Short-baseline oscillations: DAEδALUS and IsoDAR with LENA

Oxford, 3 July 2012

Michael Wurm
Universität Hamburg

Outline

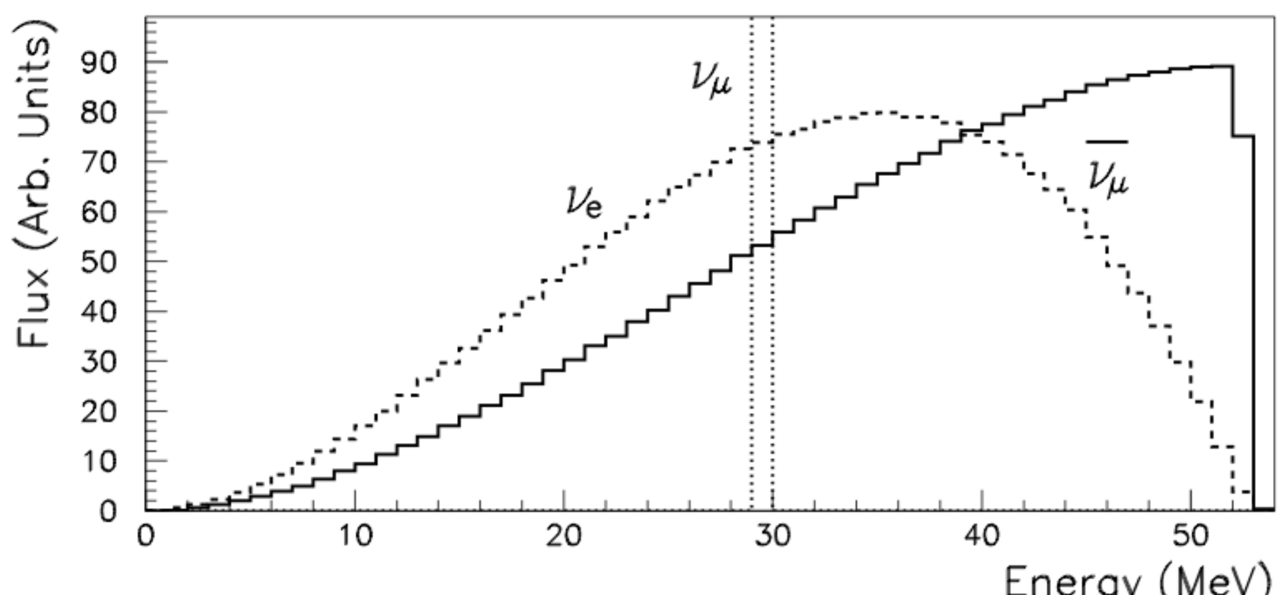
- Decay-at-rest (DAR) neutrino sources
- Experimental setup for π-DAR beam measuring CP-violating phase
  (aka DAEδALUS)
- Experimental setups for sterile neutrino search
  (piDAR and IsoDAR)
- Expected sensitivities

Pion Decay-at-Rest (piDAR) source

- Resonant production of pions by low-energy (~1GeV), high-power (~MW) proton beam
- π^+ are stopped and decay via (π⁻ absorbed in target, $\bar{\nu}_e$<0.04%)

$$\pi^+ \rightarrow \mu^+ \nu_\mu; \qquad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

→ Low energy (10-50 MeV) 'neutrino beam' of ν_e, ν_μ and $\bar{\nu}_\mu$



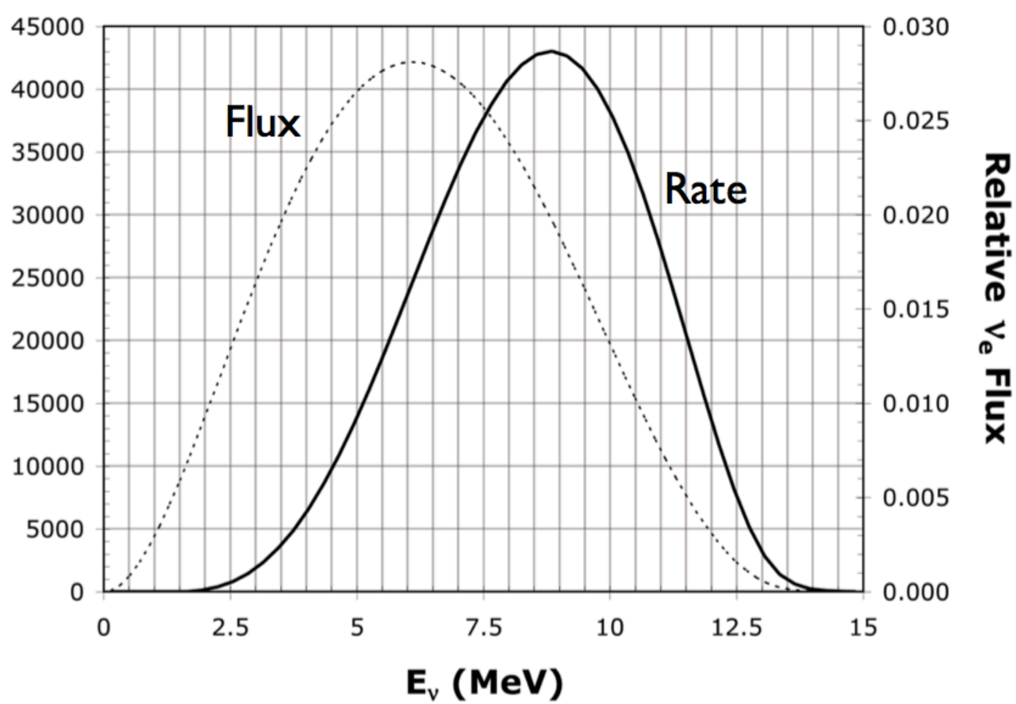
spectral shape driven by nature

Isotope Decay-at-Rest (IsoDAR) source

- Beam-induced production of b⁻-decaying isotopes
- Good candidate: ^{8}Li

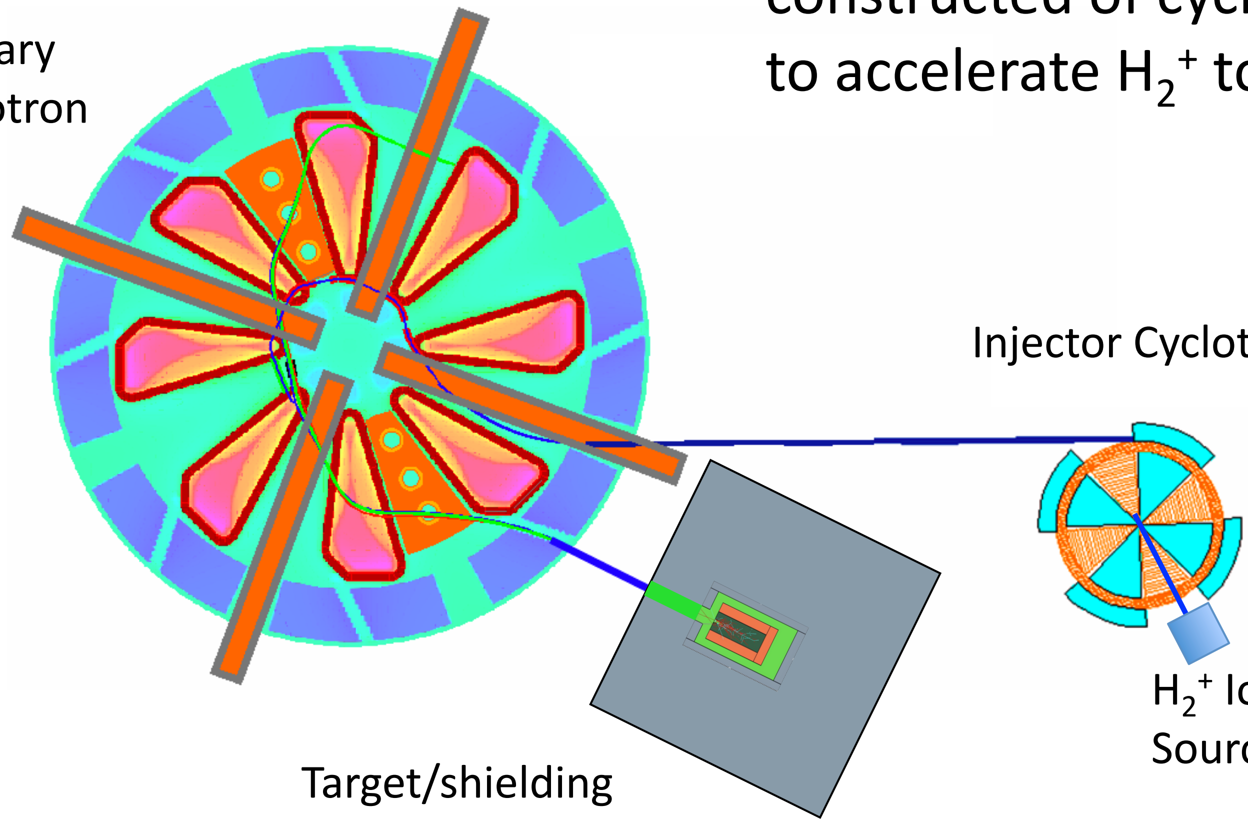
$$p + \mathrm{Be} \rightarrow \mathrm{X} + \mathrm{n}; \qquad {}^{7}\mathrm{Li} + \mathrm{n} \rightarrow {}^{8}\mathrm{Li} \rightarrow 2\alpha + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

→ Pure $\bar{\nu}_e$ ‘neutrino beam‘ at several MeV peak energy



Proton source: High-power cyclotrons

Uses Multiple "Accelerator Units" constructed of cyclotrons to accelerate H_2^+ to 800 MeV



The result is a decay-at-rest-flux
That can be used for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches

piDAR experiment for δ_{CP}

DAEδALUS

@LENA

How to measure δ_{CP} with antineutrinos only

DAEδALUS approach: Use $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance and exploit the L/E dependence in absolute rates

SBNO, so no matter effects!
→ oscillation probability in vacuum

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

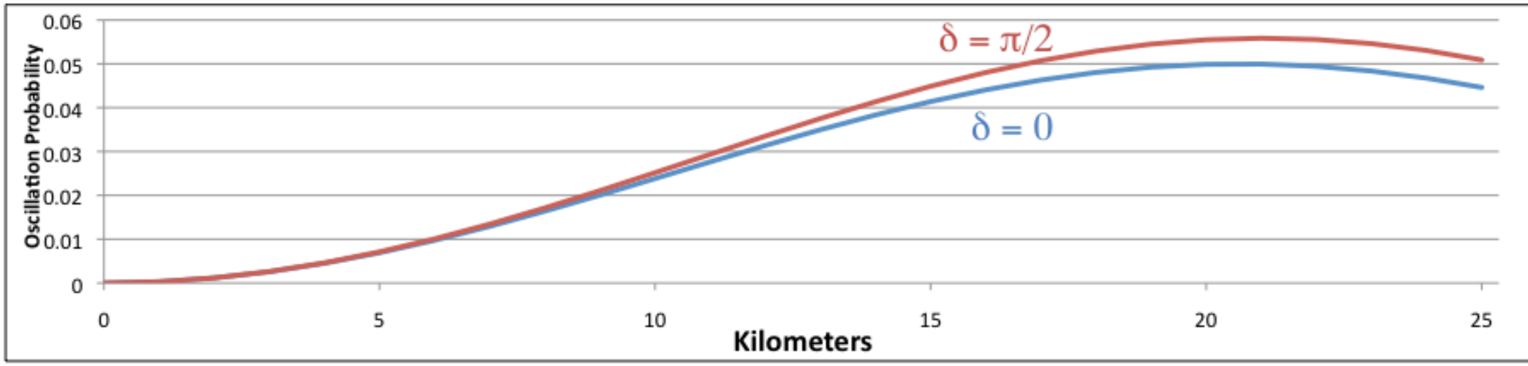
We want to see if δ is nonzero

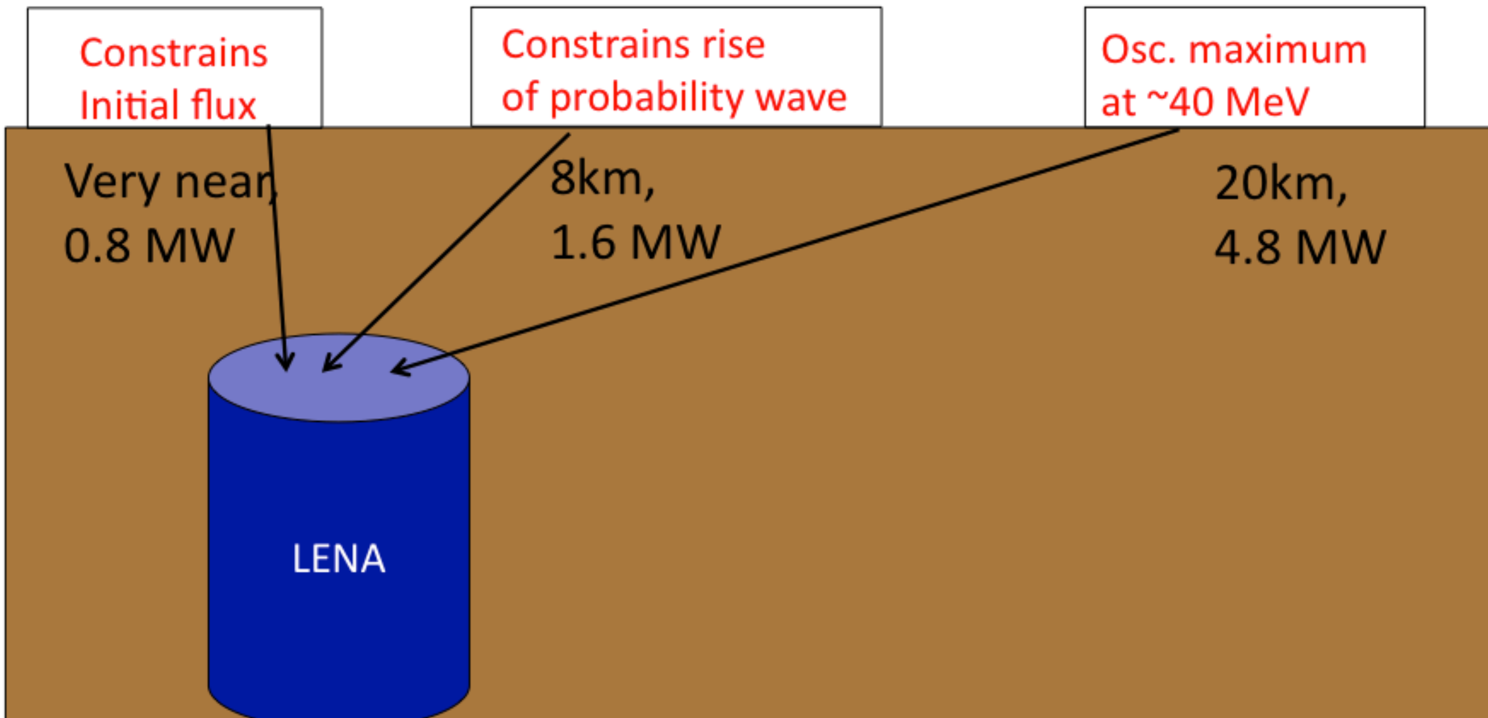
terms depending on mixing angles

terms depending on mass splittings

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

DEAδALUS‘ three-baseline design





Extraction of oscillation signature

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

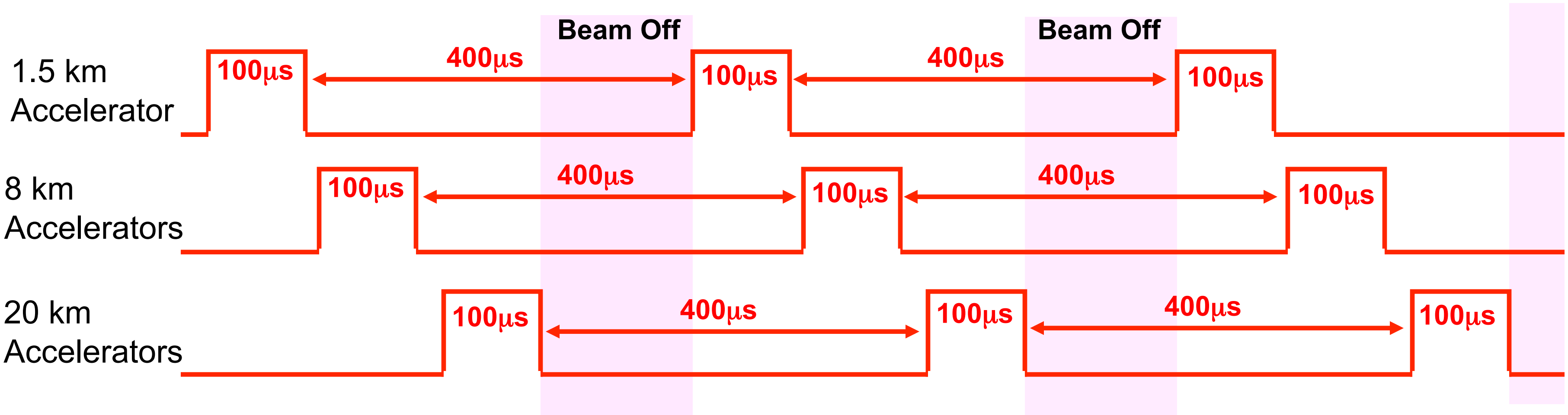
↓

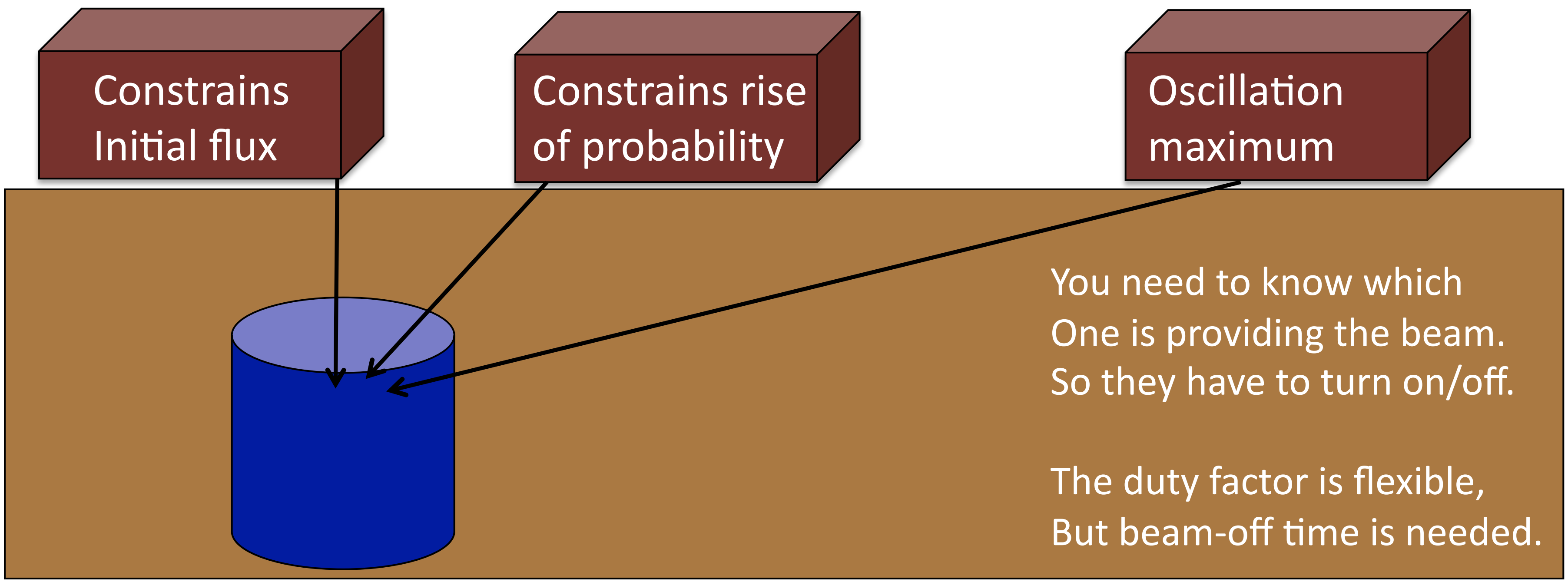
At far and mid accelerator,
Compare predicted to measured ν_eC event rates
to get the **relative flux normalizations between 3 accelerators**

↓

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

Pulsing of the beam source





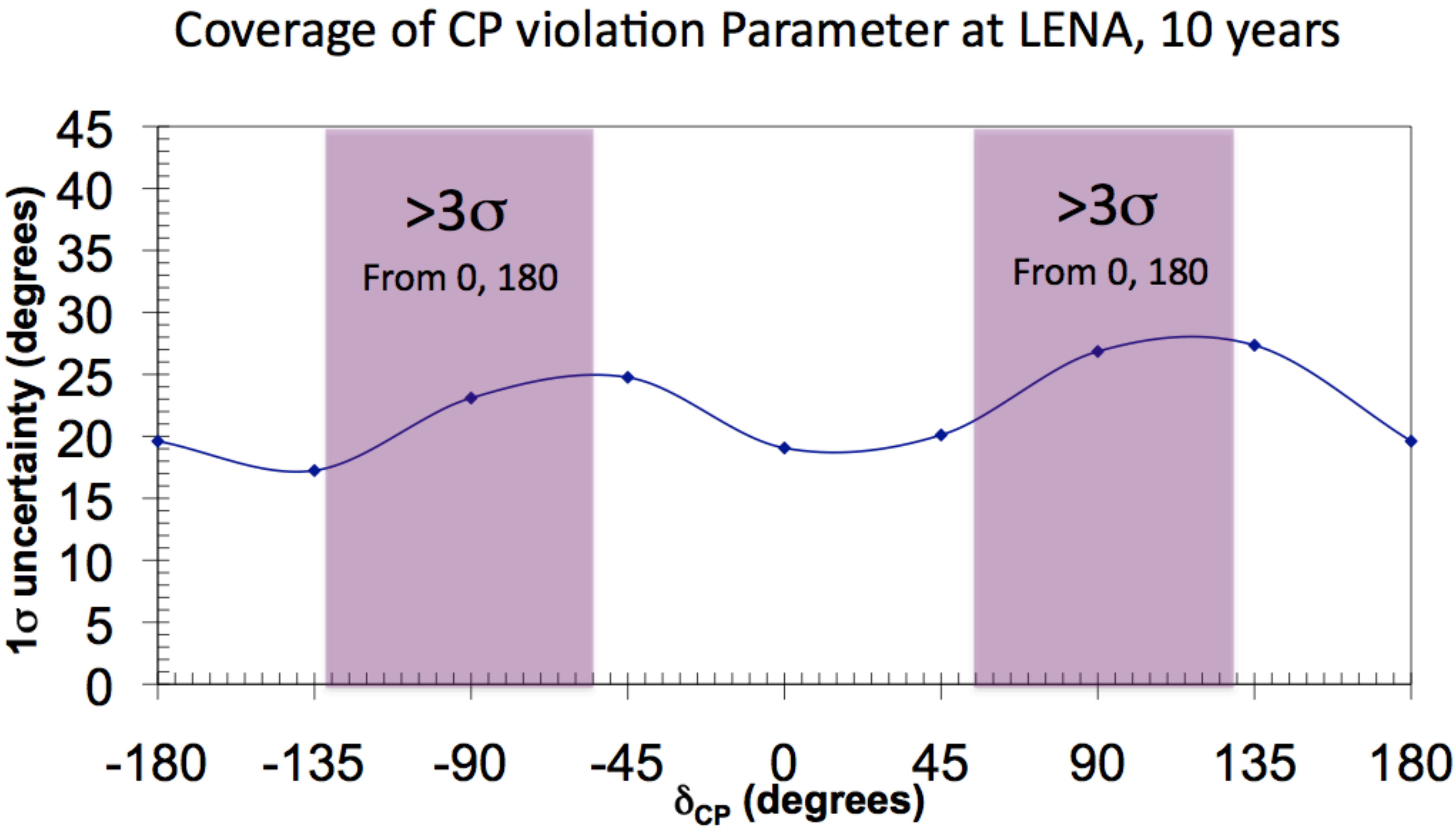
LENA as detector for DAEδALUS

- Original proposal assumed Gd-doped 200kt water Cherenkov detector (LBNE)
- LENA is smaller (50kt), but features better detection efficiency for inverse β-decay and discrimination for νe, $\nu^{12}C$ channels
- First estimate from INT conference uses

detector mass:	42.5kt	
IBD detection efficiency:	63%	*low!*
atmospheric ν background:	no	
duty cycle of cyclotrons:	75%	

→ about 100 IBD events per year for each baseline

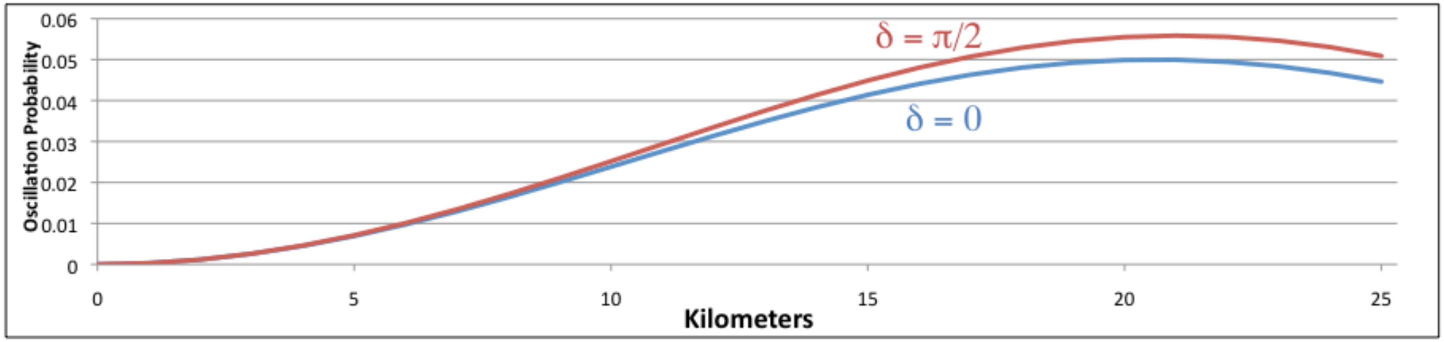
Projected sensitivity to δ_{CP}

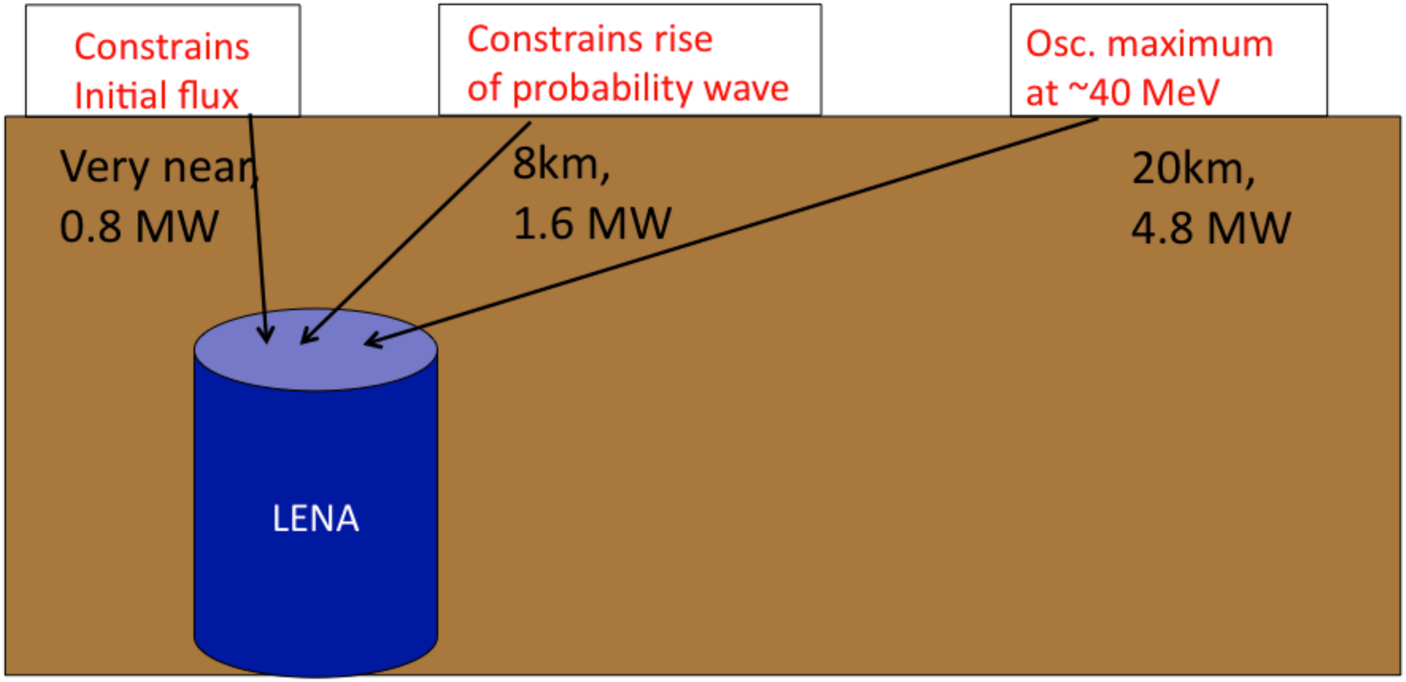


→ Predicted coverage for δ_{CP} at 3σ: 42% after 10 years

→ Sensitivity is dominated by statistical uncertainty

Experimental setup vs. knowledge of θ_{13}

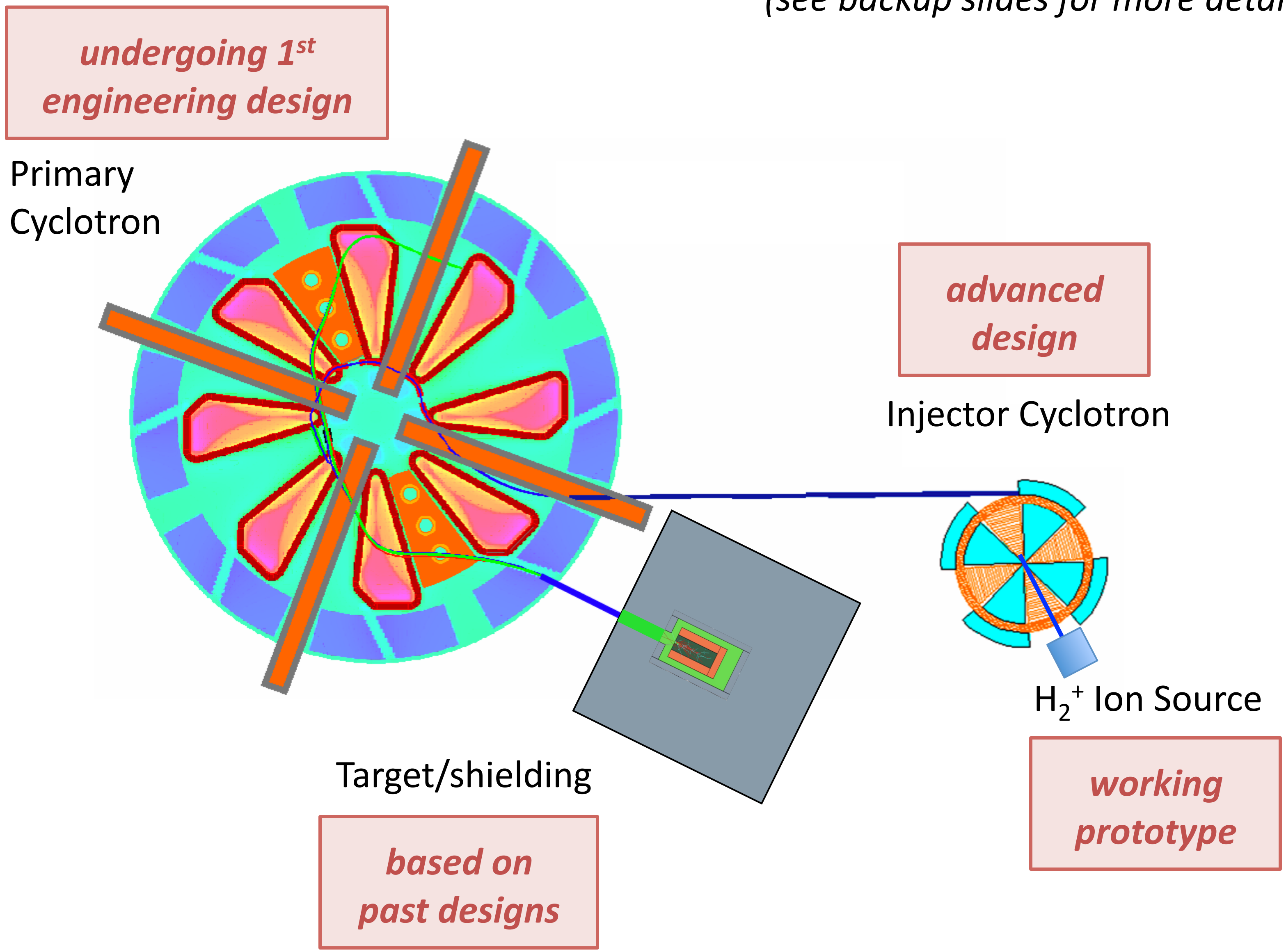




Setup assumes unknown and small θ_{13}. → could be adjusted

Status of the DAEdALUS accelerator chain

(see backup slides for more details)



Development work for high-power cyclotrons

Many European Accelerator Physicists are involved…

Multi Megawatt DAEδALUS 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. 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]*National Institute of Nuclear Physics - LNL*
[f]*National Institute of Nuclear Physics - LNS* (Italy)
[g]*Riken*
[h]*Huddersfield University, Queensgate Campus, Huddersfield HD1 3DH, UK*
[i]*IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706*
[j]*IBA-Research*

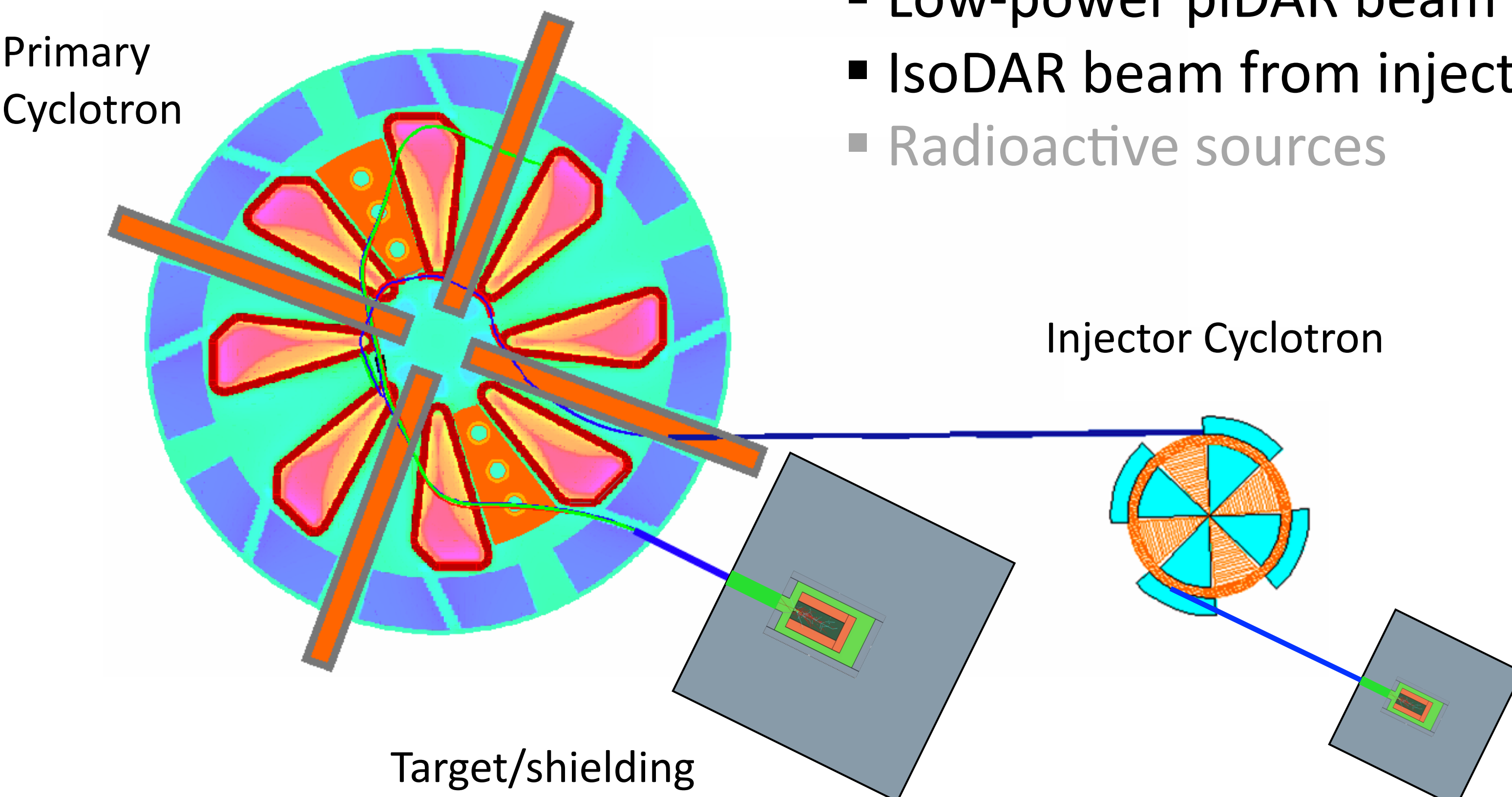
European Universities/Institutes

European industry

Sterile neutrino searches

Alternatives proposed:

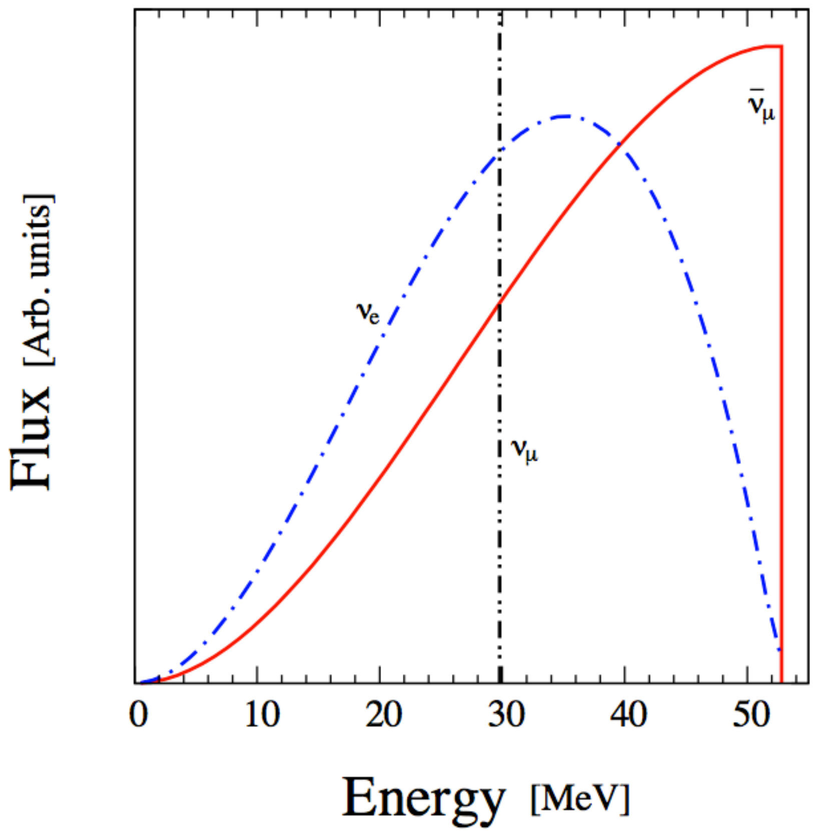
- Low-power piDAR beam (20m)
- IsoDAR beam from injector
- Radioactive sources



piDAR: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
$\nu_e \rightarrow \nu_s$ disappearance

IsoDAR:
$\bar{\nu}_e \rightarrow \bar{\nu}_s$ disappearance

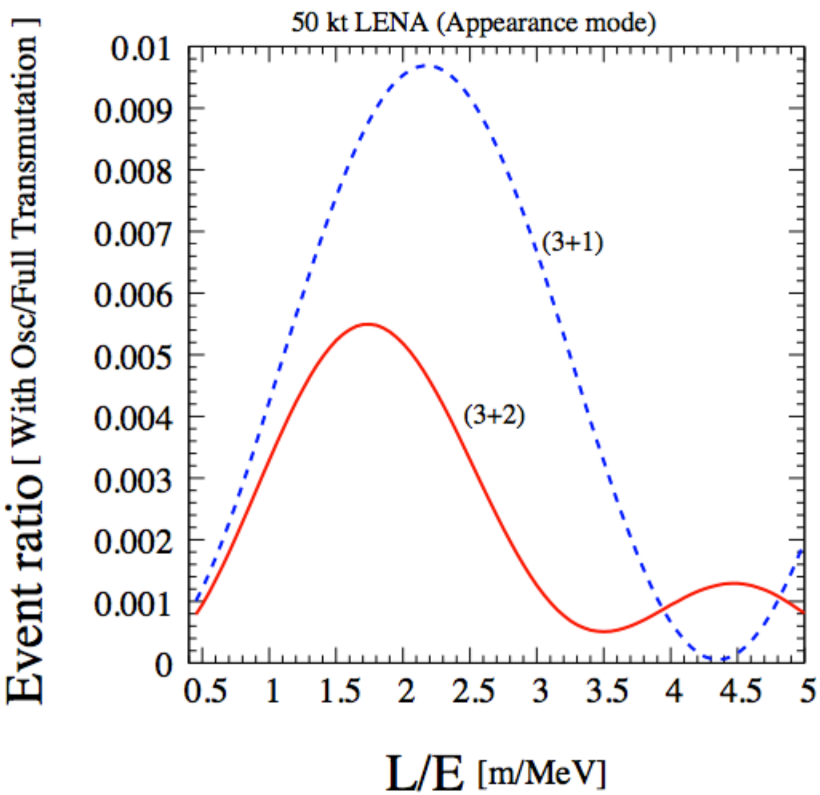
Sterile neutrinos with piDAR



Beam configuration

- Proton beam:
  E = 800 MeV, P = 100 kW
- Neutrinos (per year):
  4×10^{21} in $\nu_e, \nu_\mu, \bar{\nu}_\mu$
  1.6×10^{18} in $\bar{\nu}_e$
- Distance from LENA: 20m

Sterile neutrinos with piDAR



piDAR→LENA provides capability to distinguish 3+1 and 3+2 scenarios

Beam configuration

- Proton beam:
  E = 800 MeV, P = 100 kW
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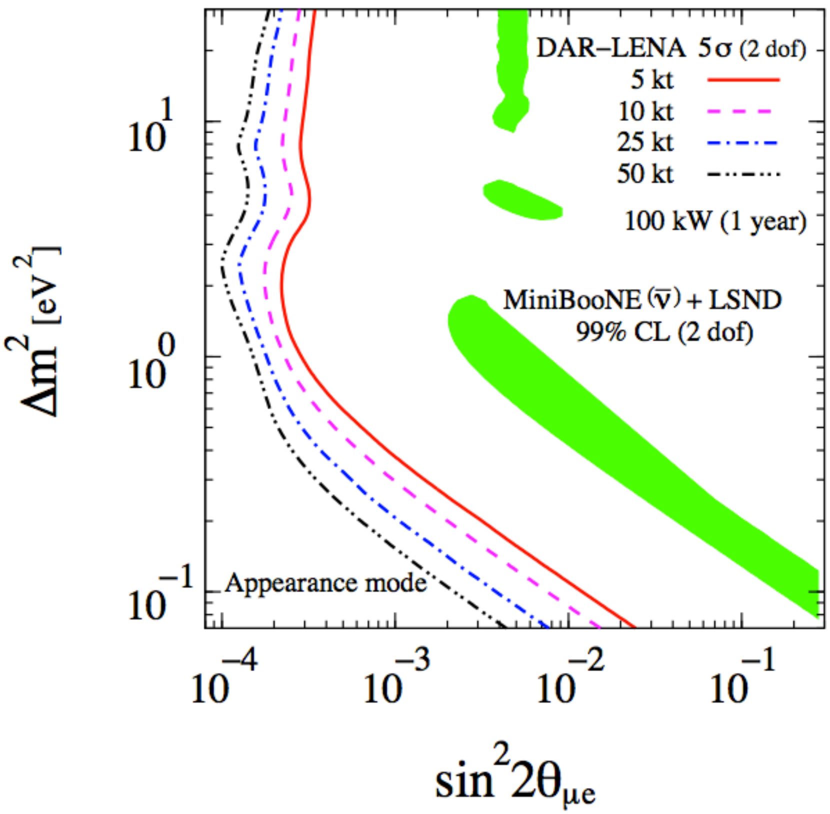
  4×10^{21} in $\nu_e, \nu_\mu, \bar{\nu}_\mu$
  1.6×10^{18} in $\bar{\nu}_e$
- Distance from LENA: 20m

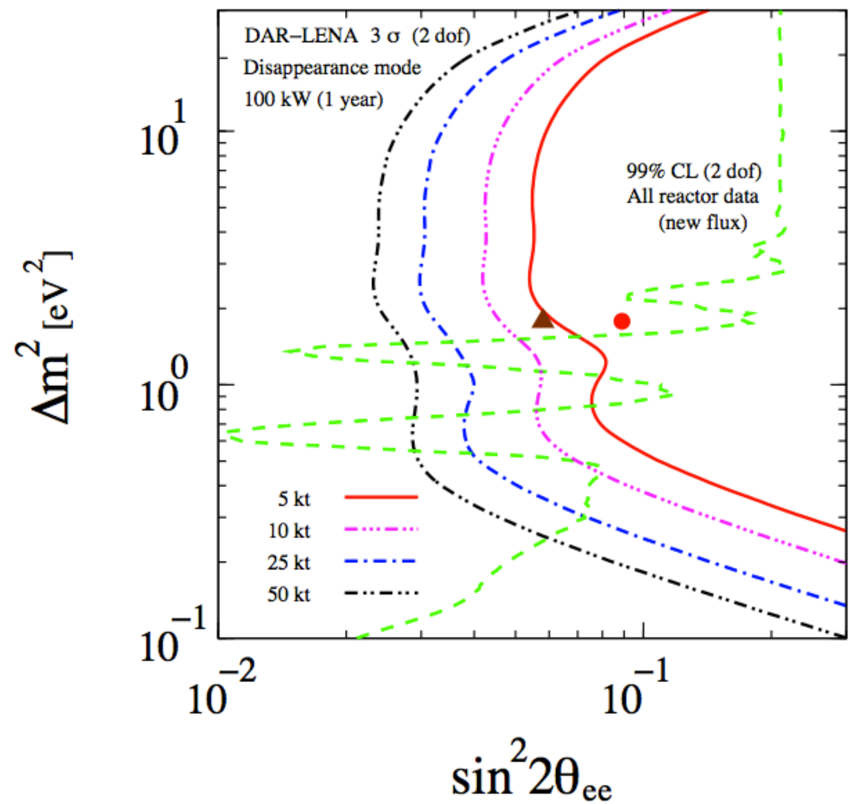
Sterile neutrino signal

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance for 3+2:
  $>10^4$ IBD events, S/B 10:1
- $\nu_e \rightarrow \nu_s$ disappearance:
  $\sim 2\times10^5$ $\nu_e{}^{12}C$ CC events

Sensitivity with piDAR beam



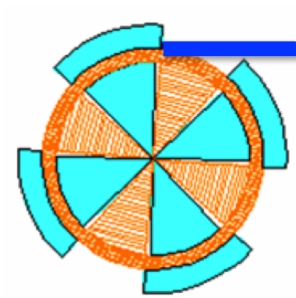
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance



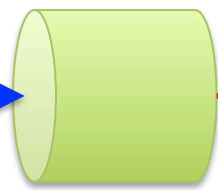
$\nu_e \rightarrow \nu_s$ disappearance

Sterile neutrinos with IsoDAR

Proton energy required for neutron production is considerably lower than for piDAR beam. A single cyclotron (the injector) is sufficient.

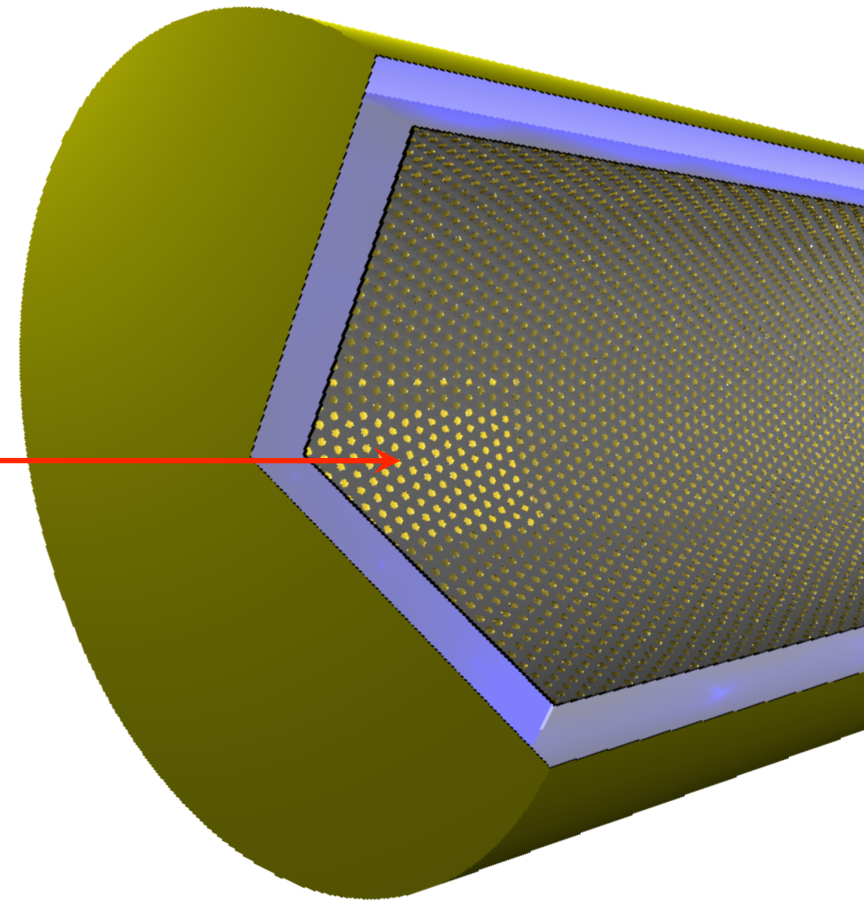


Injector cyclotron:
P = 600 kW
E_p = 60MeV



target:
production of ^{8}Li,
β-decay, $\langle E_\nu \rangle$=6MeV

$\bar{\nu}_e$ „beam“
16 m



Observation of disappearance pattern to ν_s in $>10^6$ IBD events

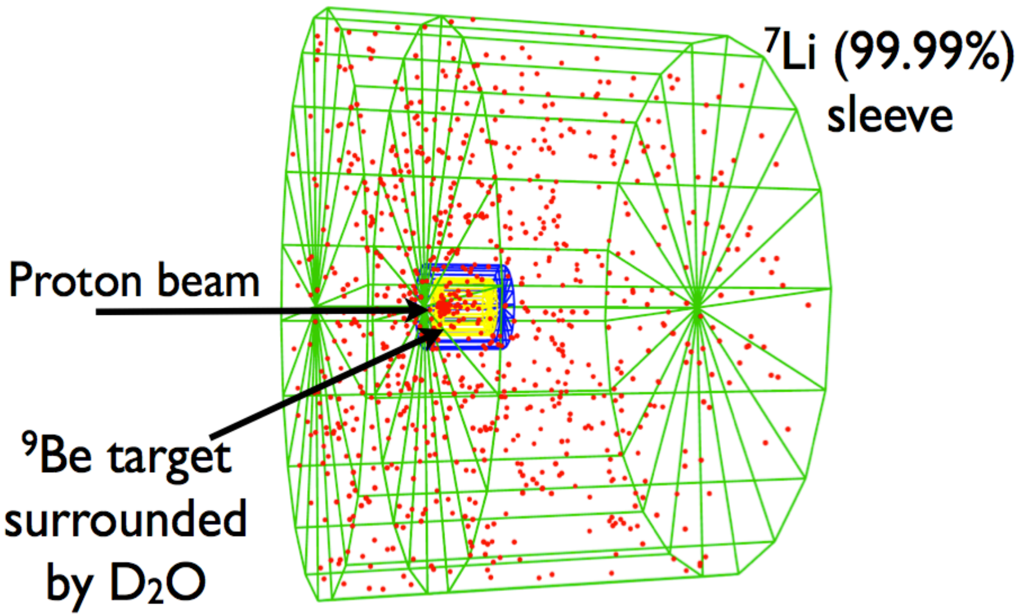
^{8}Li production target

^{9}Be target

- cylinder: 20 x 20 cm
- neutron source
- surrounded by 5 cm D_2O for moderation and cooling

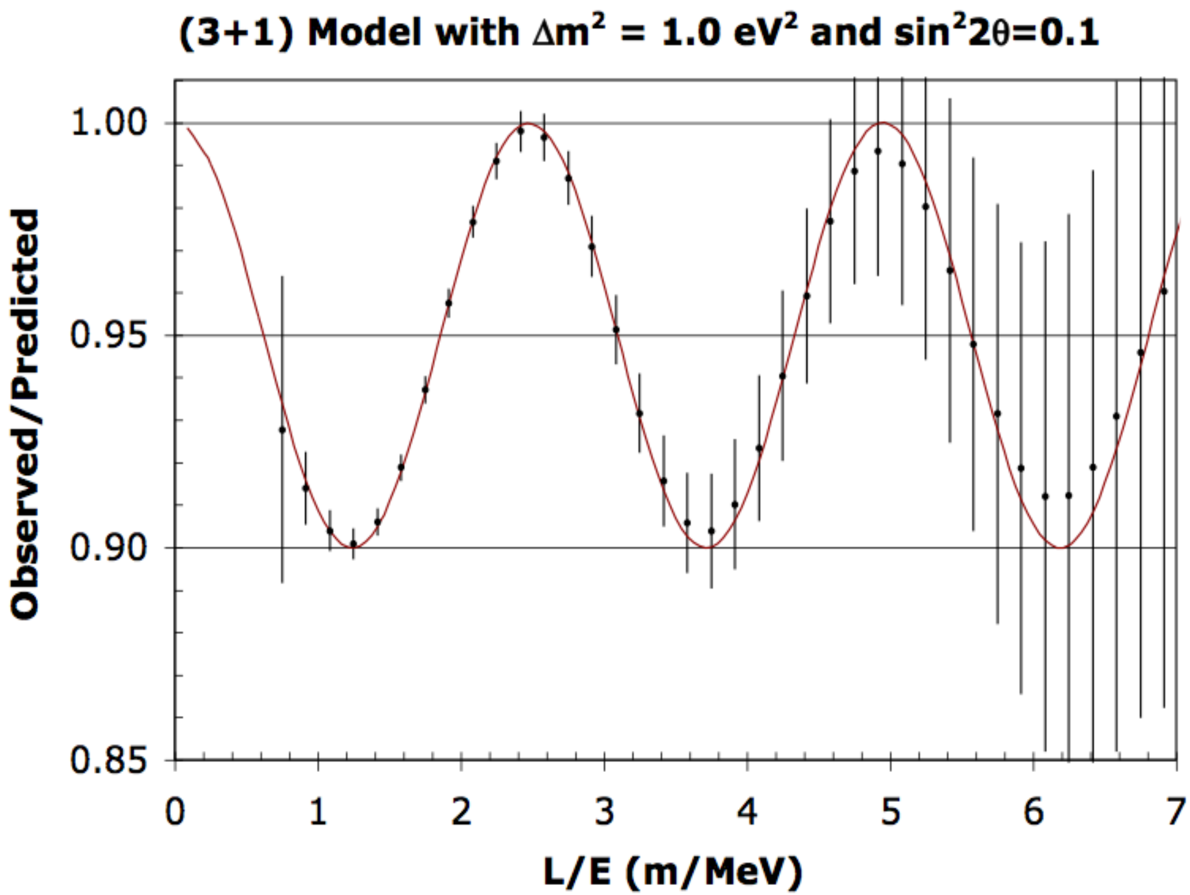
^{7}Li sleeve

- cyl.: 1.5m long, 2m diameter
- enriched to 99.99% from 92.4% of natural ^{7}Li content
- surrounded by graphite reflector
- ^{8}Li from n-capture: 14.6 ^{8}Li per 1000 pot → 1.3×10^{23} ^{8}Li in 5 yrs



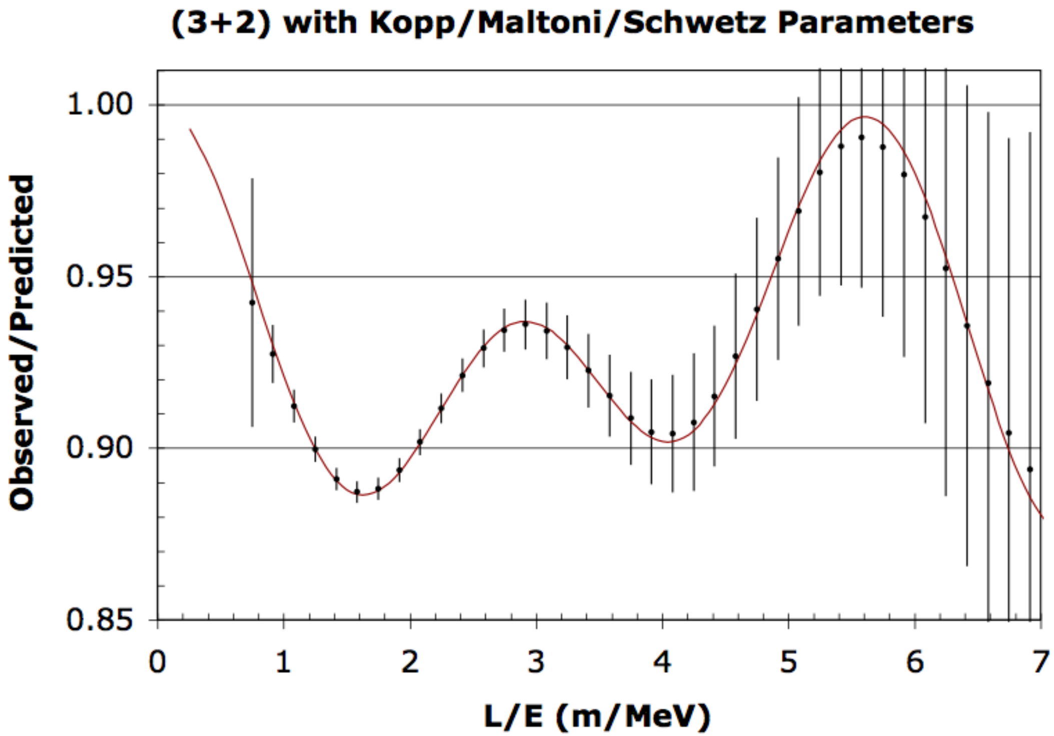
KamLAND: L/E osc. pattern for 3+1 scenario

$$P_{3+1} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2)\sin^2(\Delta m_{41}^2 L/E)$$



KamLAND: L/E osc pattern for 3+2 scenario

$$P_{3+2} = 1 - 4[(1 - |U_{e4}|^2 - |U_{e5}|^2) \times \\ (|U_{e4}|^2(\sin^2(\Delta m_{41}^2 L/E) + \\ |U_{e5}|^2(\sin^2(\Delta m_{51}^2 L/E)) + \\ |U_{e4}|^2|U_{e5}|^2(\sin^2(\Delta m_{54}^2 L/E)].$$



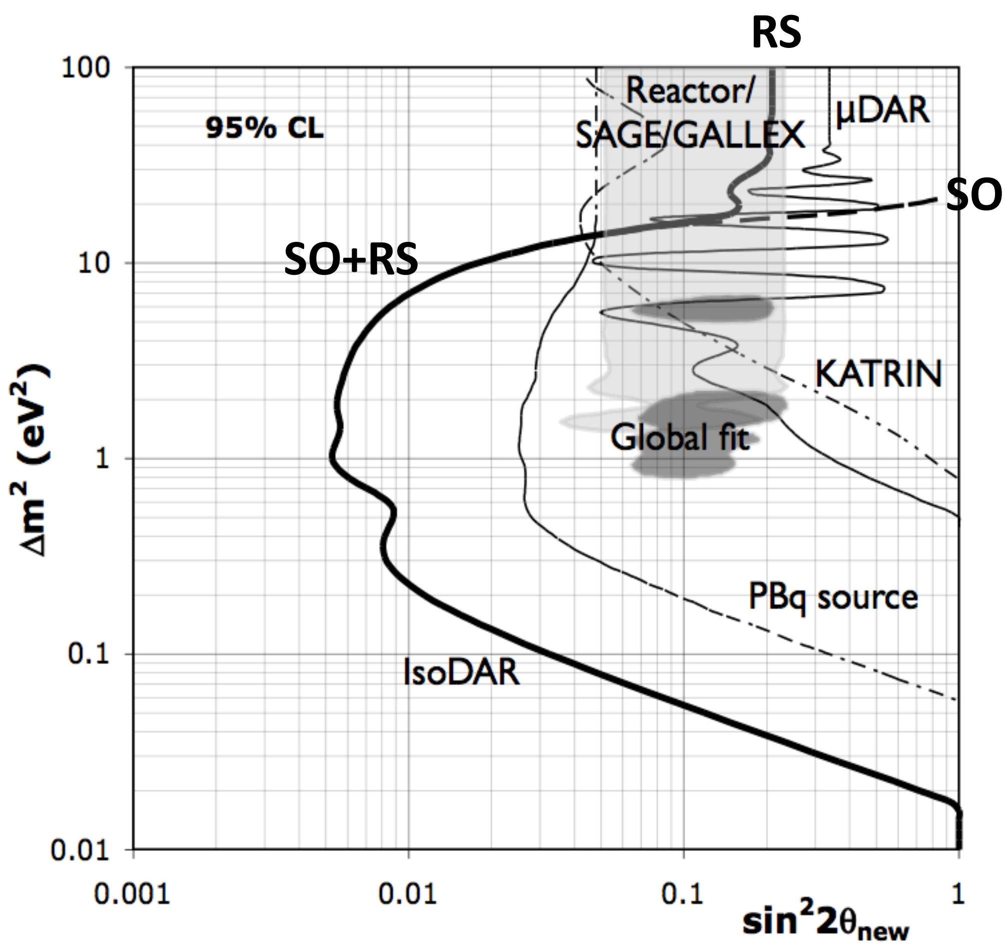
IsoDAR sensitivity for sterile neutrinos

Two analyses

- shape-only (SO): dashed line
- rate+shape (RS): solid line
  → increases reach for large Δm^2
  → requires 5% flux normalizatio

Comparison

- **Global fit** allowed region: excluded at 5σ after 0.3 yrs
- **PBq** antineutrino source ^{144}Ce at Borexino center
- **KATRIN** β decay spetral shape kink close to the endpoint



Sensitivity plot for 5yrs of KamLAND

Conclusions

- Liquid-scintillator detectors are probably the optimum receptor for DAR beams.
- DAEδALUS@LENA: first (conservative) calculations show a competitive sensitivity for δ_{CP} measurement. Refined calculations and experimental layout are needed.
- Sterile ν experiments with pi/IsoDAR:
  - 2nd generation experiments featuring sufficient sensitivity to distinguish 3+1 and 3+2 scenarios
  - several oscillation modes can be tested

    piDAR: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_e \rightarrow \nu_s$

    IsoDar: $\bar{\nu}_e \rightarrow \bar{\nu}_s$

Thank you!

Search for CP-violating phase

- DAEδALUS: arXiv:1006.0260

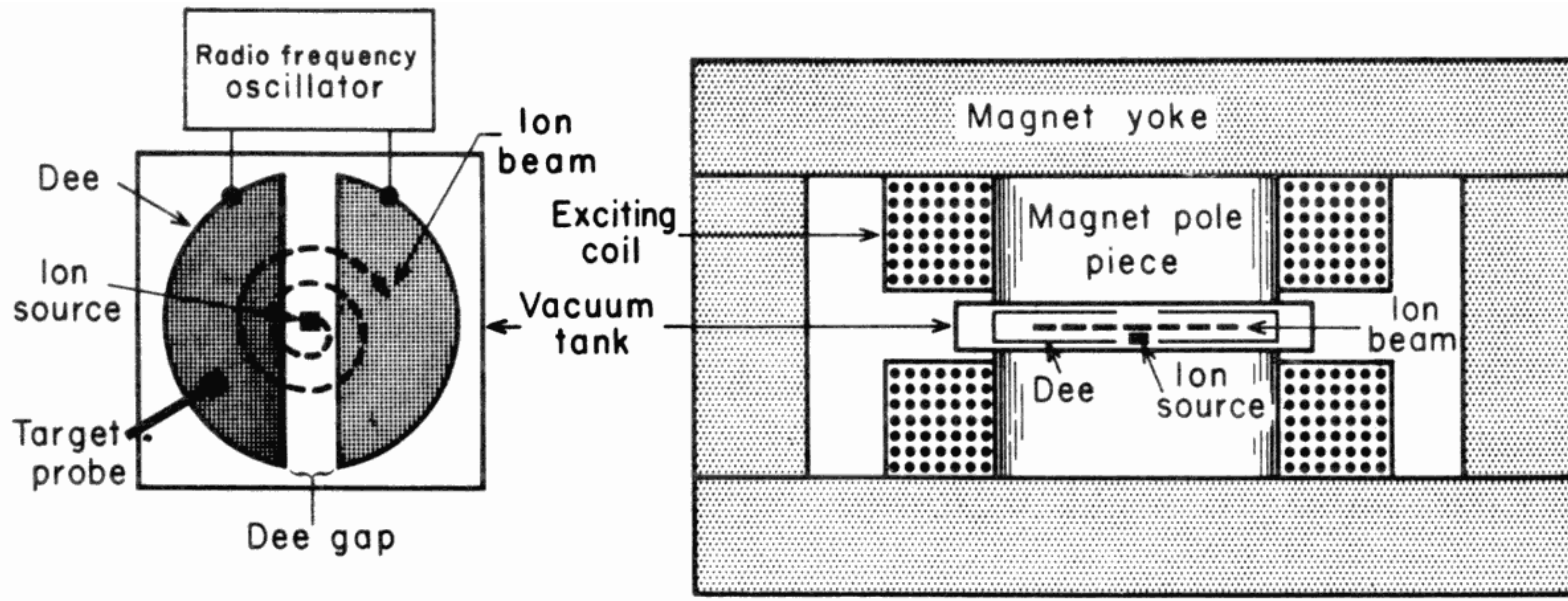
Searches for sterile neutrinos

- piDAR: arXiv:1105.4984
- IsoDAR: arXiv:1205.4419

Many thanks to Janet Conrad and Mike Shaevitz!

Backup Slides

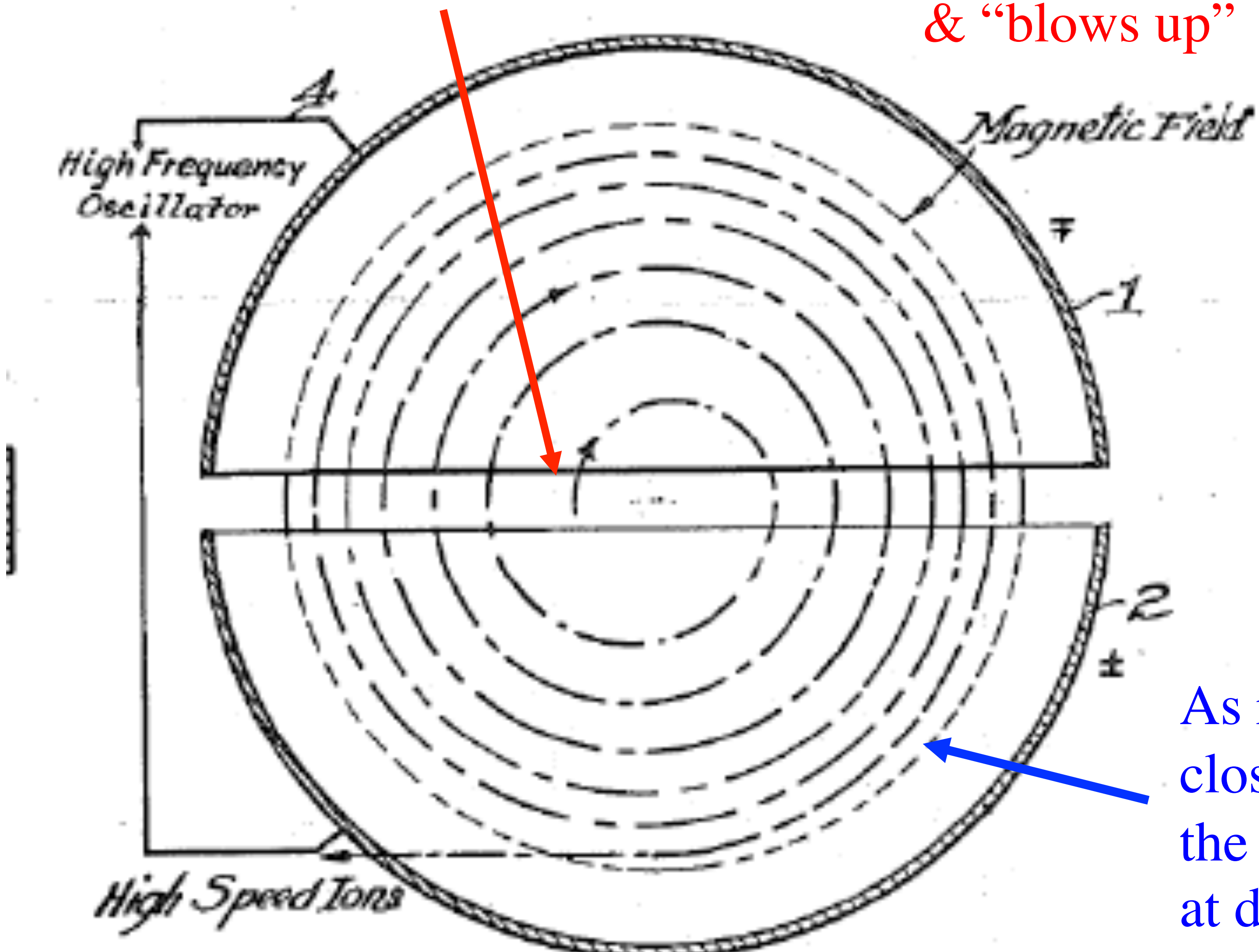
Reminder about Cyclotrons



We employ an “isochronous cyclotron” design where the magnetic field changes with radius. This can accelerate many bunches at once.

The big issue…

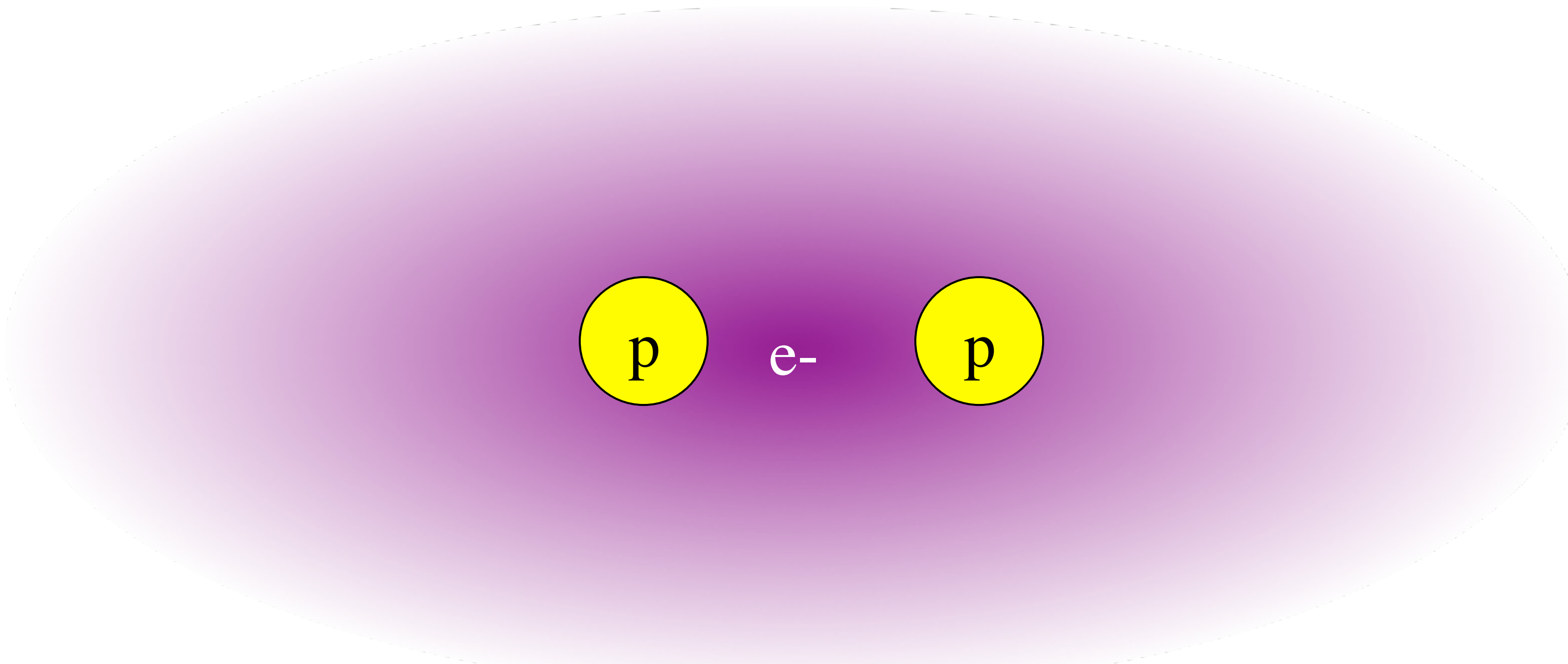
If you inject a lot of charge here, it repels & "blows up"



As radii get closer together the bunches at different radii interact

Why H_2+ ???

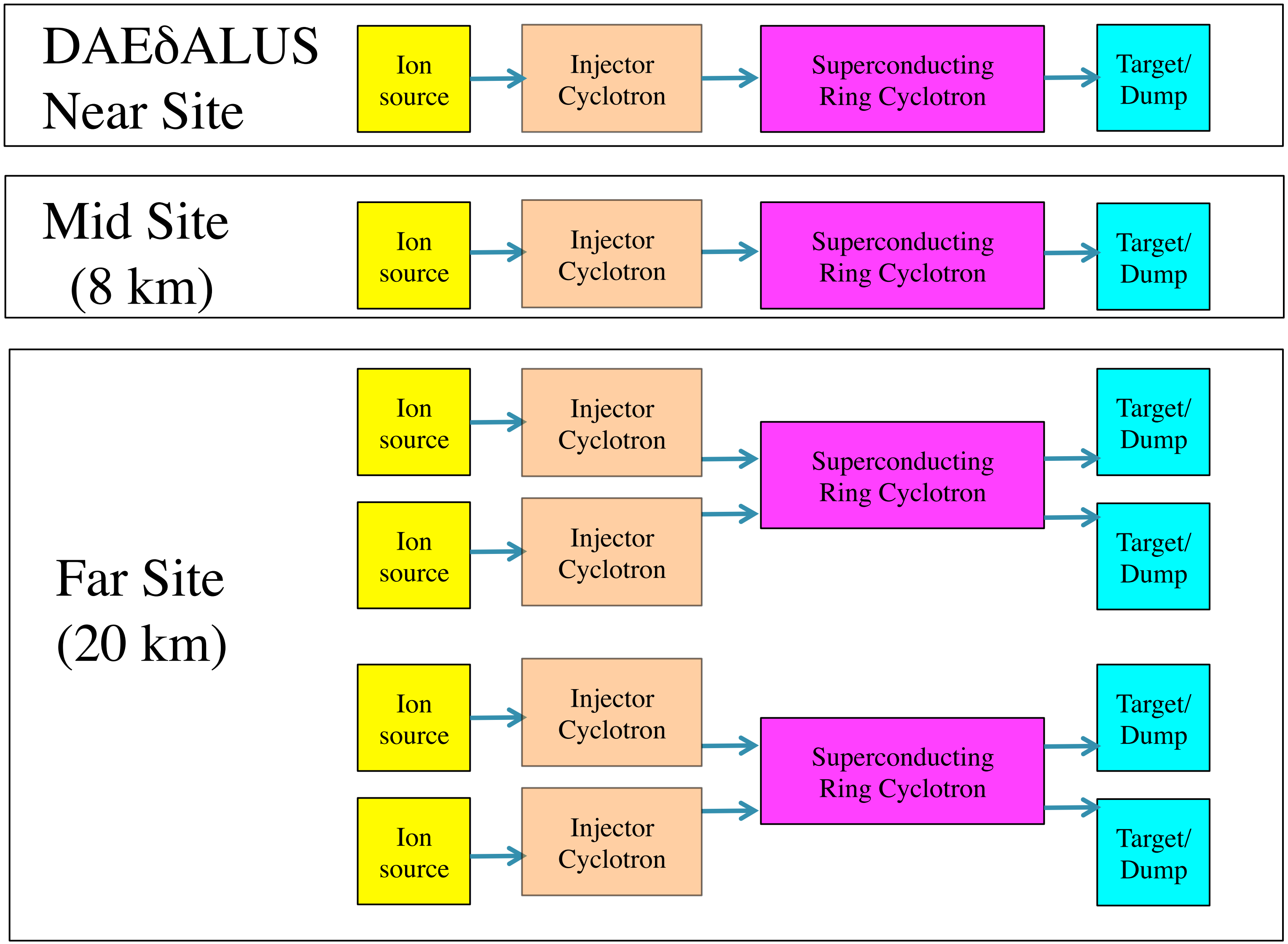
To reduce the "space charge" at injection…



H_2+ gives you 2 protons out for 1 unit of +1 charge in!

Simple to extract! Just strip the electron w/ a foil

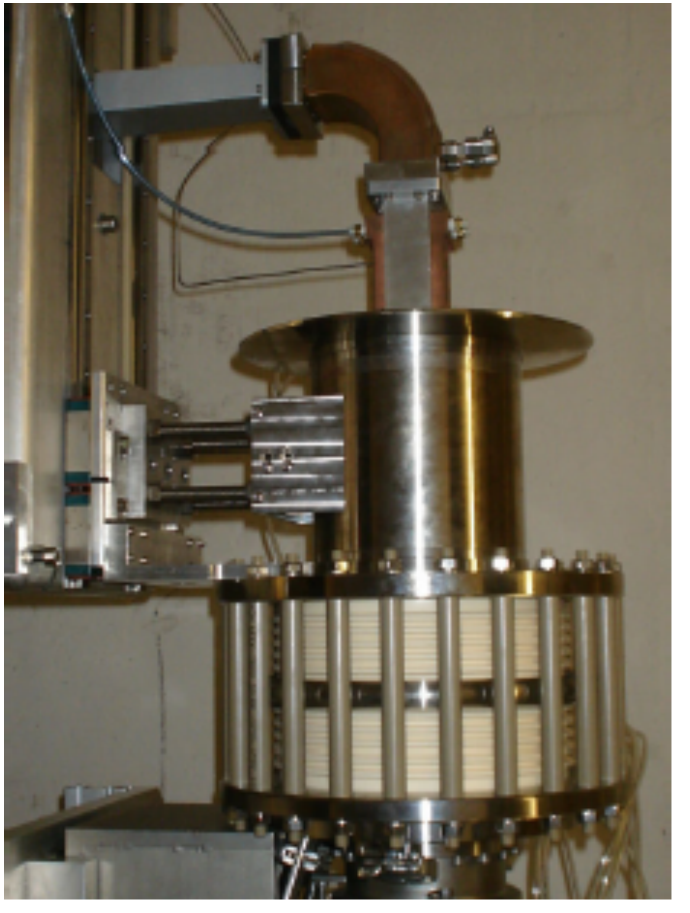
Design Principle: “Plug-and-play”



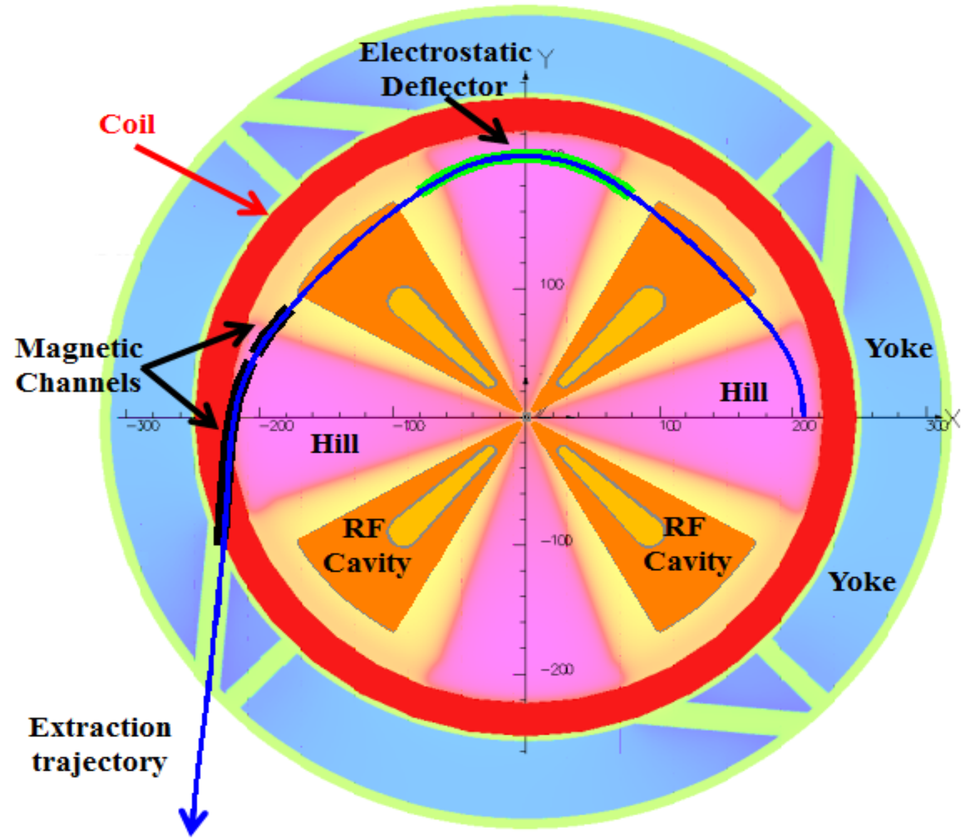
Ion Source:

Built by our collaborators
At Catania.

We will be studying
Beam extracted from this
Ion source in the
Teststand at Best Cyclotron, Inc.,
Vancouver, this winter

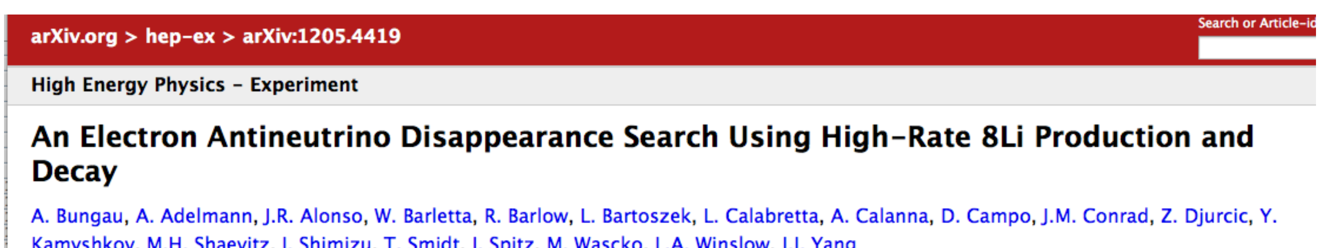


Base Design Injector
60 MeV/n @ 5 mA of H_2^+



Compact,
Non-superconducting
design

As a step in the development of DAEδALUS
We are proposing to use this as an isotope decay-at-rest source


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

Industry is interested in this injector cyclotron…

5 mA H2+ beam = 10 mA protons on target

nearly an order of magnitude higher than any existing or designed cyclotron

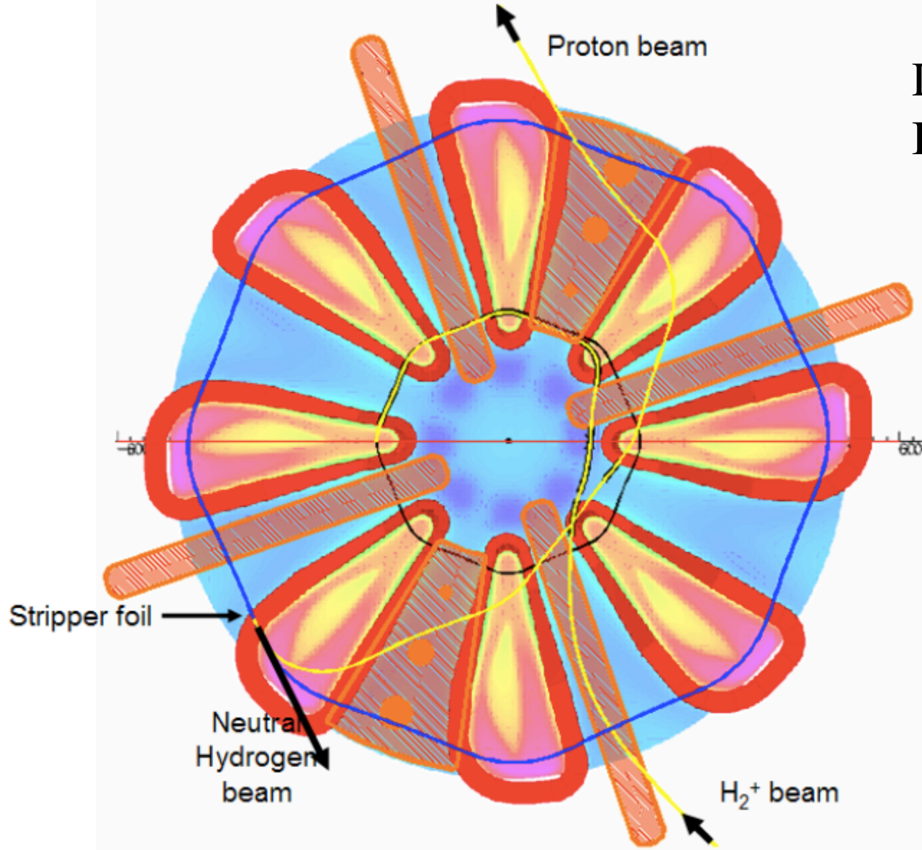
(600 kW on target)

60 MeV/n -- typical of many medical isotope machines

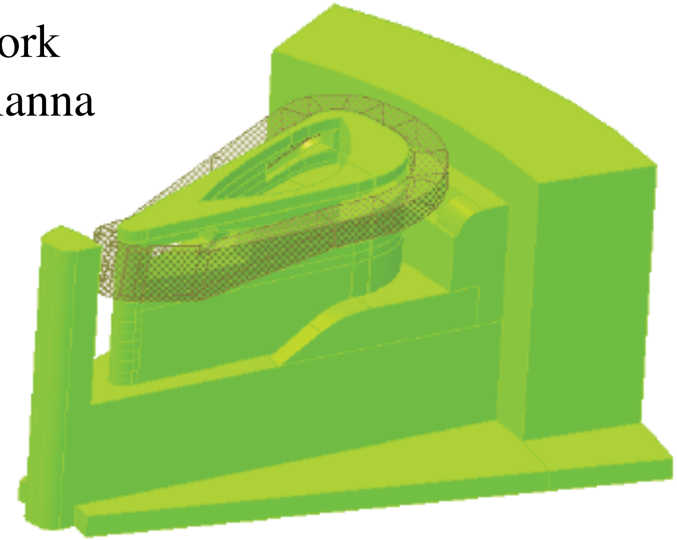
Table 2: *Medical isotopes relevant to IsoDAR energues, from Ref. [29].*

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 γ-emitter used for spinal fluid and liver studies.
^{117m}Sn	13.6 d	A γ-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.

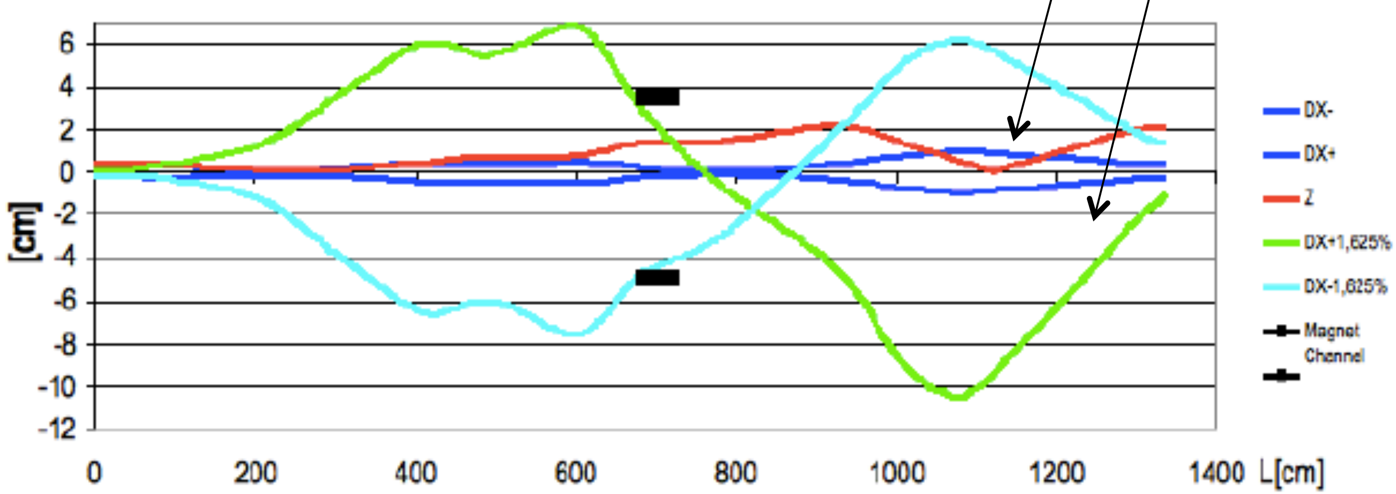
Potentially very useful outside of neutrino physics



Design work
By A. Calanna

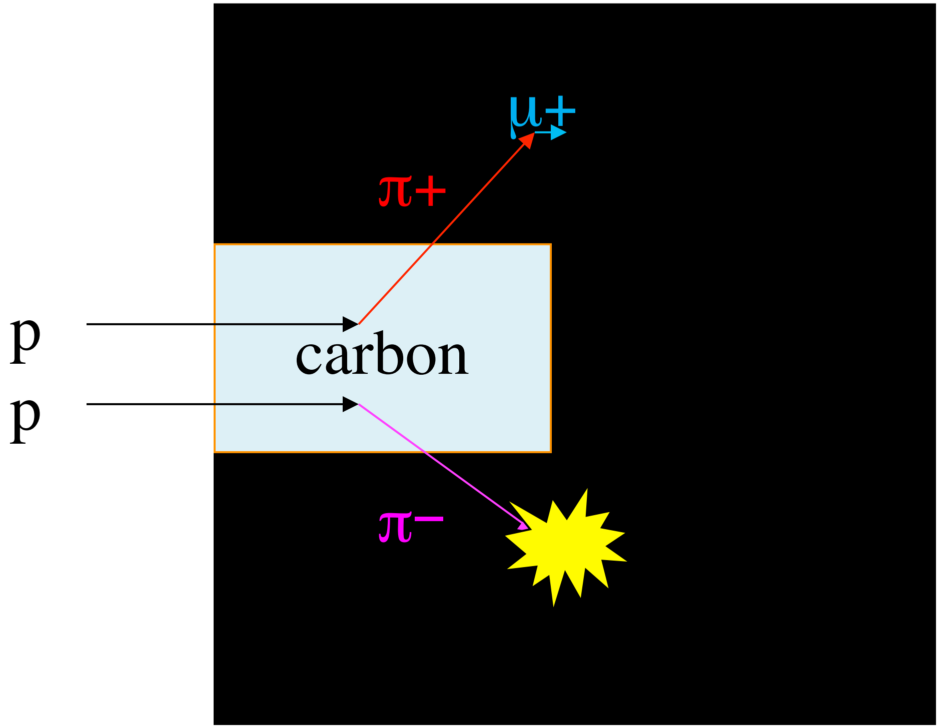


Beam envelope,
No energy spread,
1% spread



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

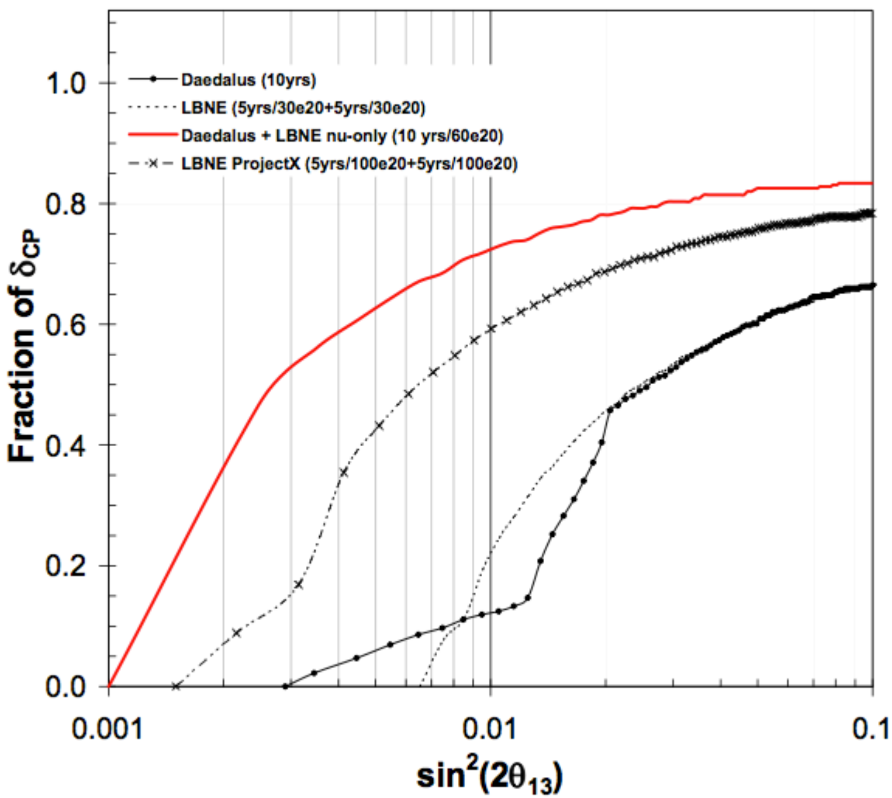
Light target embedded in a heavy target



Also,
no upstream
targets!!!

Synergy with LBNO experiments

δ_{CP} sensitivity predictions for original LBNE-WCD (Homestake) and DAEδALUS proposals



- LBNO experiments usually suffer from low $\bar{\nu}$ statistics
- Optimal sensitivity can be reached if LBNO running ν-only are combined with piDAR for $\bar{\nu}$ osc. data
- δ_{CP} coverage for DUSEL LBNE+DAEδALUS would increase from 65% to 85%