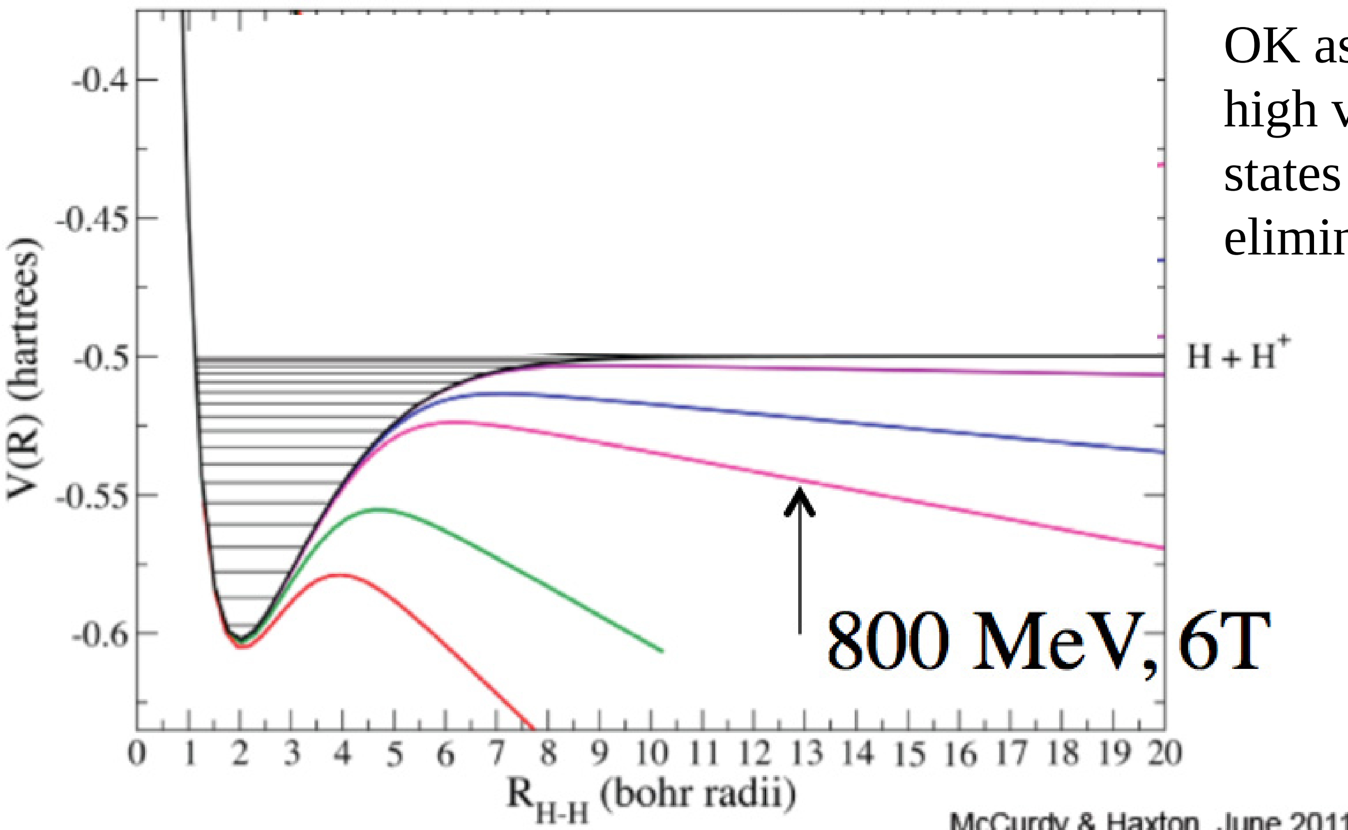
Beam to be characterized at
Best Cyclotrons, Inc, Vancouver
This winter (NSF funded)

*Test results to be available by*
*Cyclotrons'13 Conference, Sept 2013, Vancouver*



# Open Issue: Lorentz stripping

Can induce unacceptable losses of $H_2^+$ beam in the 800 MeV SRC

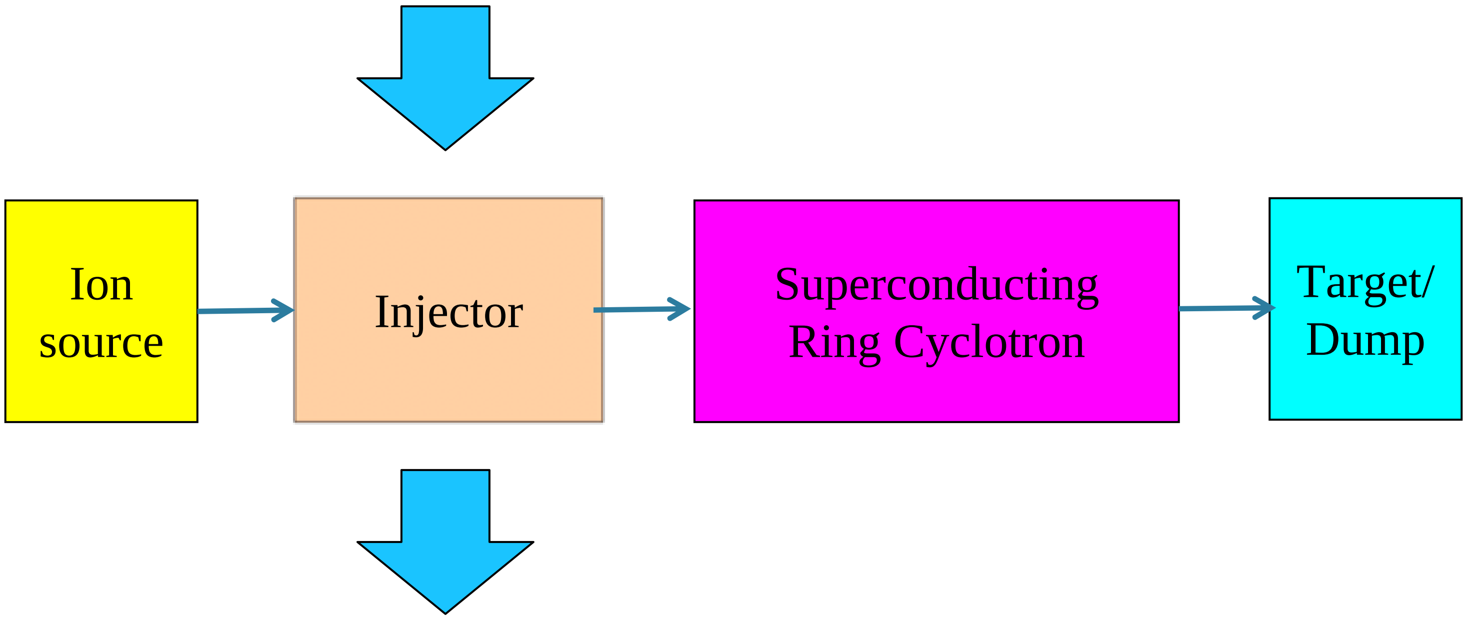



Should be OK as long as high vibrational states are eliminated

We are doing tests at Oakridge to study vibrational states from ion sources

So: some important questions remain for DAEδALUS,
But we have a workable ion source for a

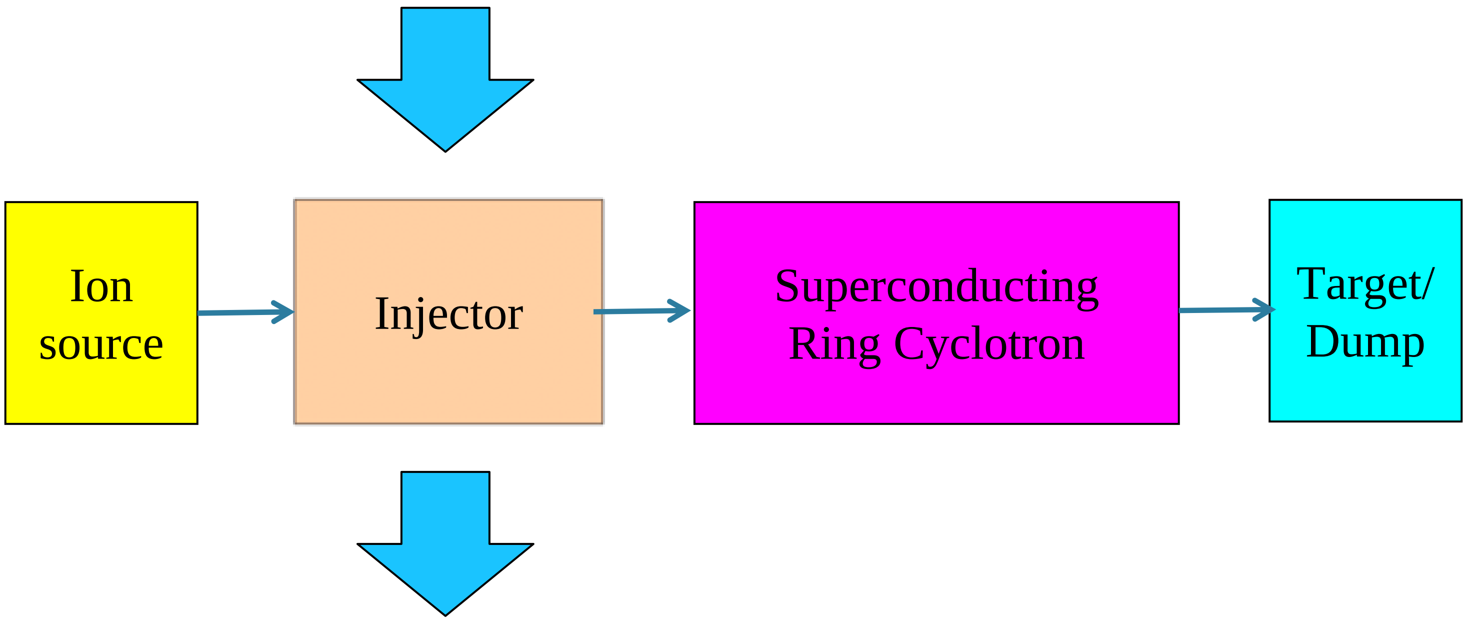
**Phase II**




# IsoDAR: A sterile neutrino experiment

So: some important questions remain for DAEδALUS,
But we have a workable ion source for a

**Phase II**




# IsoDAR: A sterile neutrino experiment


arXiv.org > hep-ex > arXiv:1205.4419

High Energy Physics – Experiment

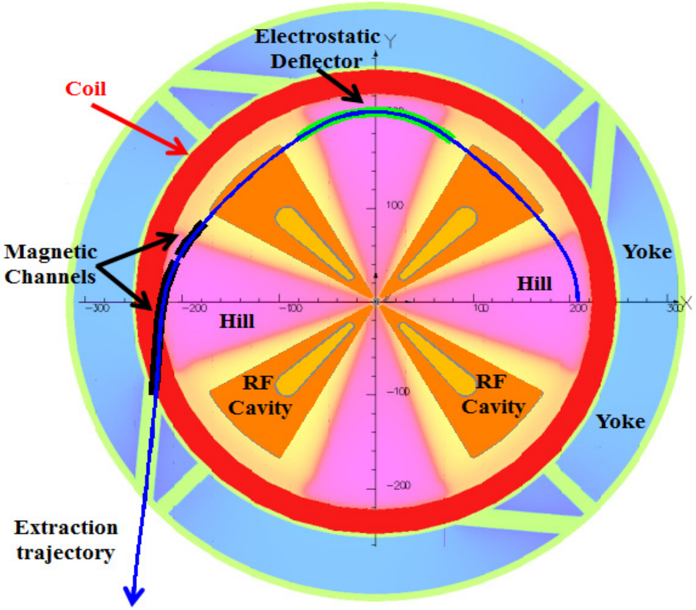
**An Electron Antineutrino Disappearance Search Using High-Rate 8Li Production and Decay**

A. Bungau, A. Adelmann, J.R. Alonso, W. Barletta, R. Barlow, L. Bartoszek, L. Calabretta, A. Calanna, D. Campo, J.M. Conrad, Z. Djurcic, Y. Kamyshkov, M.H. Shaevitz, I. Shimizu, T. Smidt, J. Spitz, M. Wascko, L.A. Winslow, J.J. Yang

← Accepted for publication in PRL

# Base Design Injector:

60 MeV/n @ 5 mA of $H_2^+$




Industry (IBA, BEST) produces ~1 mA *p* machines for isotope production:

Table 2: *Medical isotopes relevant to IsoDAR energues, from Ref. [29].*

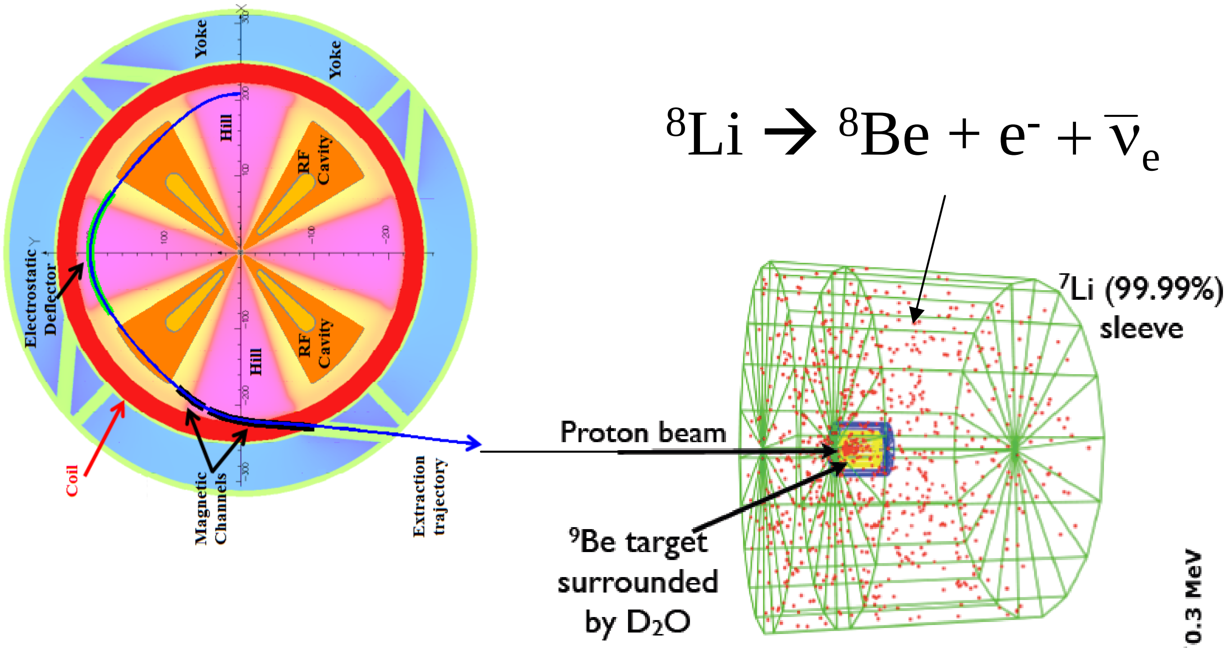
| Isotope | half-life | Use |
|---|---|---|
| $^{52}$Fe | 8.3 h | The parent of the PET isotope $^{52}$Mn and iron tracer for red-blood-cell formation and brain uptake studies. |
| $^{122}$Xe | 20.1 h | The parent of PET isotope $^{122}$I used to study blood brain-flow. |
| $^{28}$Mg | 21 h | A tracer that can be used for bone studies, analogous to calcium |
| $^{128}$Ba | 2.43 d | The parent of positron emitter $^{128}$Cs. As a potassium analog, this is used for heart and blood-flow imaging. |
| $^{97}$Ru | 2.79 d | A $\gamma$-emitter used for spinal fluid and liver studies. |
| $^{117m}$Sn | 13.6 d | A $\gamma$-emitter potentially useful for bone studies. |
| $^{82}$Sr | 25.4 d | The parent of positron emitter $^{81}$Rb, a potassium analogue This isotope is also directly used as a PET isotope for heart imaging. |

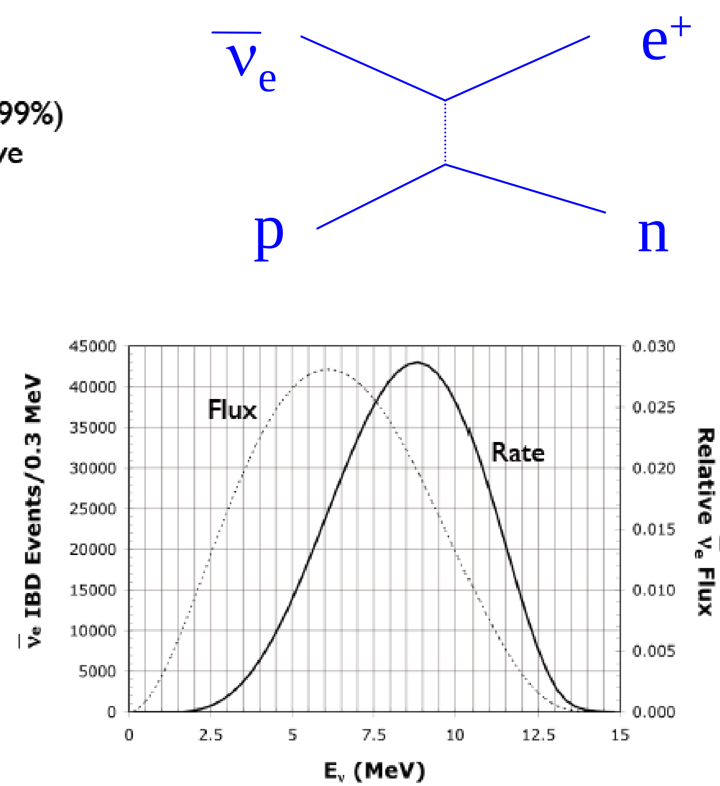
At 60 MeV/n, we can use this to make isotopes that beta-decay-at-rest…

# IsoDAR

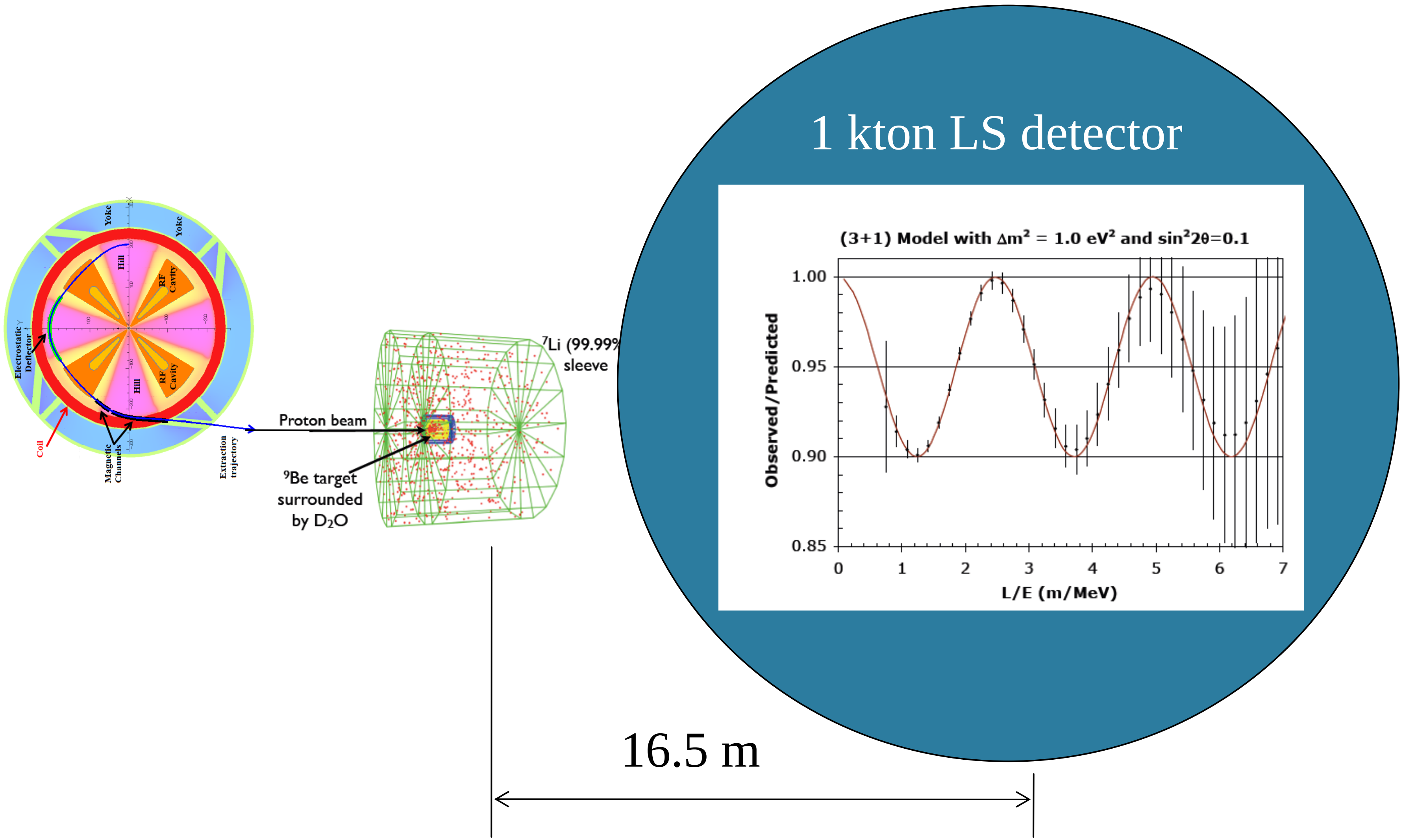
$^{8}Li \rightarrow {}^{8}Be + e^- + \bar{\nu}_e$

In liquid scintillator



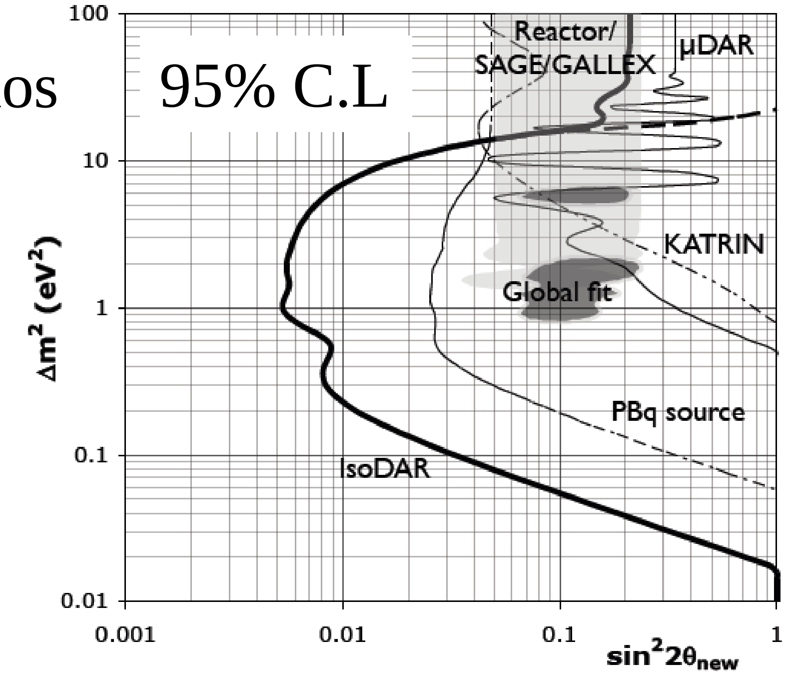
# Use this low-energy pure $\bar{\nu}_e$ source to search for sterile neutrinos!




Potential locations: KamLAND, SNO+, Borexino

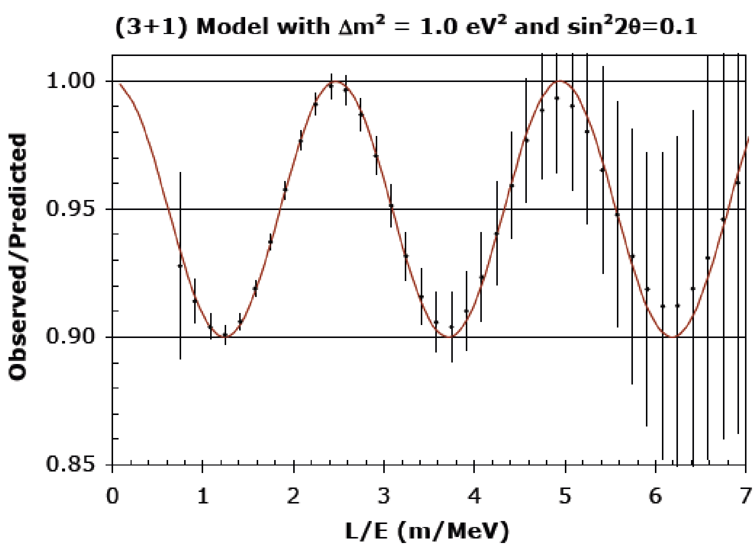
Outstanding sensitivity to sterile neutrinos à la the reactor neutrino anomaly…

…can be ruled out at > 5σ
in 4 months of running!

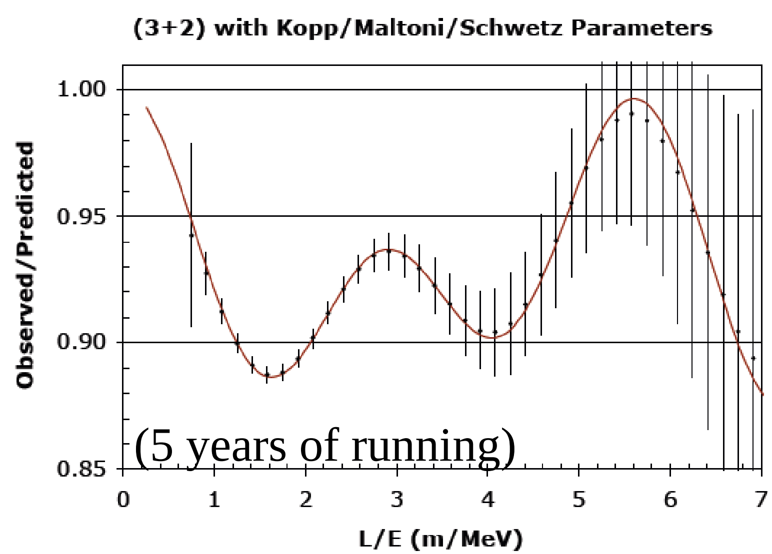



Ability to discriminate between models!

3+1




3+2

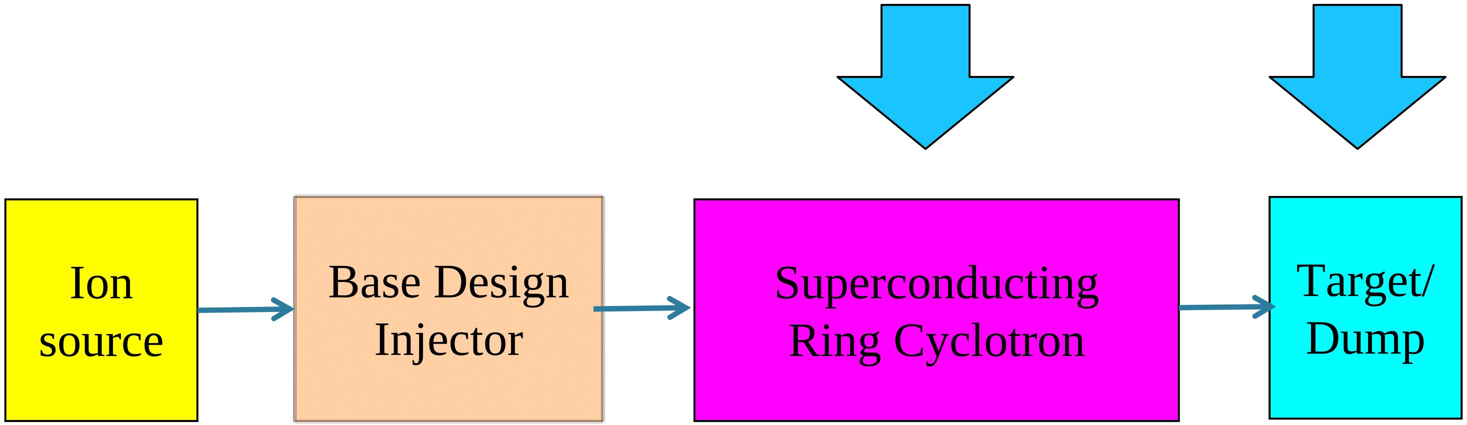


Along with sterile neutrino searches…

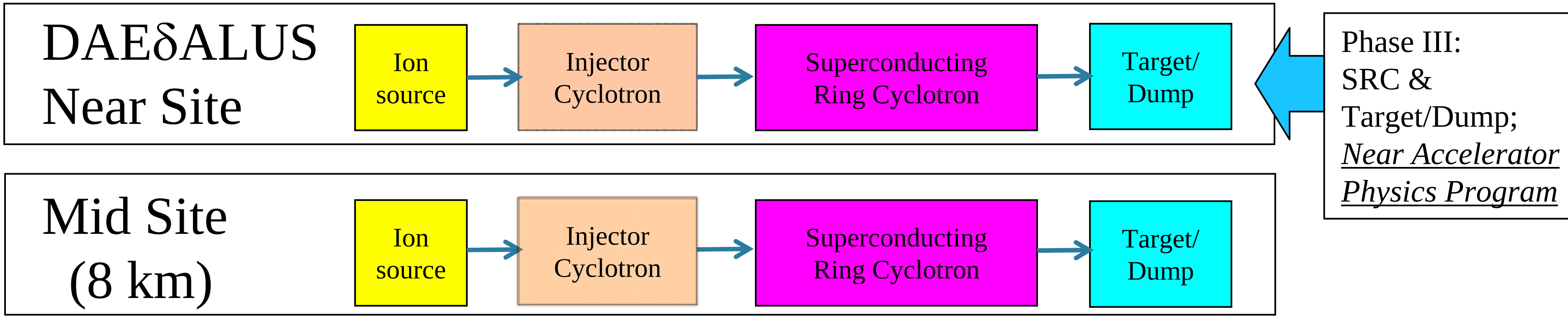
- Searches for new particles produced in dump
- Studies of antineutrino-electron scattering
- More ideas welcome!

The science capability is outstanding.
This is of interest to the medical isotope industry!
This moves DAE$\delta$ALUS forward!

# Phases III and IV

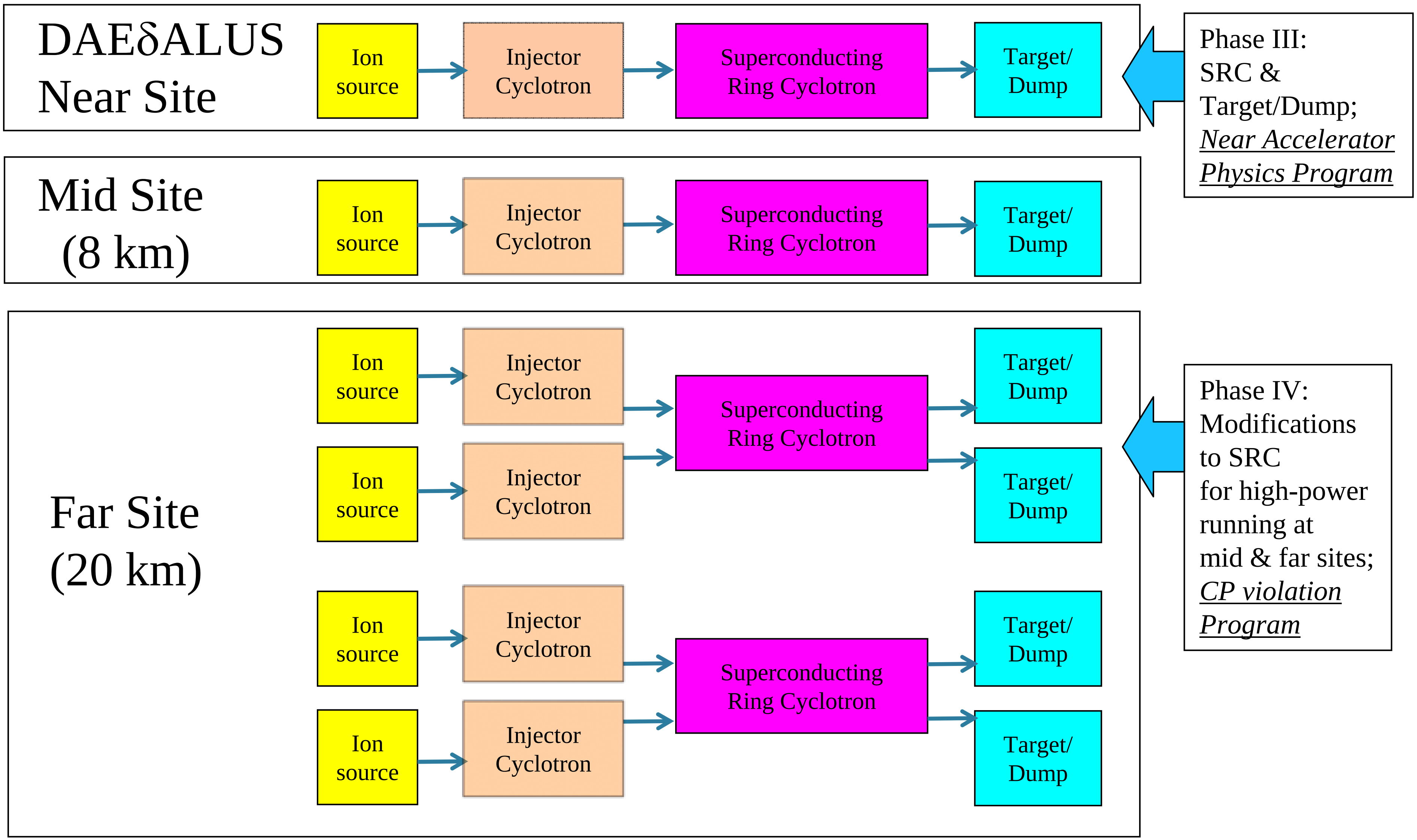



Establish the “standard” system
And the the high-power system

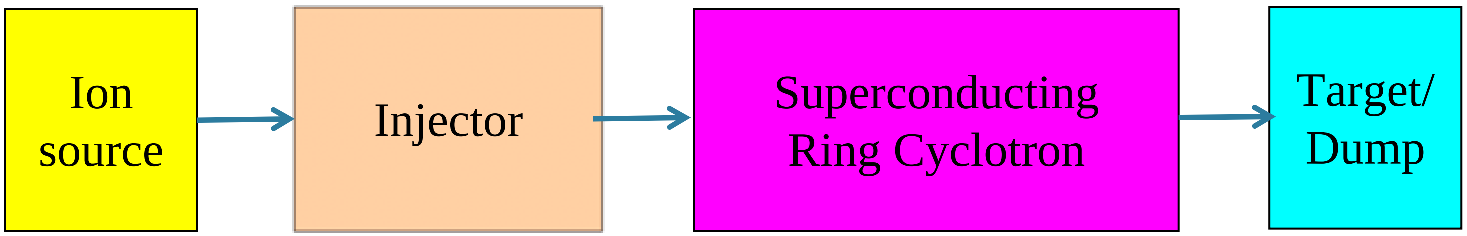



## Many exciting possibilities for a near accelerator physics program:

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

# Summary…




Existing Prototype, Tests Funded & Ongoing.

Advanced Design, Proposing A physics Program: **IsoDAR**

1st Engineering Design soon to undergo external review

Least Advanced, But based On past designs

# Conclusions

DAEδALUS

Is…

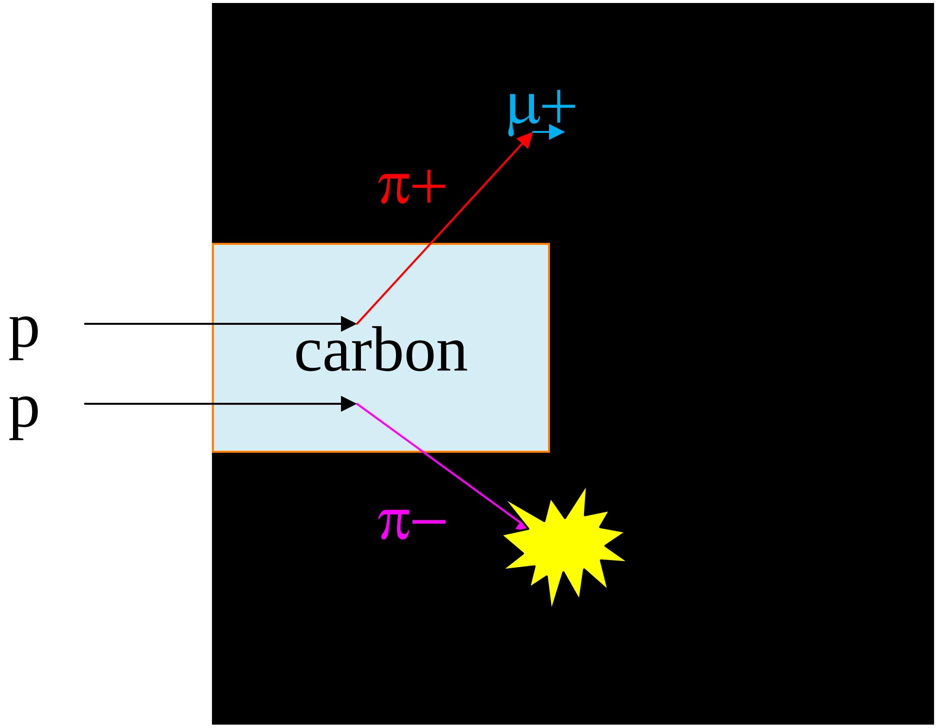
A phased program with strong physics along the way
(especially the IsoDAR sterile neutrino search!)

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

# Other Slides

We will use 1 MW targets (we can use multiple targets)
Design is well understood from past DAR experiments…

Light target embedded in a heavy target




Also,
no upstream
targets!!!

# Our proposed 800 MeV cyclotron is very similar to the existing Riken, Japan, cyclotron:

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

…will be available this autumn

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 | |

# Some other useful articles (beyond those already highlighted)…

arXiv:1205.5790 [pdf, ps, other]

**Target Studies for the Production of Lithium8 for Neutrino Physics Using a Low Energy Cyclotron**
Adriana Bungau, Roger Barlow, Michael Shaevitz, Janet Conrad, Joshua Spitz
Comments: 3 pages, 6 figures, IPAC 2012
Subjects: **Accelerator Physics (physics.acc-ph)**; Nuclear Experiment (nucl-ex)

arXiv:1205.5528 [pdf, ps, other]

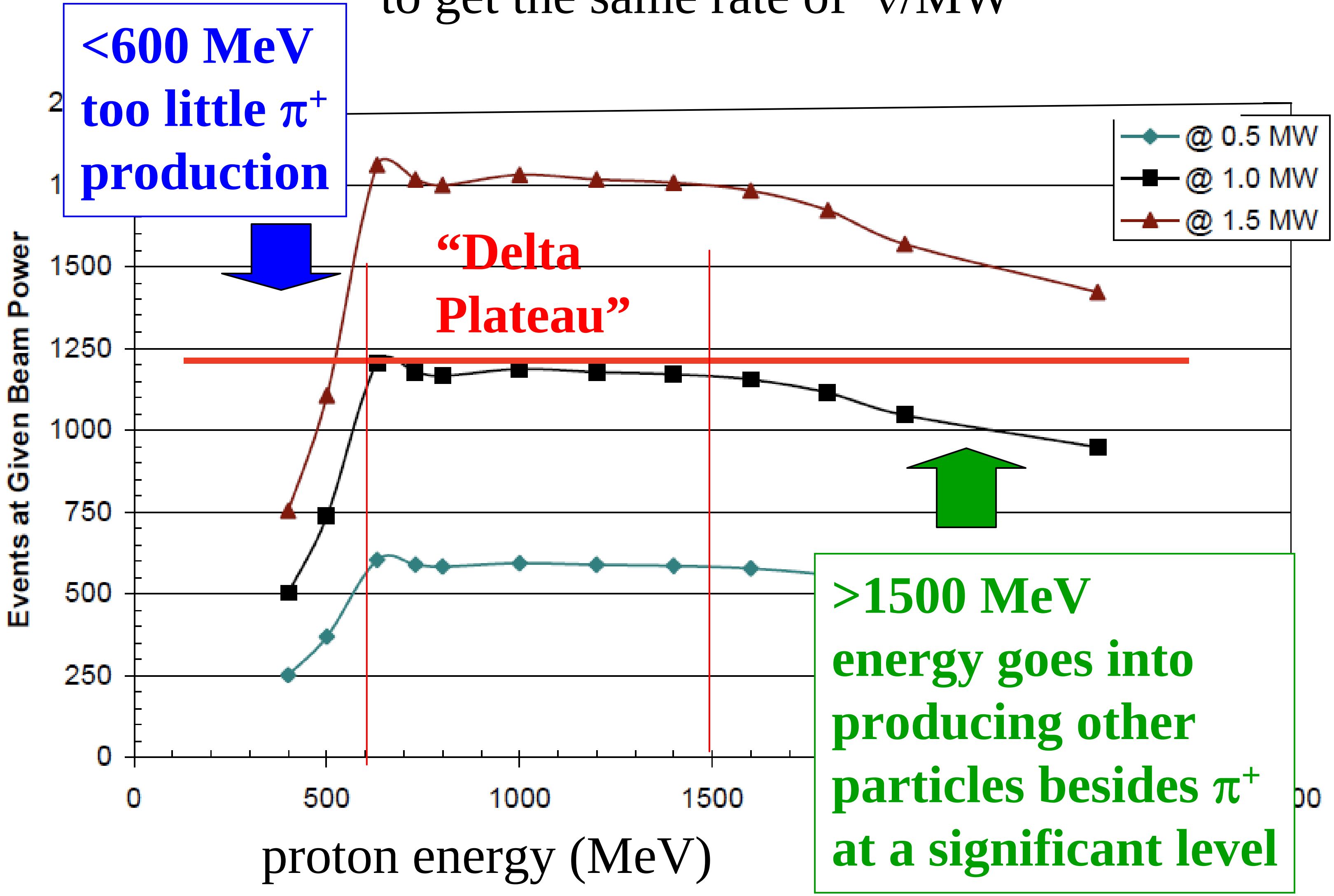
**Simulations of Pion Production in the DAEδALUS Target**
Adriana Bungau (1), Roger Barlow (1), Mike Shaevitz (2), Janet Conrad (3), Joshua Spitz (3), Tess Smidt (3) ((1) University of Huddersfield, (2) Columbia University, (3) Massachusetts Institute of Technology), for the DAEδALUS Collaboration
Comments: 3 pages, 3 figures, IPAC 2012
Subjects: **Instrumentation and Detectors (physics.ins-det)**; High Energy Physics - Experiment (hep-ex); Nuclear Theory (nucl-th)

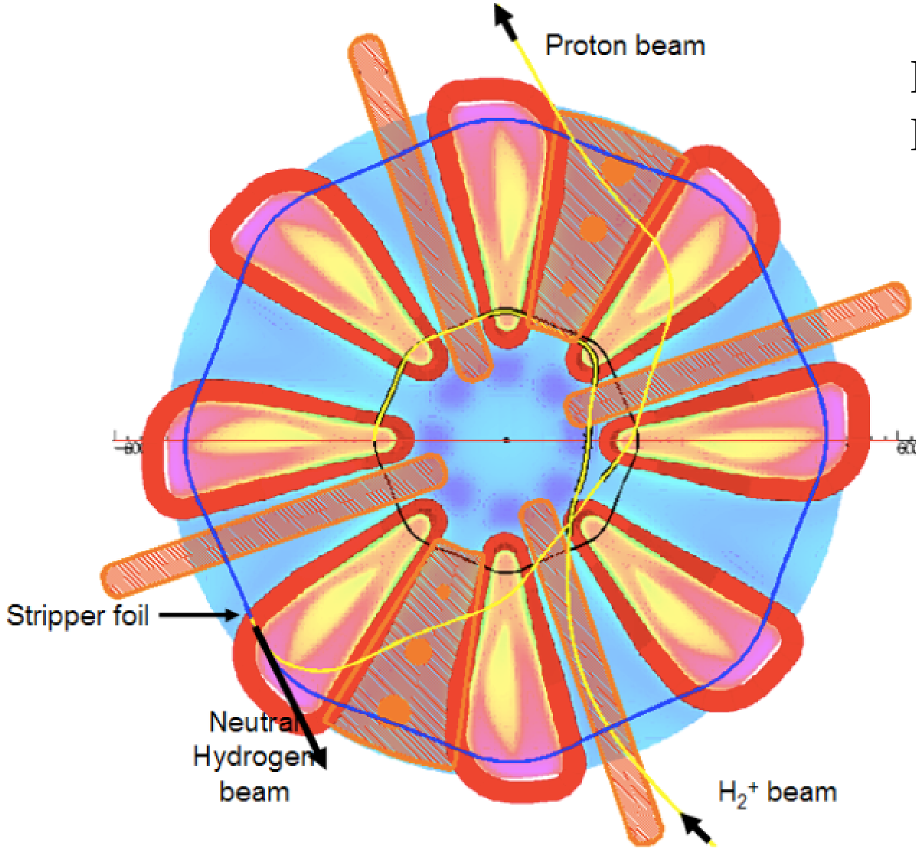
arXiv:1107.0652 [pdf]

**Preliminary Design Study of High-Power H2+ Cyclotrons for the DAEdALUS Experiment**
L. Calabretta, L. Celona, S. Gammino, D. Rifuggiato, G. Ciavola, M. Maggiore, L.A.C. Piazza, J.R. Alonso, W.A. Barletta, A. Calanna, J.M. Conrad
Subjects: **Accelerator Physics (physics.acc-ph)**; High Energy Physics - Experiment (hep-ex)

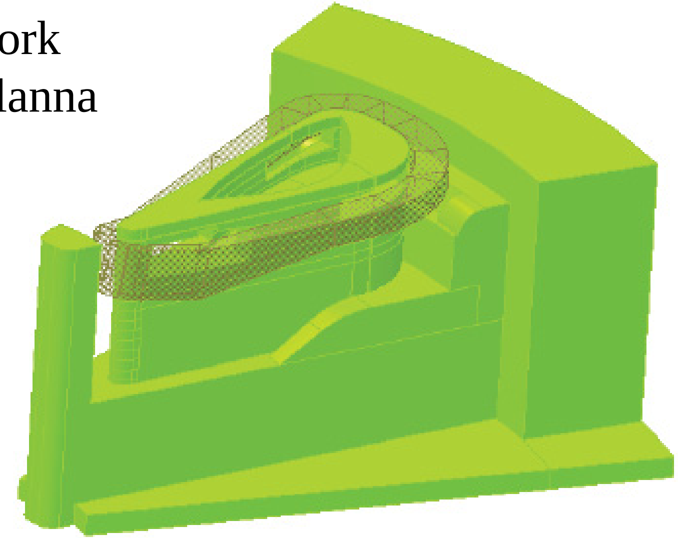
What proton energy is required?

There is a "Delta plateau" where you can trade energy for current to get the same rate of $\nu$/MW

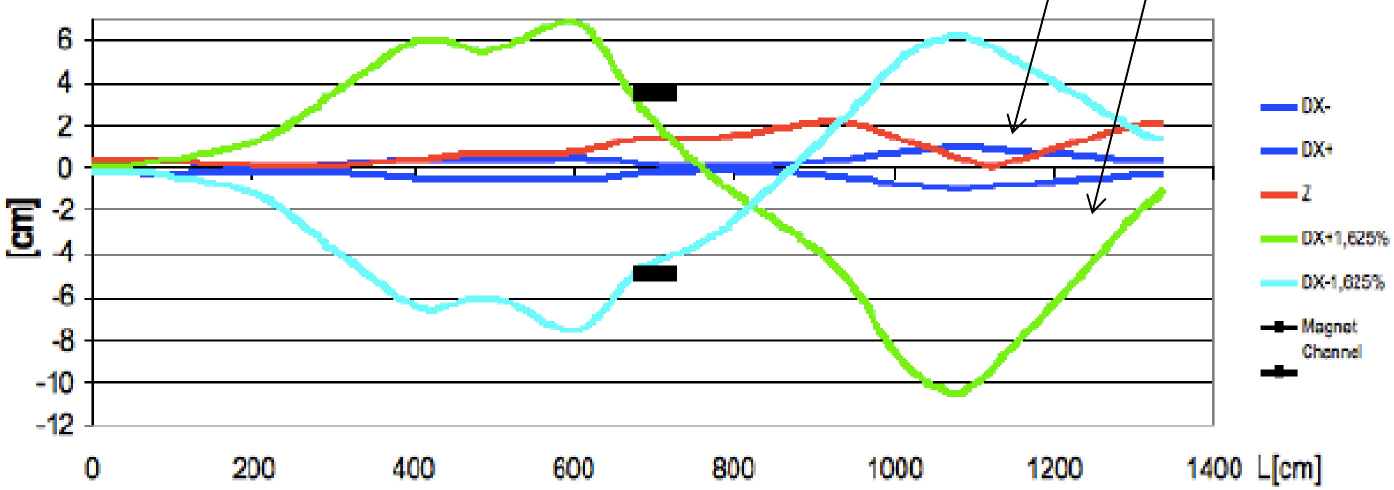





Design work
By A. Calanna

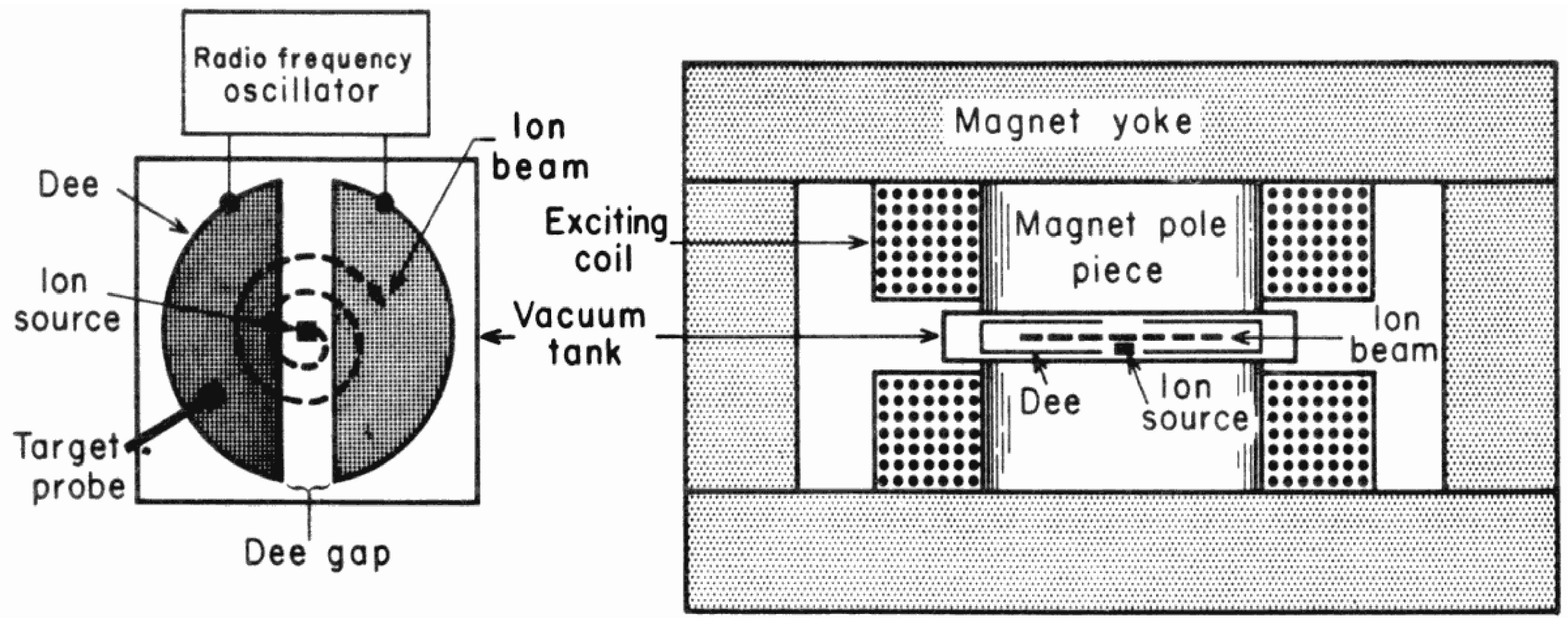


Beam envelope,
No energy spread,
1% spread



# To produce the 800 MeV protons, we use Cyclotrons:

- Inexpensive,
- Practical below ~1 GeV
- Good if you don't need short timing structure
- Typically single energy
- Taps into existing industry




We use an "isochronous cyclotron" design (magnetic field changes with radius)

⟶ Allows multi-bunch acceleration

The most challenging aspect:
The Superconducting Ring Cyclotron

Original design

# Multi Megawatt DAEδALUS Cyclotrons for Neutrino Physics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For ADS/thorium reactor applications,
see web for our talk at

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