# Neutrinos From Decays at Rest

NuFact 2014

Matt Toups, MIT

# Neutrinos From Decays at Rest

Produced With High Power Accelerators

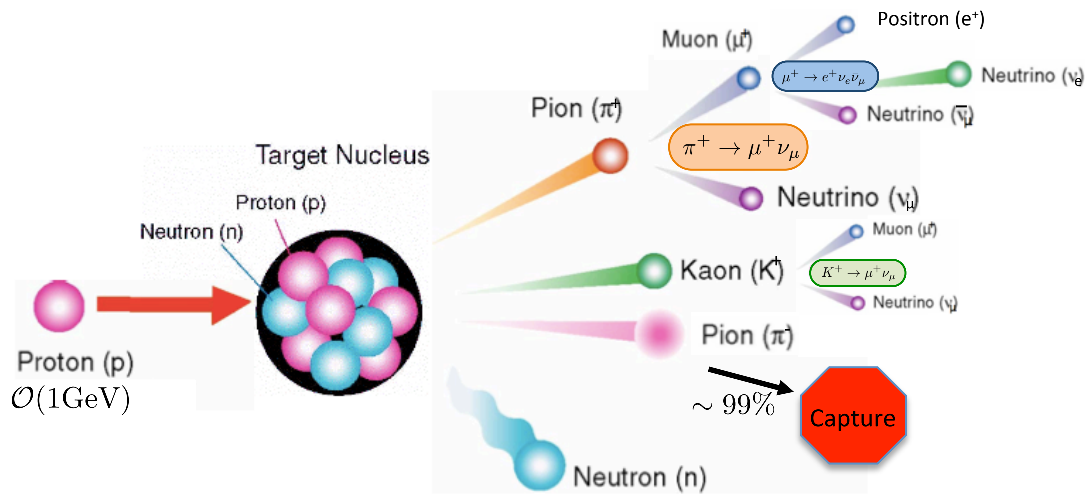
NuFact 2014

Matt Toups, MIT

# Outline

- Decay-at-rest (DAR) neutrino sources
- The physics of DAR neutrino sources
  - CP violation searches
  - Sterile neutrino searches
  - Coherent elastic neutrino-nucleus scattering searches
- Concluding remarks

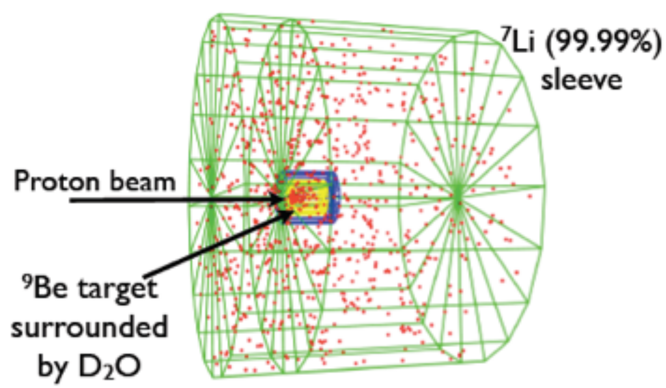
# Pion/Muon/Kaon DAR Neutrinos



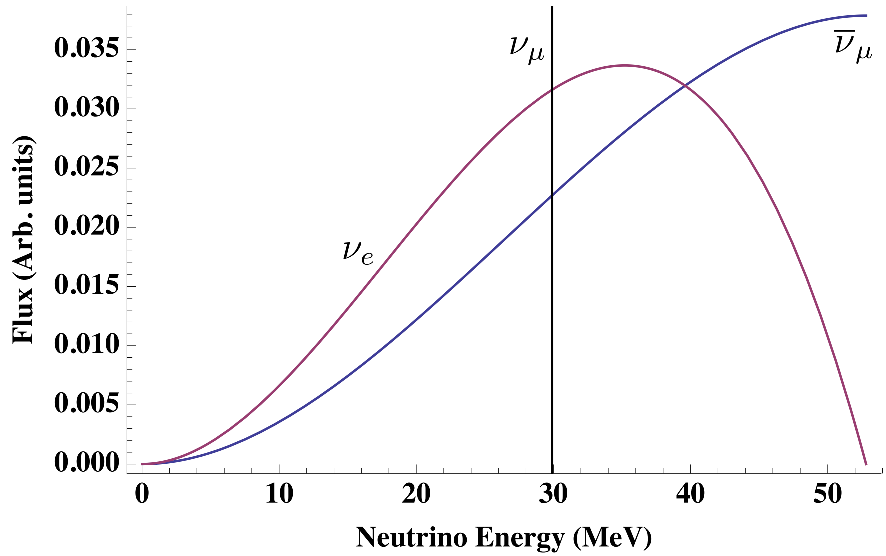

# Isotope DAR Neutrinos

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

60 MeV



# Pion/Muon DAR Neutrinos

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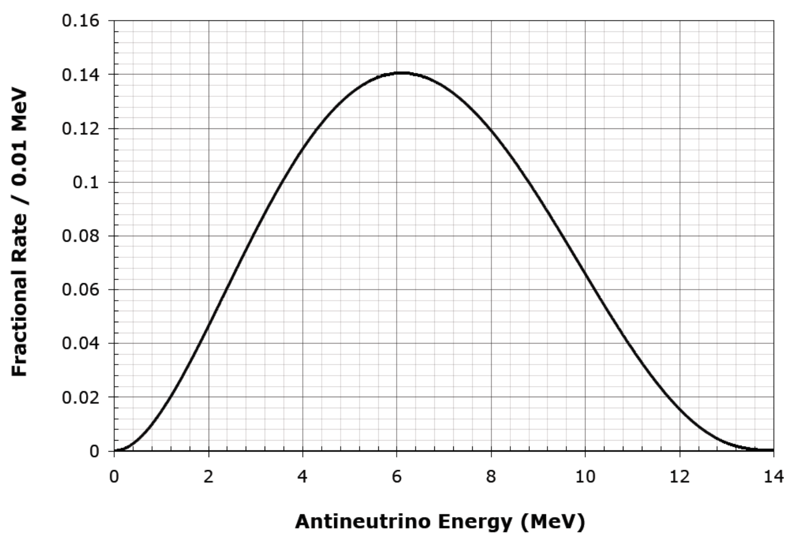

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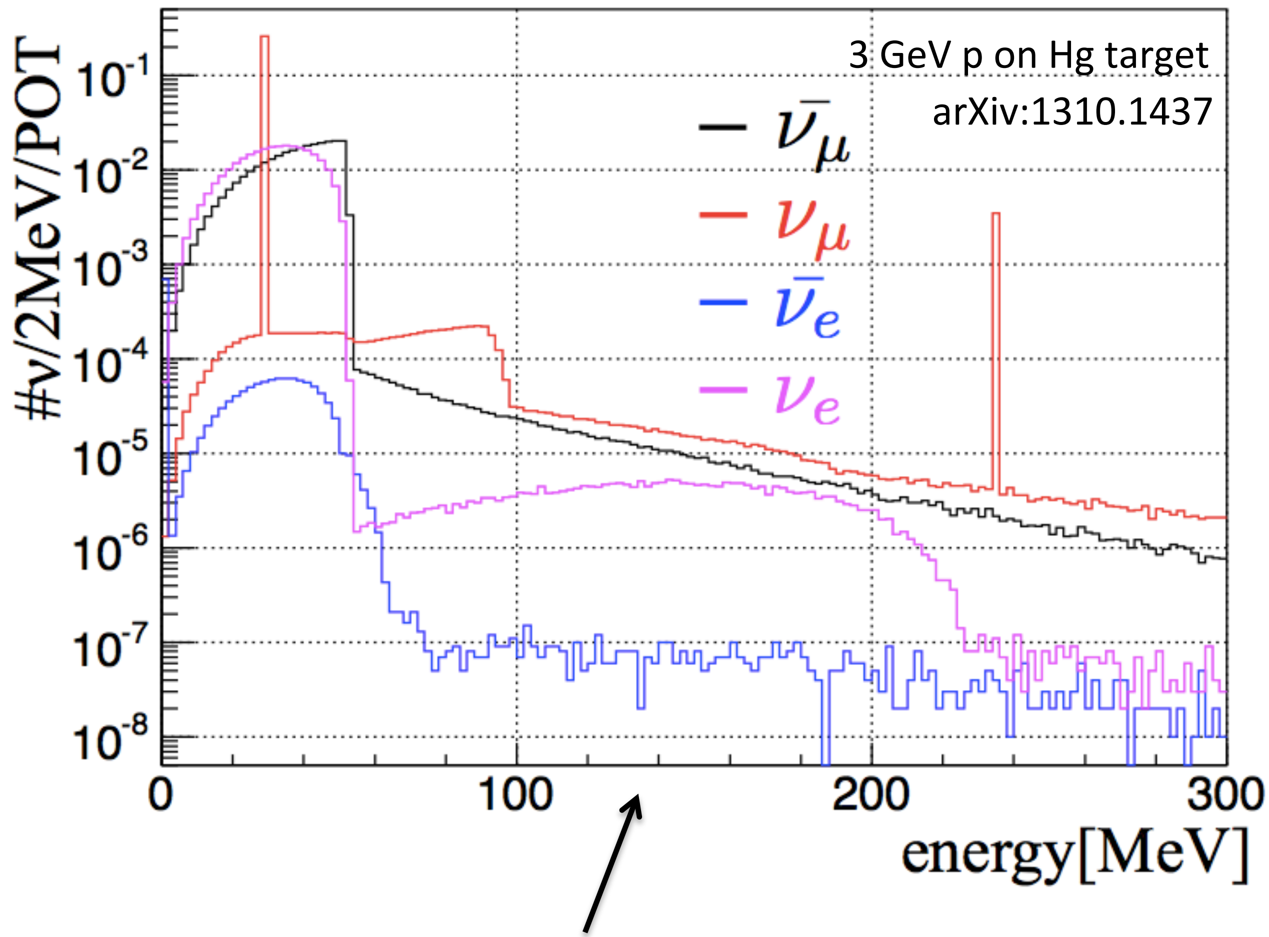



For incident proton energies of $\gtrsim 3\ \mathrm{GeV}$, kaon production also becomes important

# DAR Neutrinos vis-à-vis Decay-in-flight (DIF) Neutrinos

- Pros:
  - Well understood energy spectra
  - Well understood flavor content

- Con:
  - Isotropic (flux falls as $1/L^2$)

- Differences:
  - Lower energy O(10-100 MeV)

- Similarities:
  - Duty factor, though depends on DAR neutrino source

# DAR Neutrinos vis-à-vis Decay-in-flight (DIF) Neutrinos

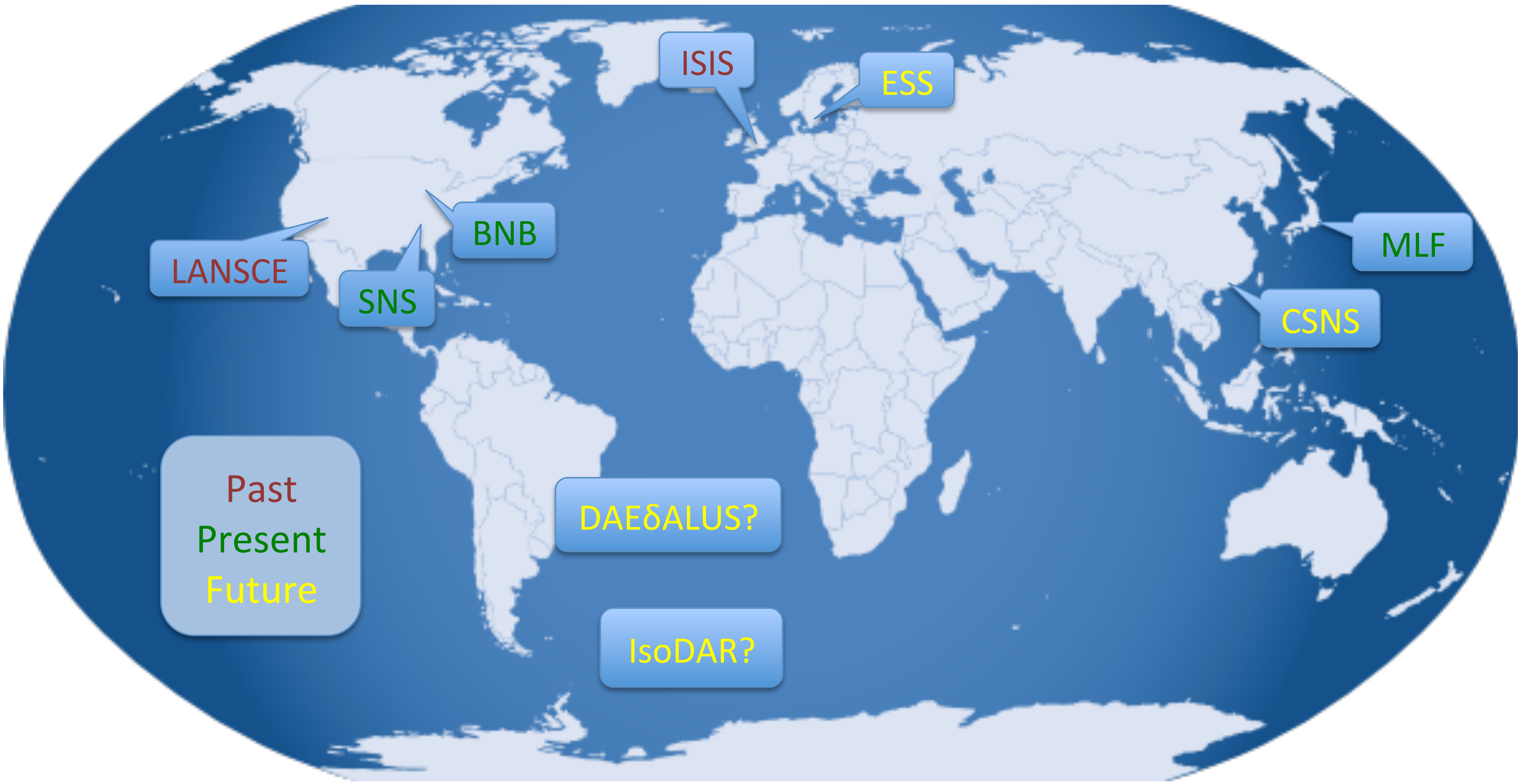
- Pros:
  - Well understood energy spectra
  - Well understood flavor content

- Con:
  - Isotropic (flux falls as $1/L^2$) → Drives detectors closer to source, limiting L/E reach

- Differences:
  - Lower energy O(10-100 MeV) → Lower thresholds needed, no CC-$\nu_\mu$ interactions (except for kaon DAR $\nu_\mu$s )

- Similarities:
  - Duty factor, though depends on DAR neutrino source

# Locations of DAR Neutrino "Beams"




Adapted from K. Scholberg

# DAR Neutrino Beam Figures of Merit

| Facility | Proton Energy (GeV) | Power (MW) | Bunch Structure | Rate |
|---|---|---|---|---|
| LANSCE | 0.8 | 0.8 | 600 us | 120 Hz |
| ISIS | 0.8 | 0.16 | 2 x 100 ns | 50 Hz |
| BNB | 8 | 0.032 | 1.6 μs | 5-11 Hz |
| SNS | 1.0 | 1.4 | 700 ns | 60 Hz |
| MLF | 3 | 1 | 2 x 80 ns | 25 Hz |
| CSNS | 1.6 | 0.1 | <500 ns | 25 Hz |
| ESS | 2.5 | 5 | 2.86 ms (~1.5μs) | 14 Hz |
| DAEδALUS | 0.8 | 1, 2, 2 x 2.5 | 62.5, 125, 125 ms | 2 Hz |
| IsoDAR | 0.06 | 0.6 | n/a | CW |

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Higher power ⟶ Larger flux

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- Small duty factors ⟶ reject cosmics
  - Also addressed by going underground or beam-off subtraction

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- $\lesssim 2.2\ \mu s$ bunch structure $\longrightarrow$ π/μ DAR ν separation

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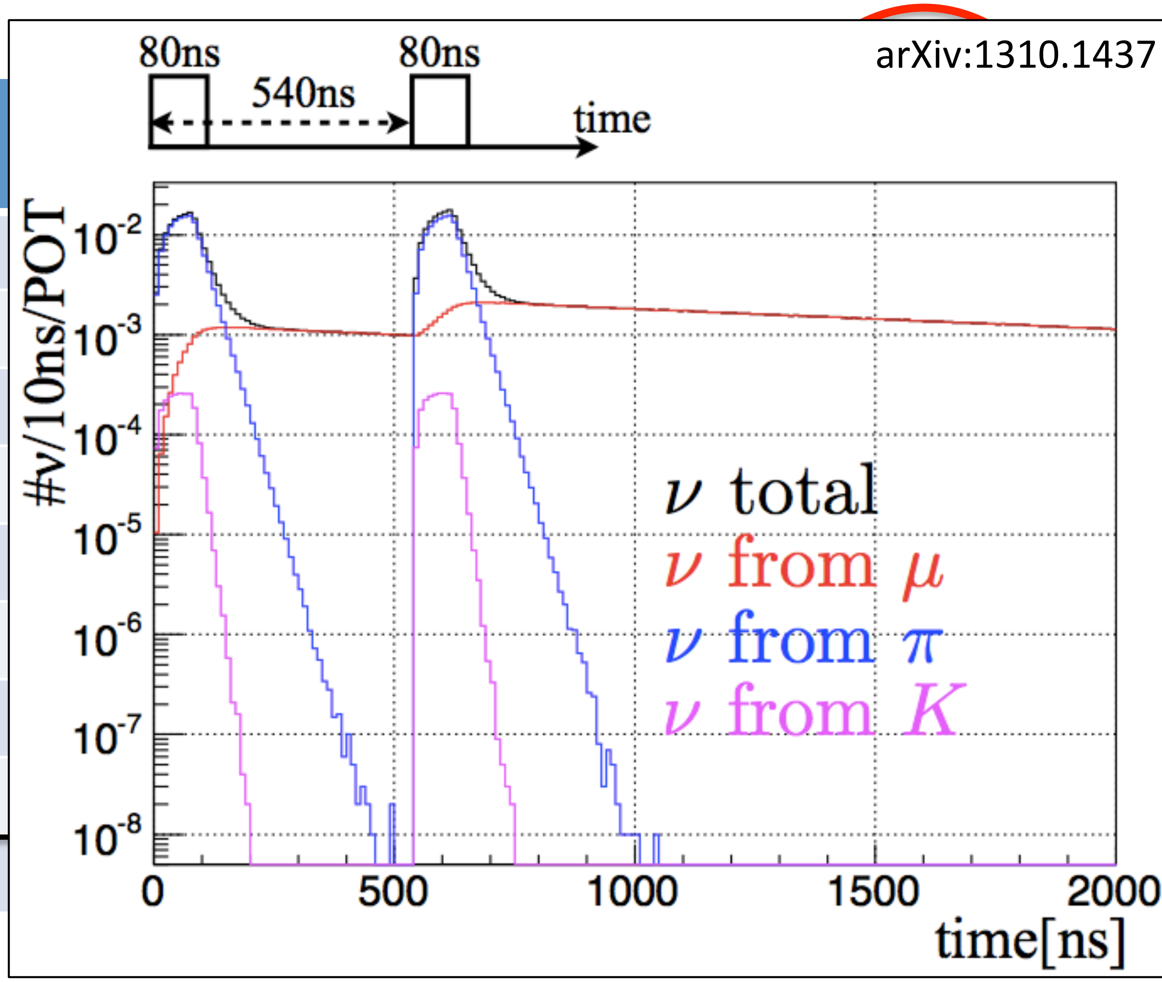


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$T_p << 1\ \mathrm{GeV}$ → Isotope DAR

$T_p \sim 1\ \mathrm{GeV}$ → π/µ DAR

$T_p \gtrsim 3\ \mathrm{GeV}$ → π/µ DAR + K DAR

# Physics of DAR Neutrino Sources

- CP violation searches
- Sterile neutrino searches
- Coherent elastic neutrino-nucleus scattering
- Neutrino non-standard interactions
- Standard Model tests (e.g. weak mixing angle)
- Charged current cross section measurements

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  - IsoDAR, OscSNS, J-PARC MLF, KDAR
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I will not talk about these today

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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…

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

We want to see if δ is nonzero

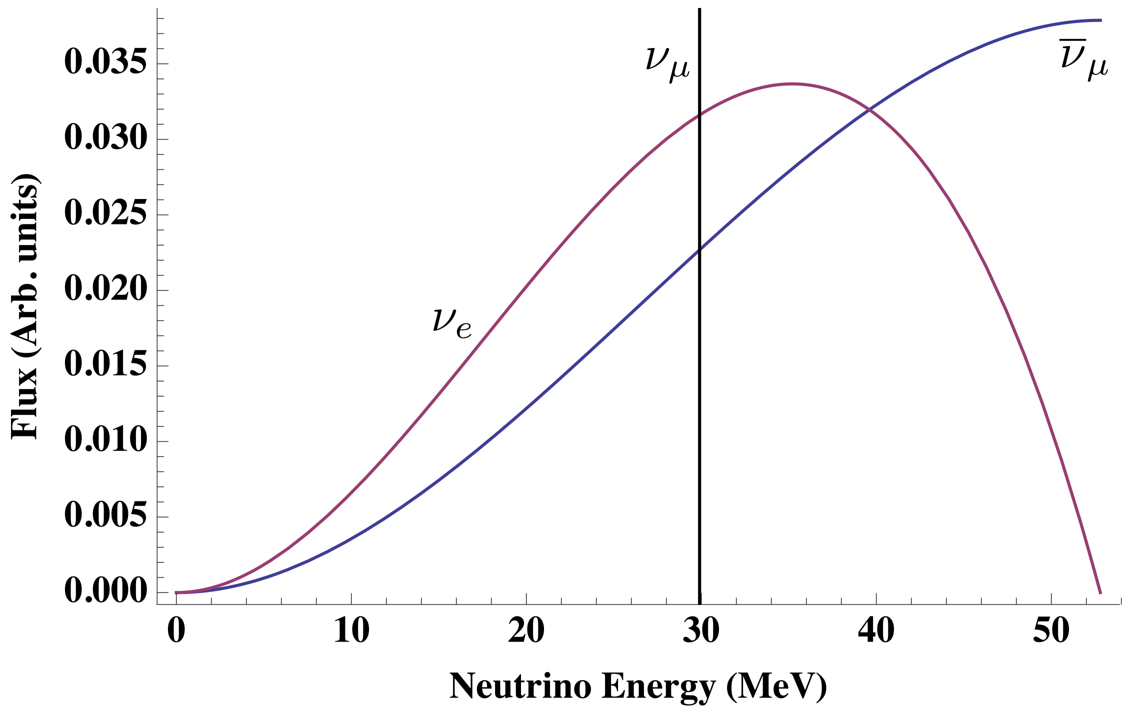
terms depending on mixing angles

terms depending on mass splittings

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

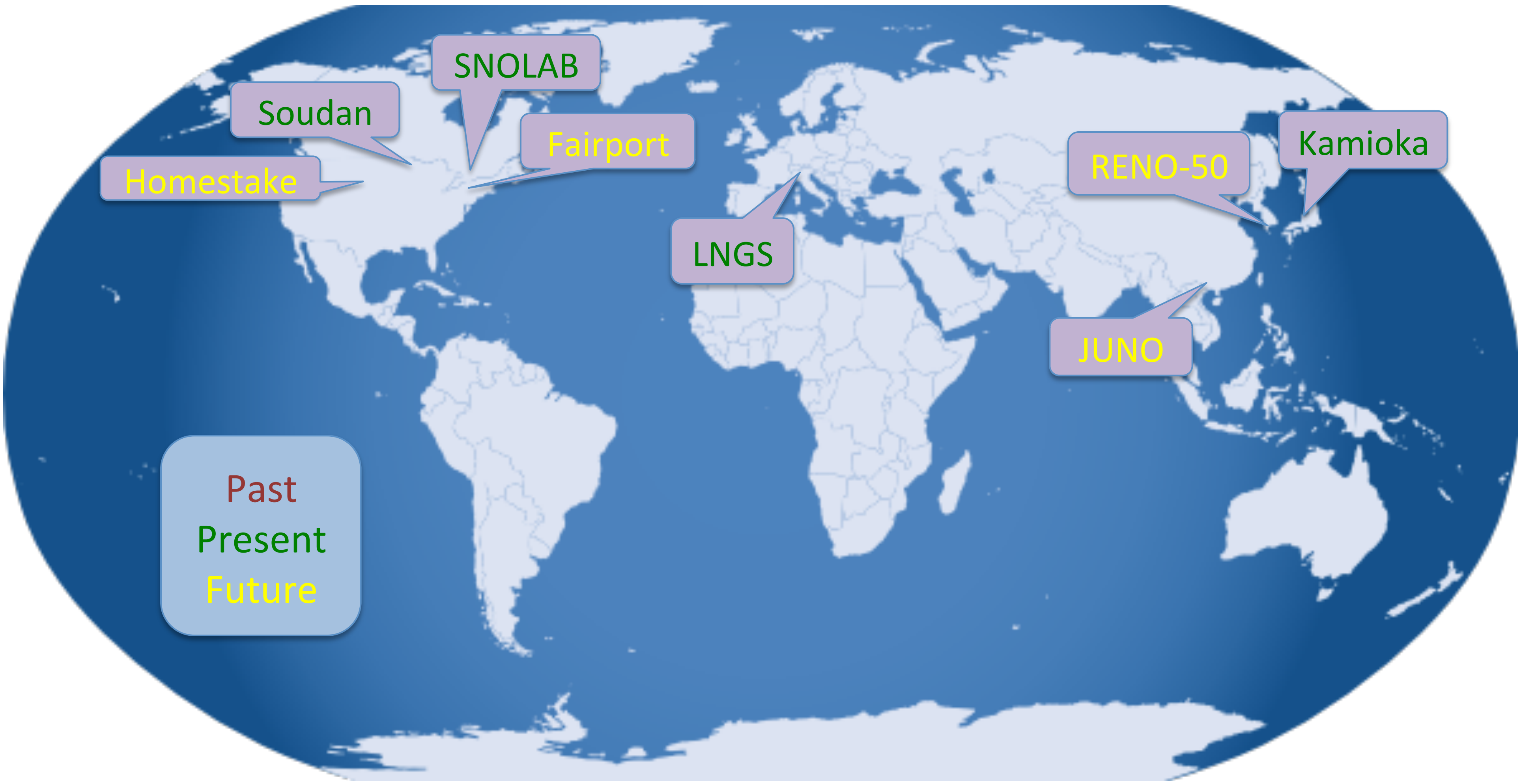
# CP Violation Searches with π/μ DAR Neutrinos

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

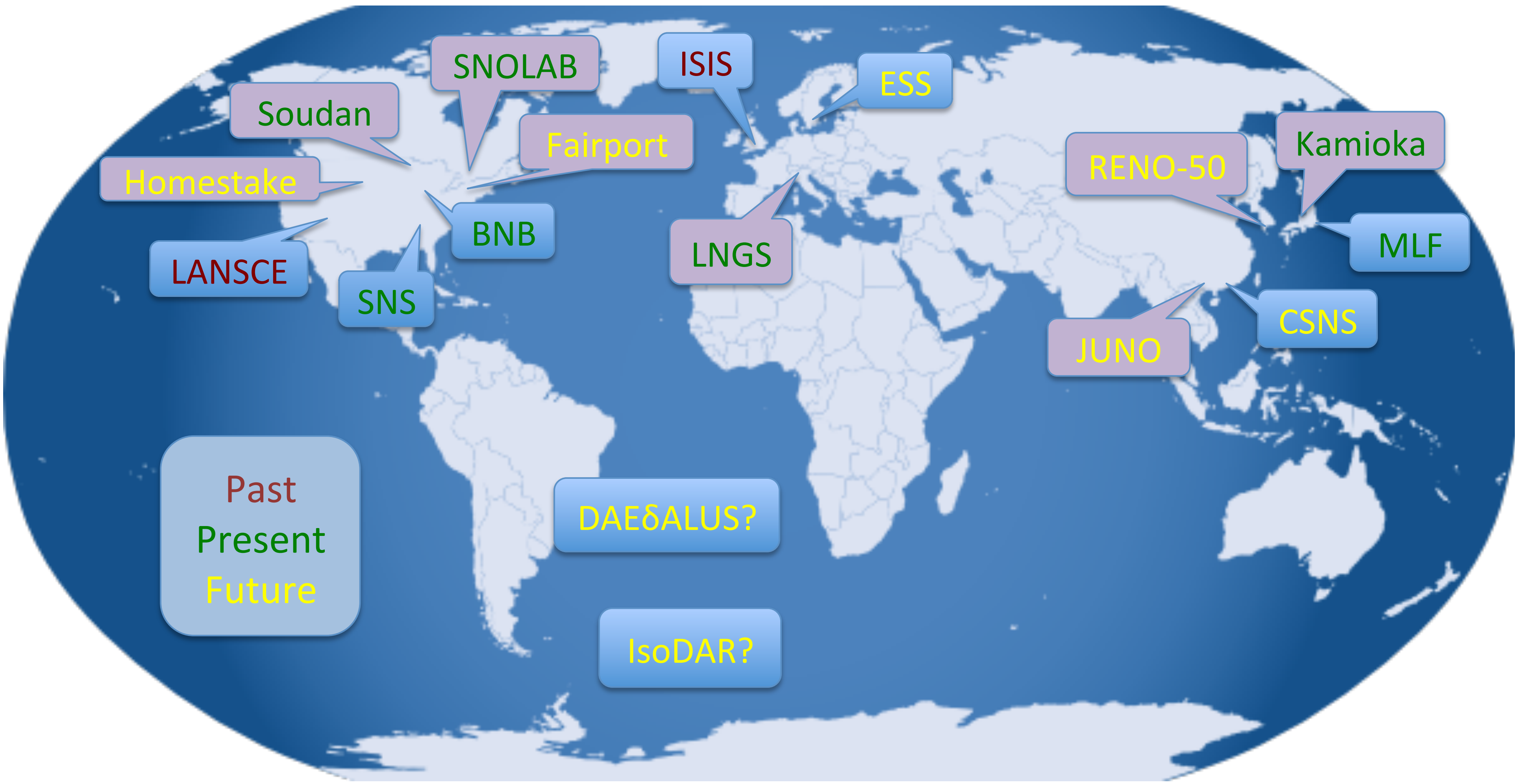



Measure $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations over distances of ~20 km

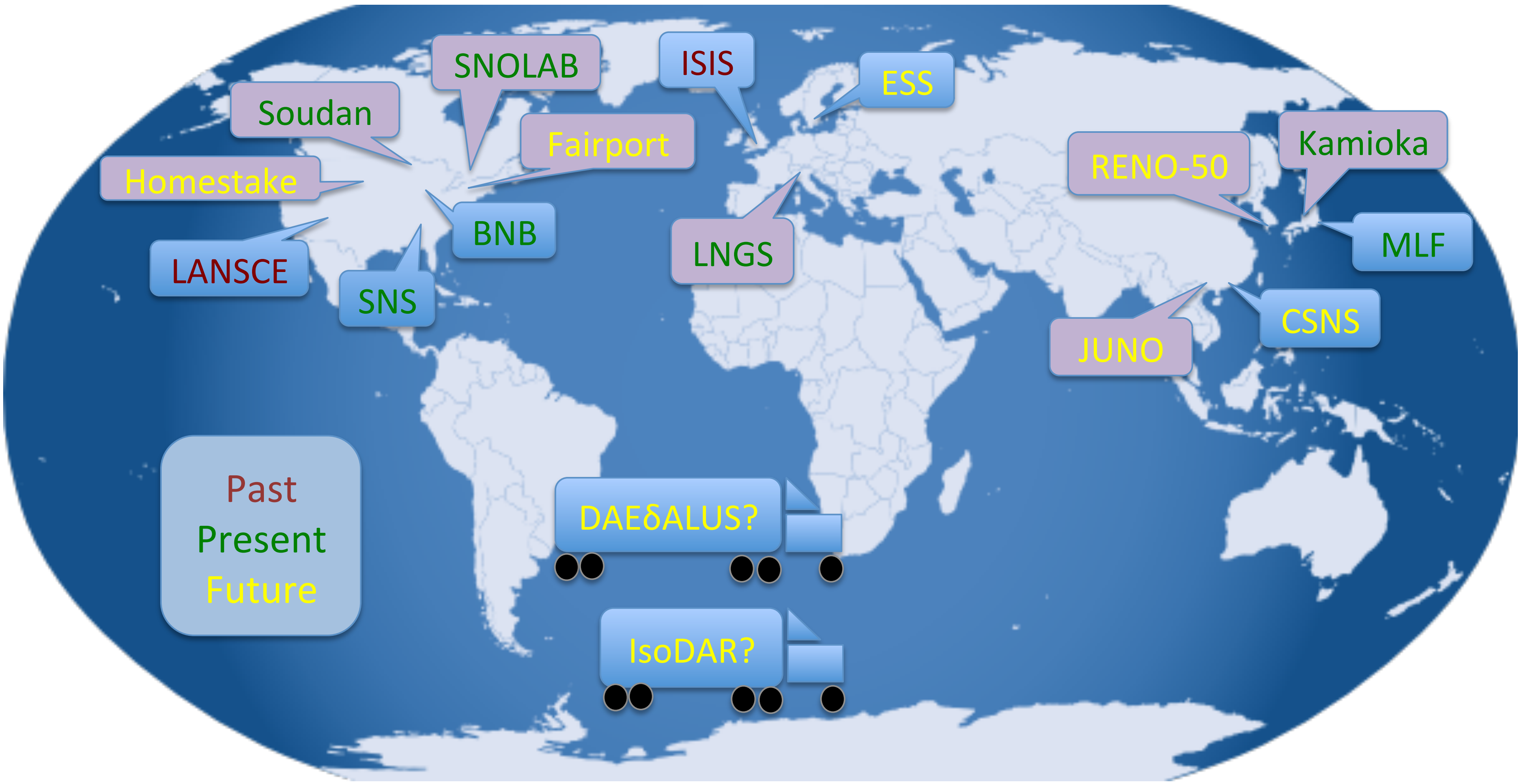
# Locations of large, underground, low energy (LULE) Neutrino Detectors



# DAR neutrino beams are not near LULE detectors



# DAEδALUS/IsoDAR Concept: Bring Source(s) to Detector

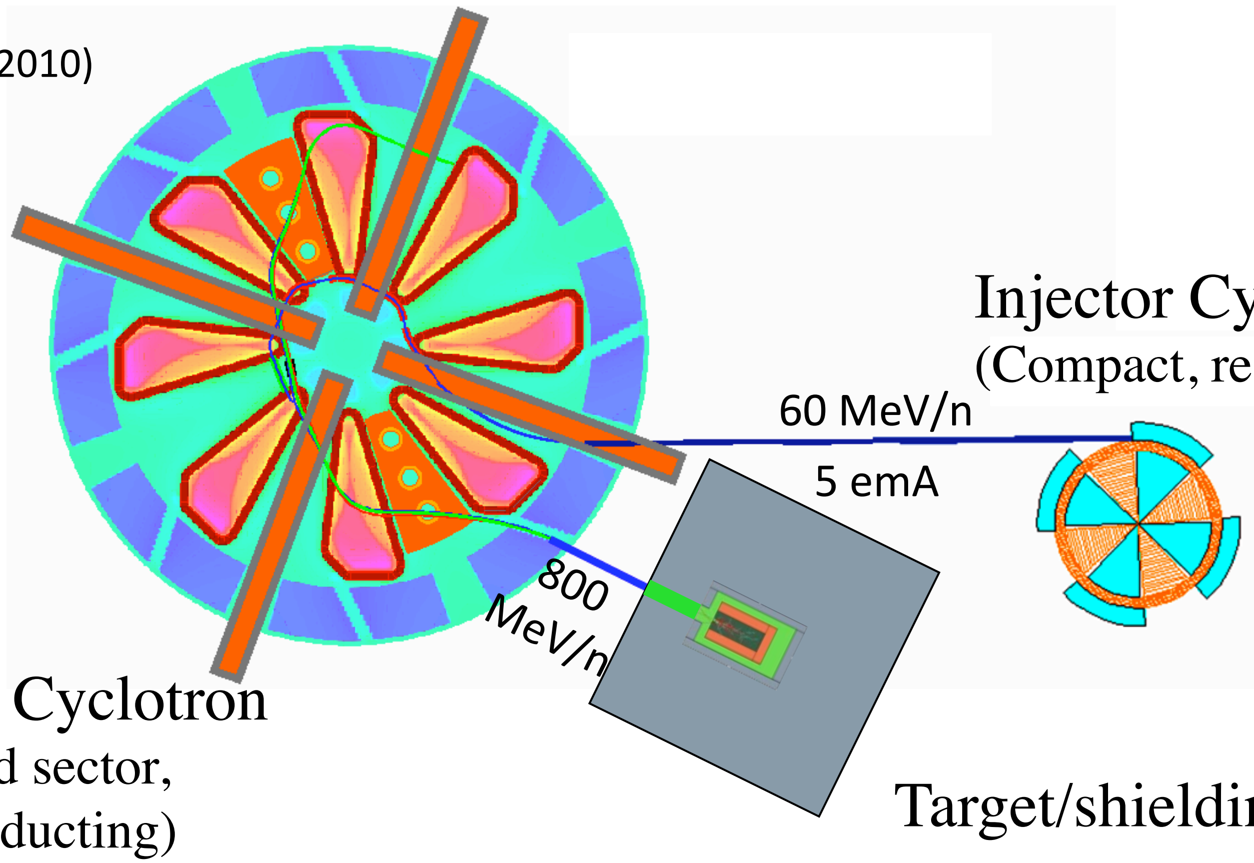


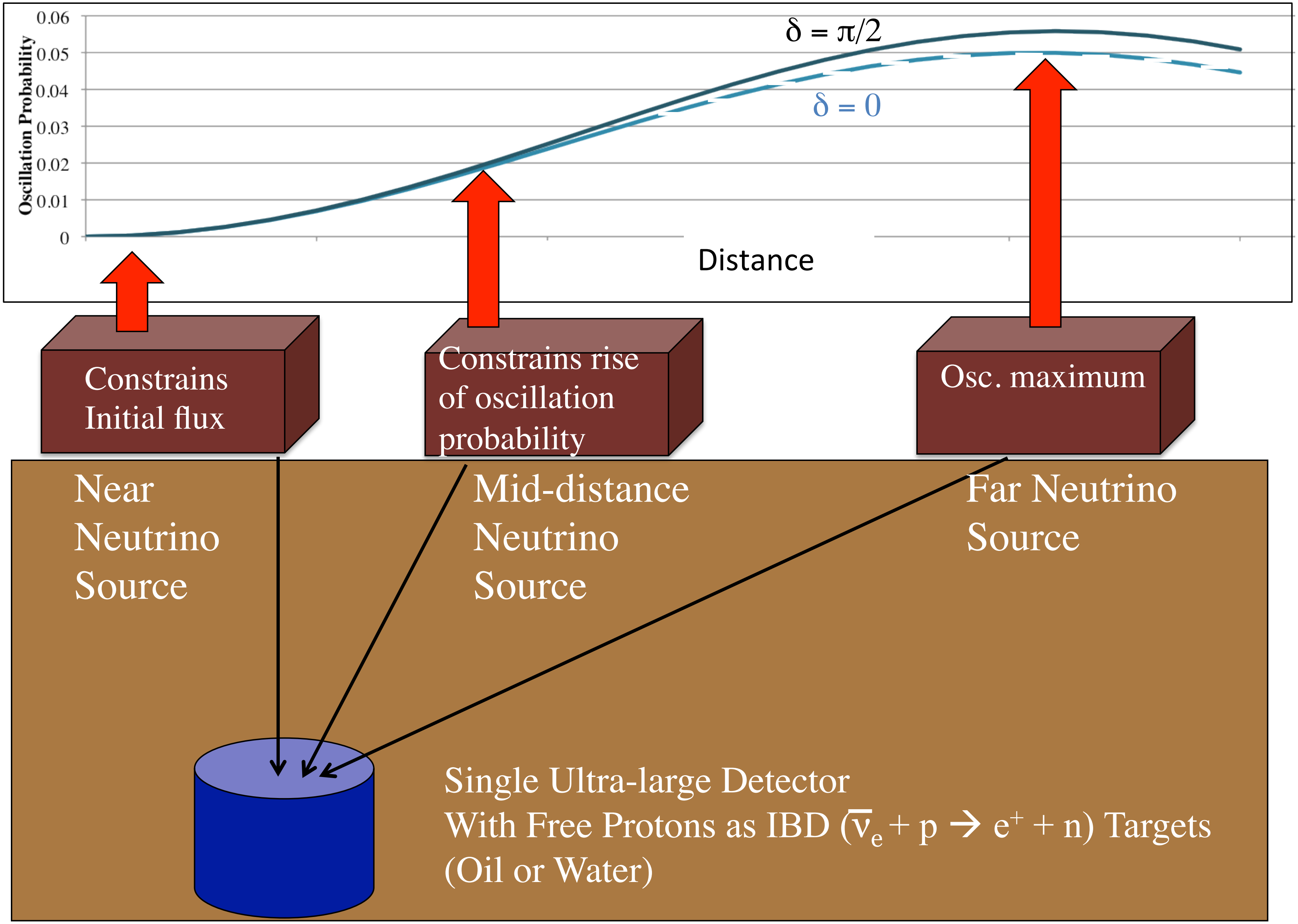
DAEδALUS uses high power cyclotrons to accelerate $H_2^+$ to 800 MeV/amu

1. Modest size
2. Relatively inexpensive

1. Reduce space charge
2. Stripping extraction

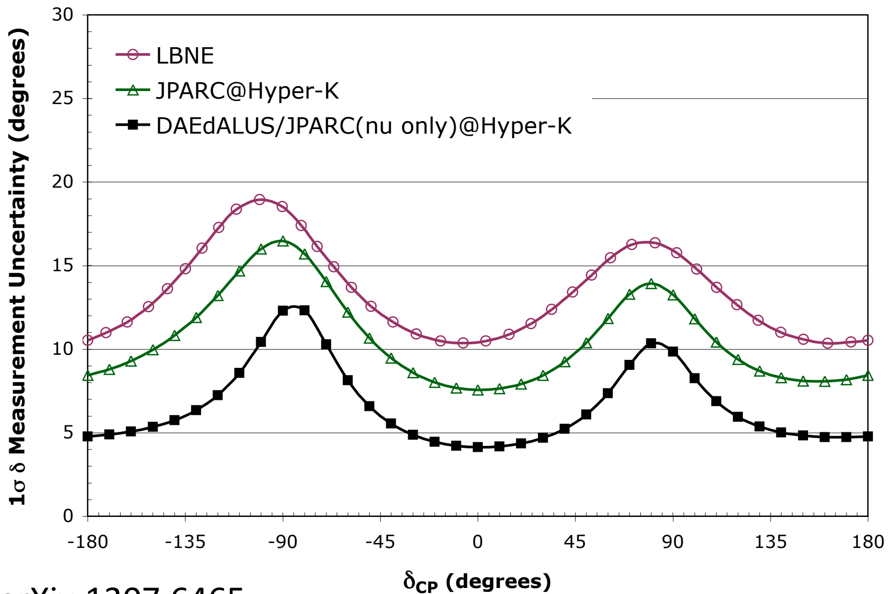
PRL 104, 141802 (2010)

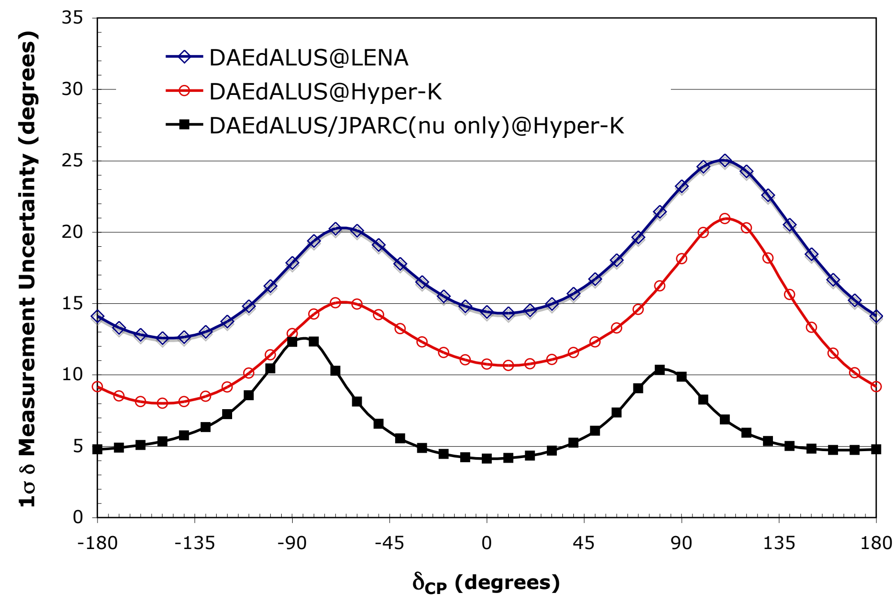



Oscillation Probability
0.06
0.05
0.04
0.03
0.02
0.01
0
δ = π/2
δ = 0
Distance
Constrains Initial flux
Constrains rise of oscillation probability
Osc. maximum
Near Neutrino Source
Mid-distance Neutrino Source
Far Neutrino Source
Single Ultra-large Detector
With Free Protons as IBD ($\bar{\nu}_e + p \rightarrow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

# DAEδALUS $\delta_{CP}$ Sensitivities

(Normal hierarchy assumed known)



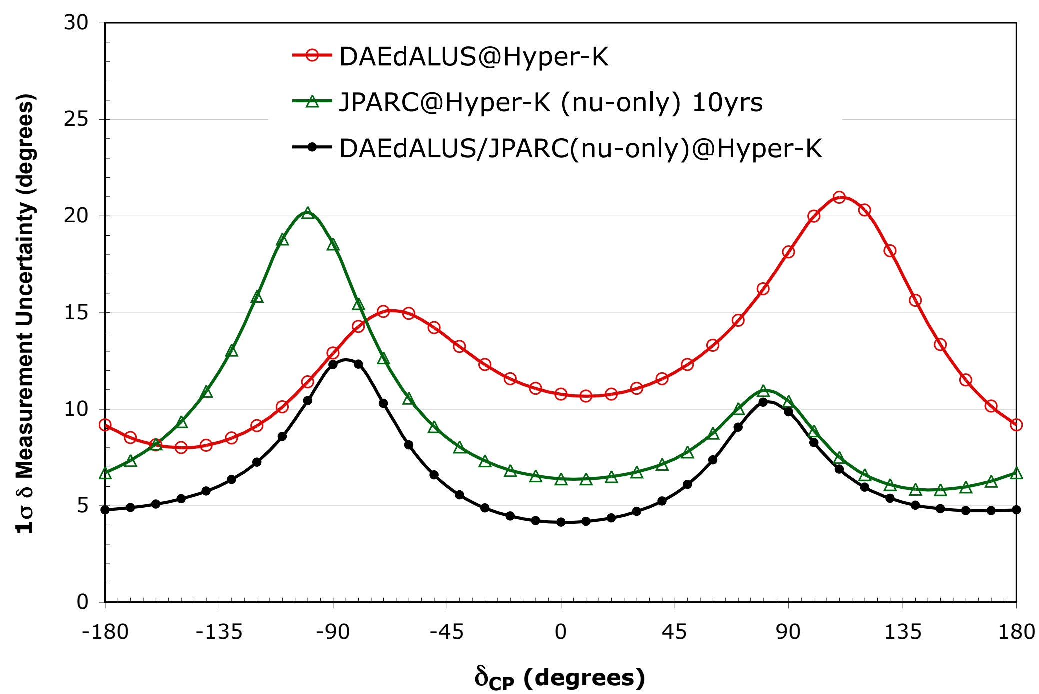




arXiv:1307.6465

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

# Complementarity With LBL Experiments

- Simultaneous running using same detector
- Different energies and systematics
  - Negligible cross section uncertainties
- Very different baseline
  - No matter effects
  - No NSI propagation effects
- Powerful sensitivity combination when paired with LBL in neutrino mode

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  - IsoDAR, OscSNS, J-PARC MLF, KDAR
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- Charged current cross section measurements
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# Physics of DAR Neutrino Sources

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  - DAEδALUS
- Sterile neutrino searches → See also J. Spitz's talk on Searches for Sterile Neutrino Mixing on Wed.
  - IsoDAR, OscSNS, J-PARC MLF, KDAR
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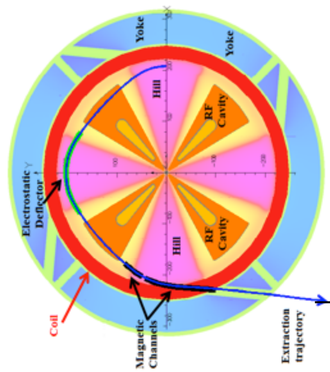
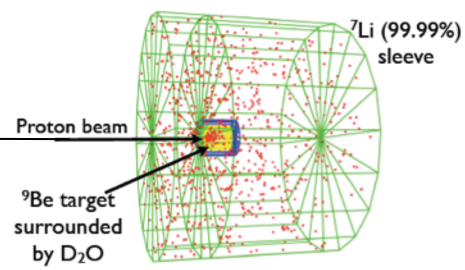
# IsoDAR: Phase 2 of DAEδALUS Program

Accelerates 5mA $H_2^+$
to 60 MeV/amu

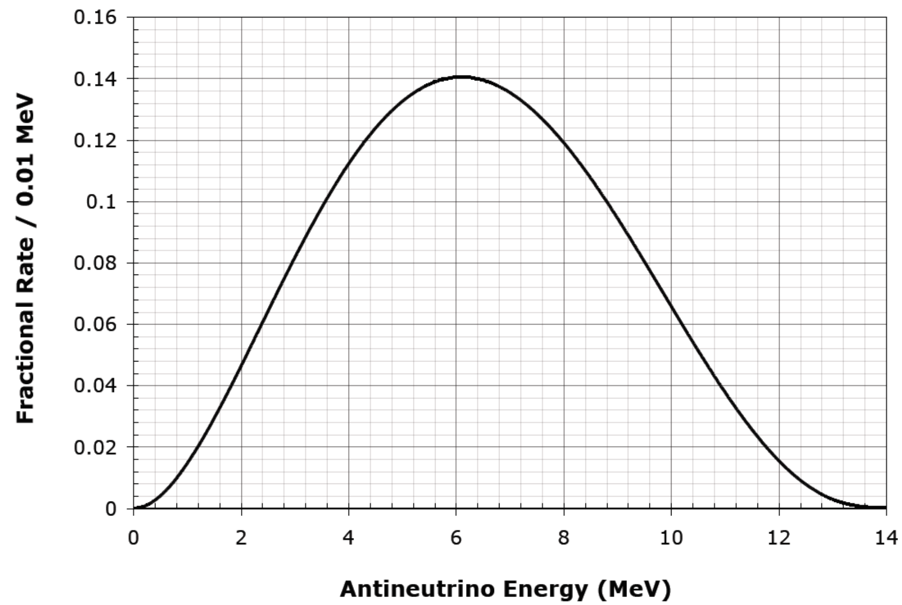



Not to scale

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




Phys. Rev. Lett. **109**, 141802



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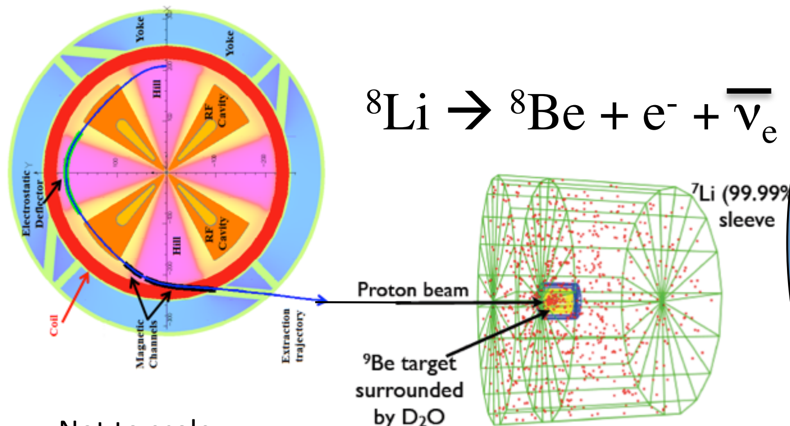


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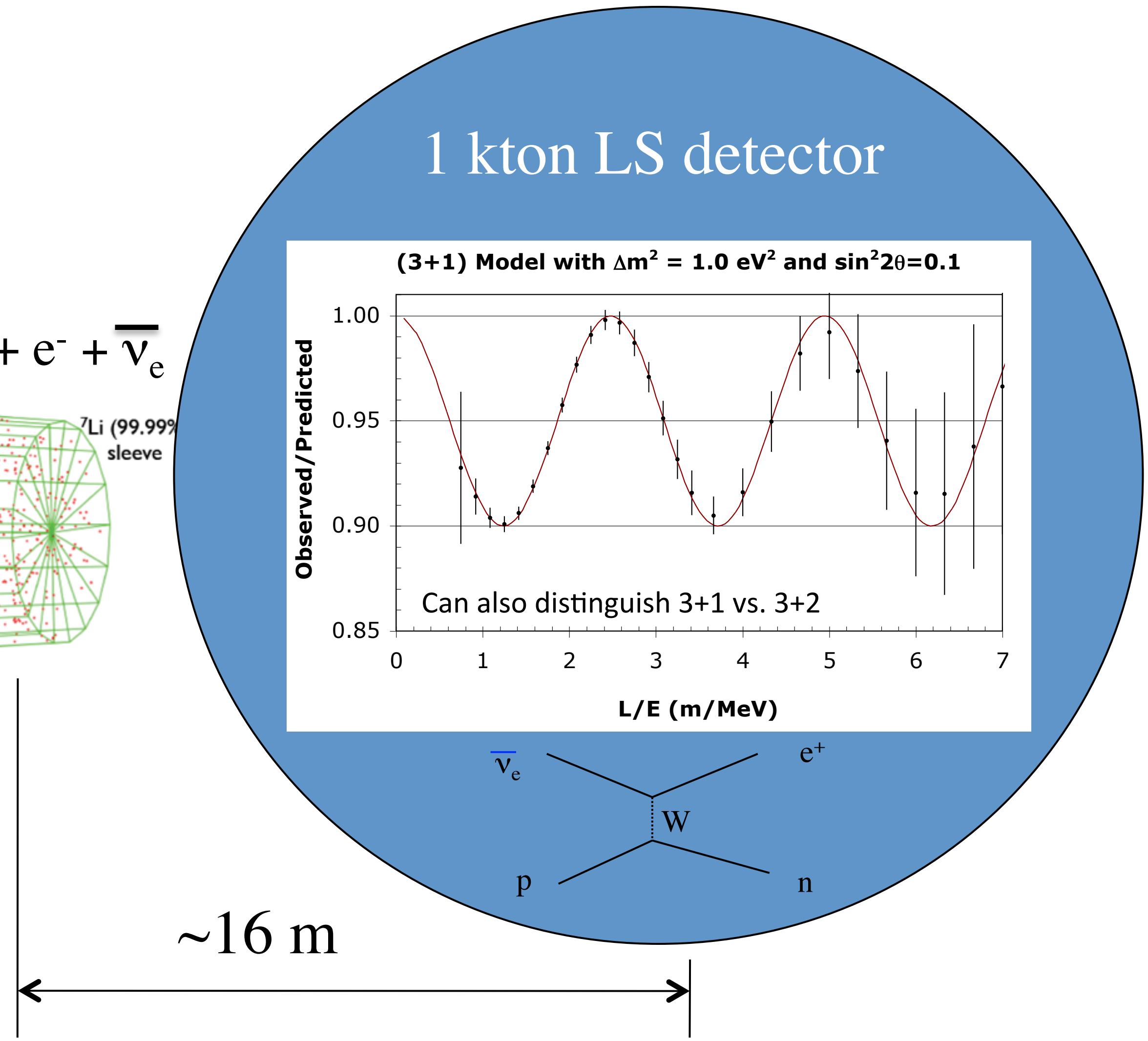
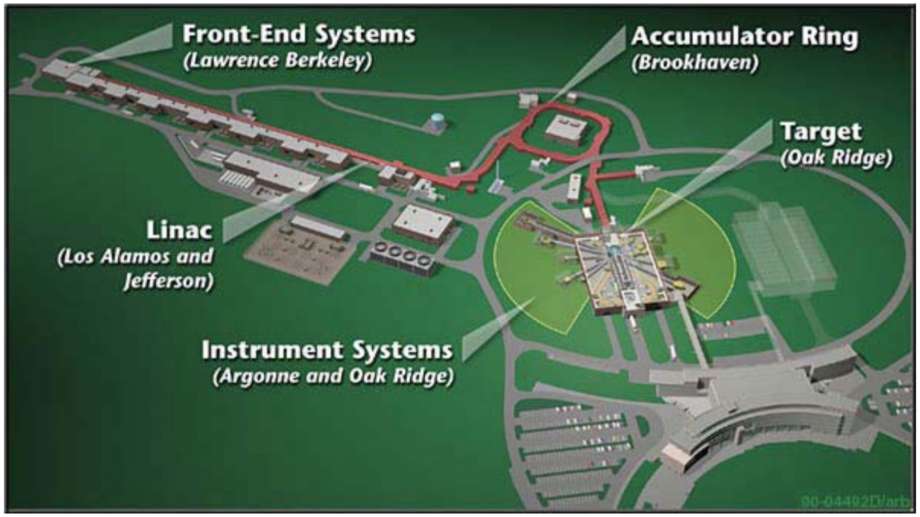
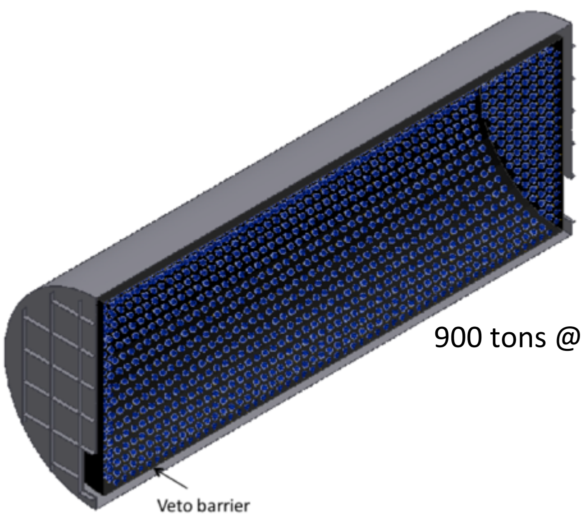



Potential locations: KamLAND, WATCHMAN

# "LSND-like" $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Experiments

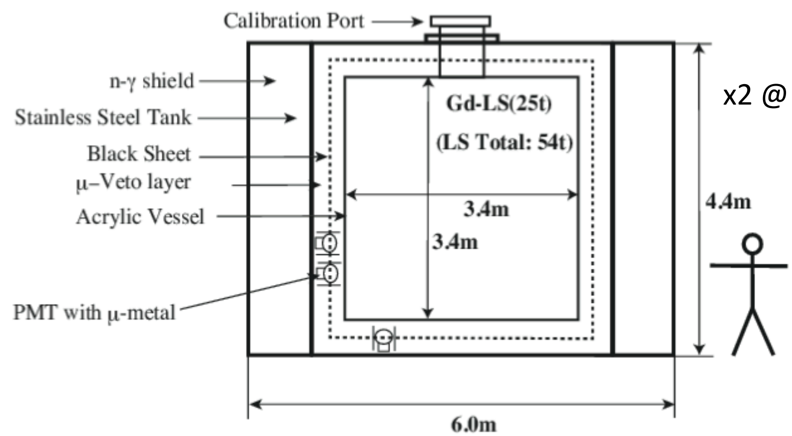
**OscSNS (arXiv:1307.7097)**




900 tons @ 60 m

**J-PARC MLF (arXiv:1310.1437)**

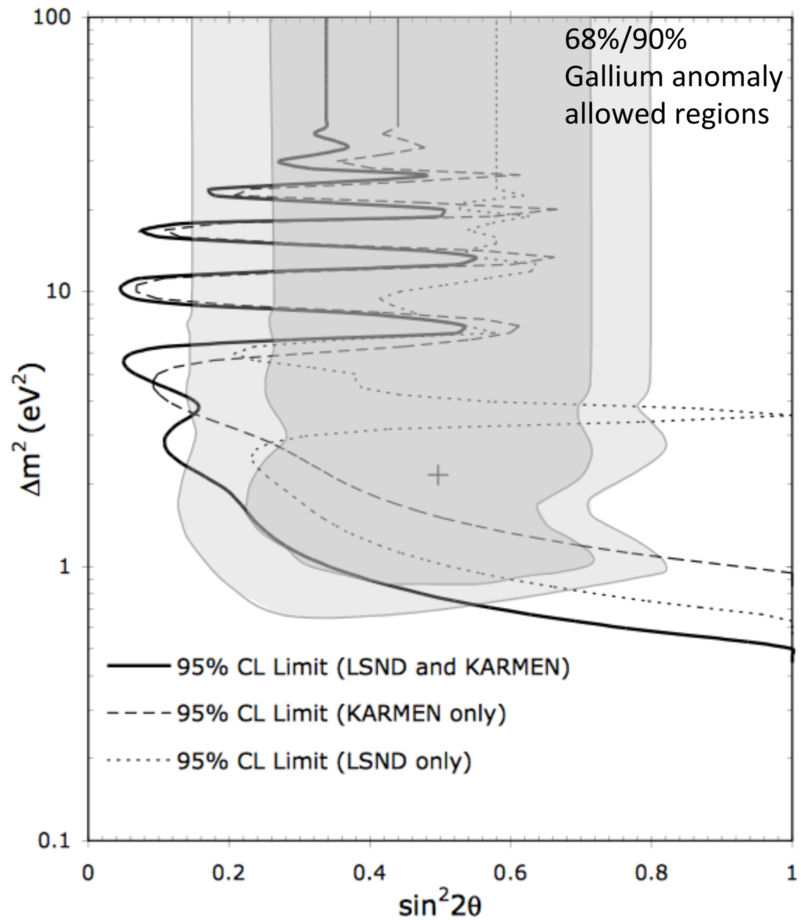

x2 @ 17m

# Additional π/μ DAR ν Channels

| Channel | Events/2 years |
| --- | --- |
| $\nu_e$ C -> $e^-$ $N_{gs}$ | 4705 |
| $\nu_e$ C -> $e^-$ $N^*$ | 2247 |
| $\nu_\mu$ C -> $\nu_\mu$ $C^*$(15.11) | 1490 |
| ν C -> ν $C^*$(15.11) | 7070 |
| $\nu_e$ $e^-$ -> $\nu_e$ $e^-$ | 1353 |
| $\nu_\mu$ $e^-$ -> $\nu_\mu$ $e^-$ | 450 |
| 100% $\bar{\nu}_\mu$ -> $\bar{\nu}_e$, $\bar{\nu}_e$ p -> $e^+$ n | 92,308 |
| 0.26% $\bar{\nu}_\mu$ -> $\bar{\nu}_e$, $\bar{\nu}_e$ p -> $e^+$ n | 240 |

OscSNS Event Rates at 60m

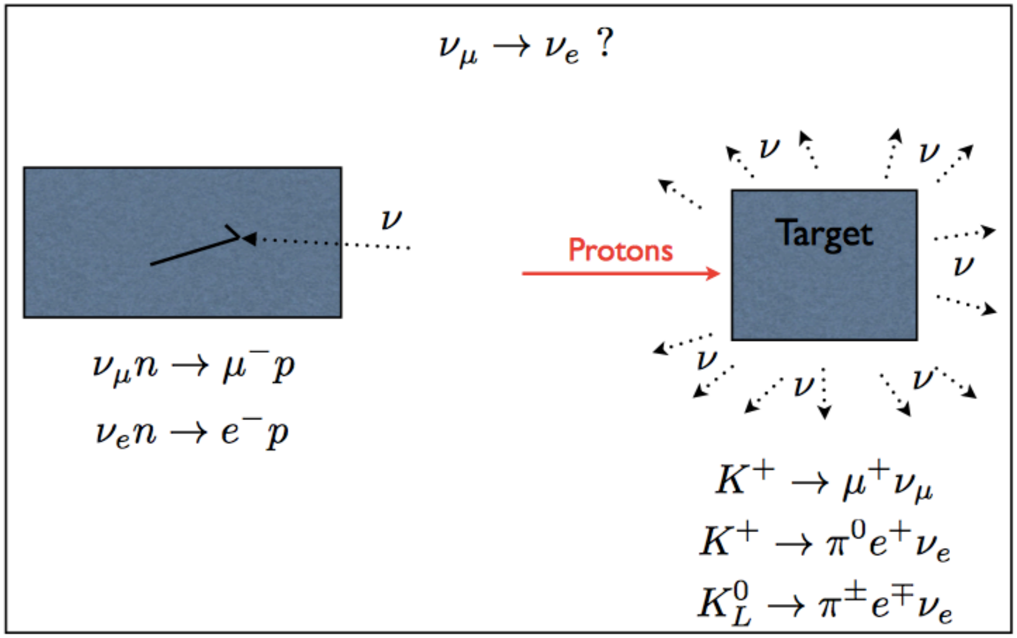
Example $\nu_e$ disappearance limits using $\nu_e + ^{12}\mathrm{C} \rightarrow ^{12}\mathrm{N}_{gs} + e^-$

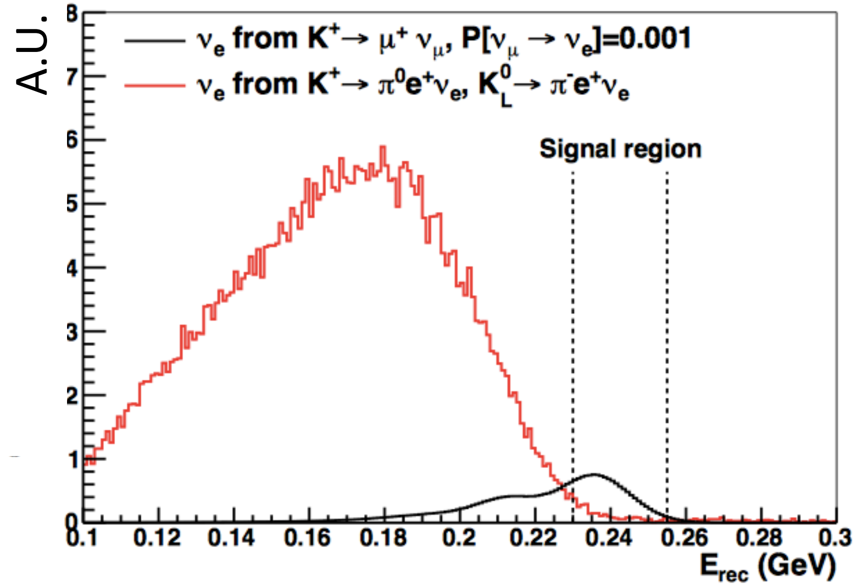



Phys. Rev. D **85**, 013017

# Kaon DAR Concept

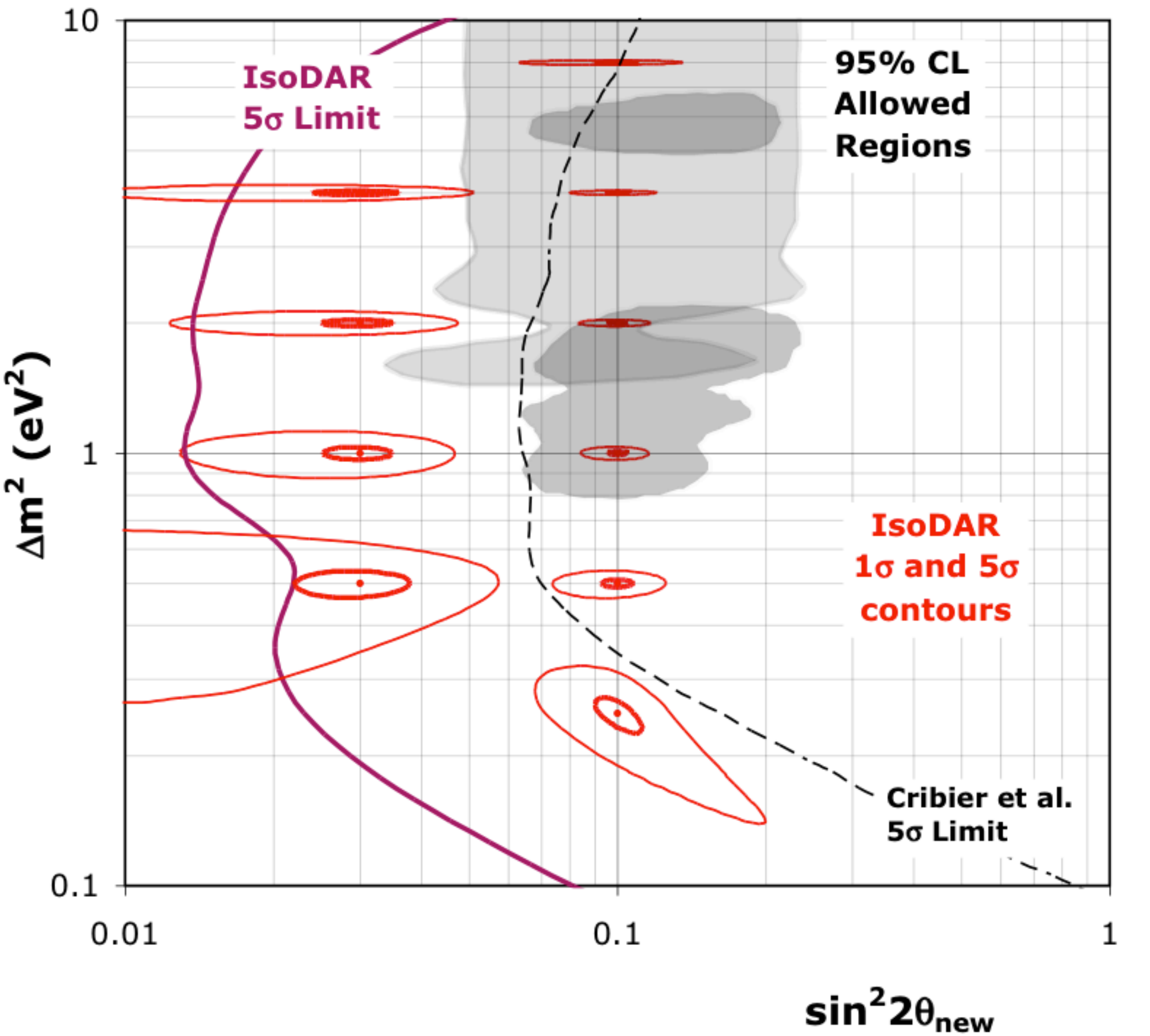
Phys.Rev. D85 (2012) 093020



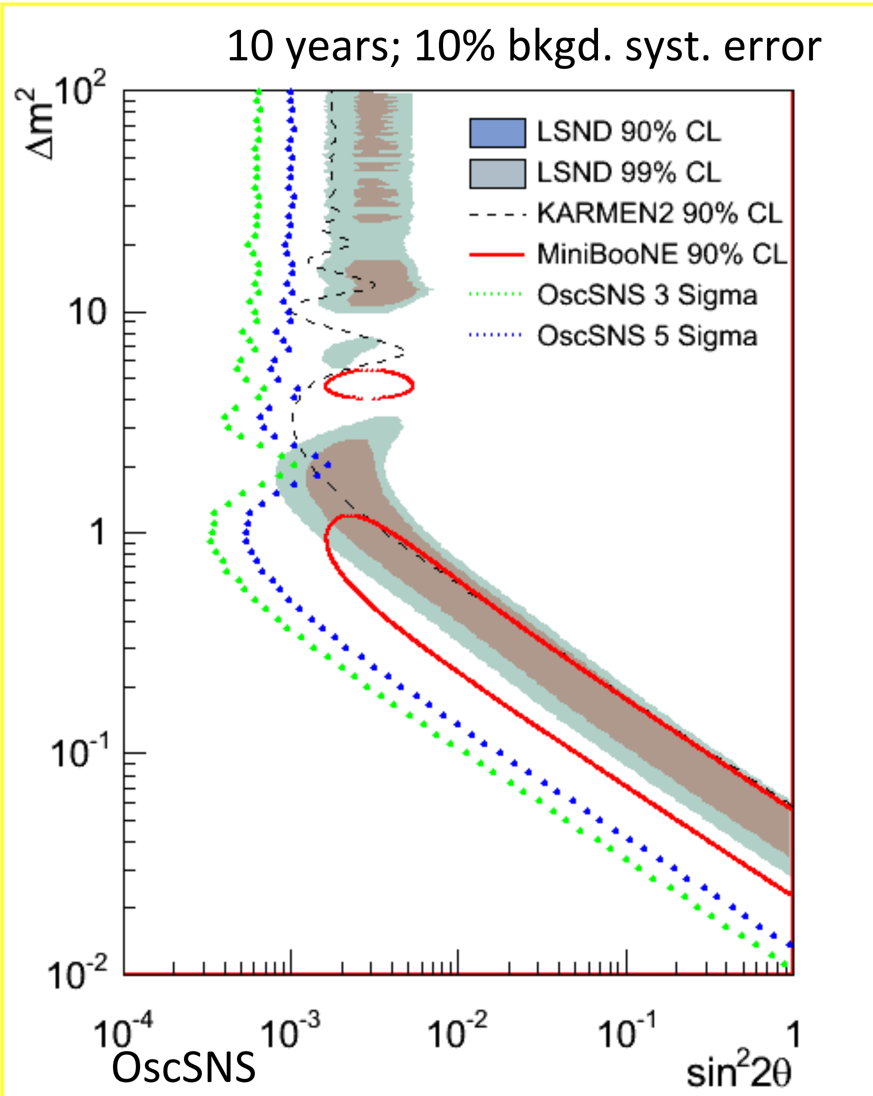



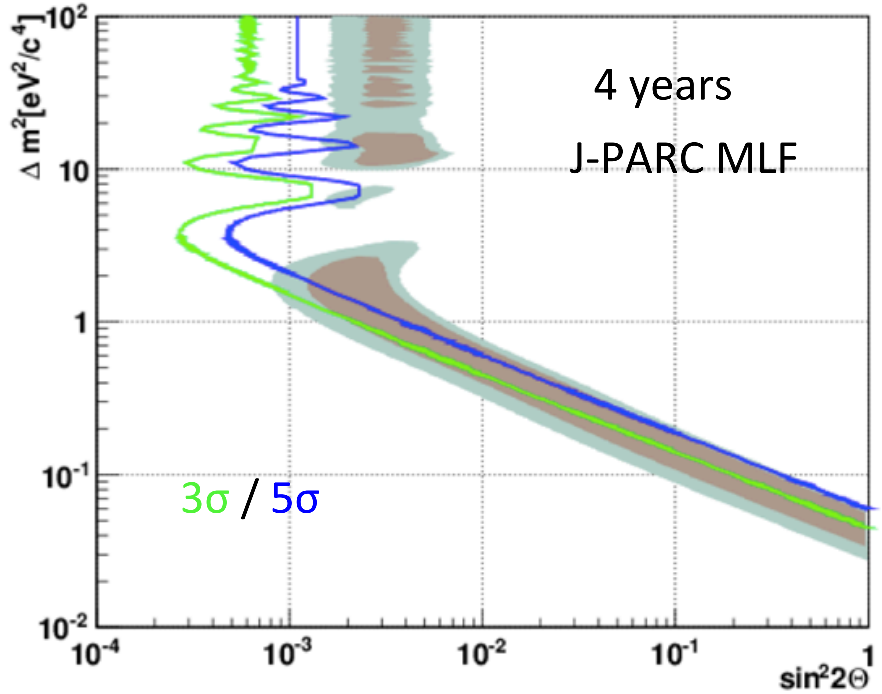

Opens up a potential $\nu_e$ appearance channel at e.g. J-PARC MLF

# IsoDAR@KamLAND Measurement Sensitivity



# $\pi/\mu/K$ DAR $\bar{\nu}_e$ Appearance Sensitivities

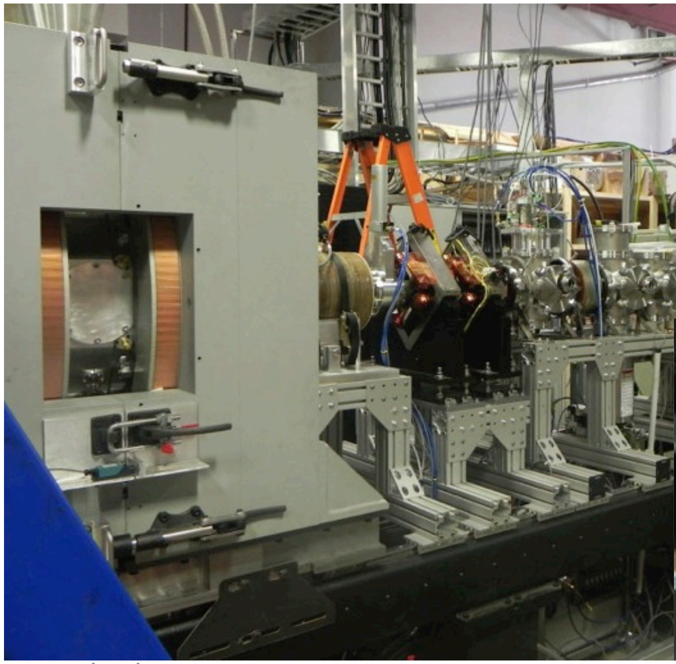


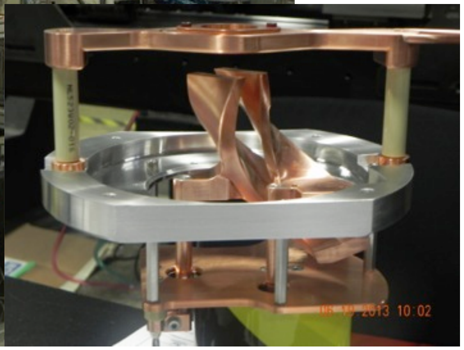



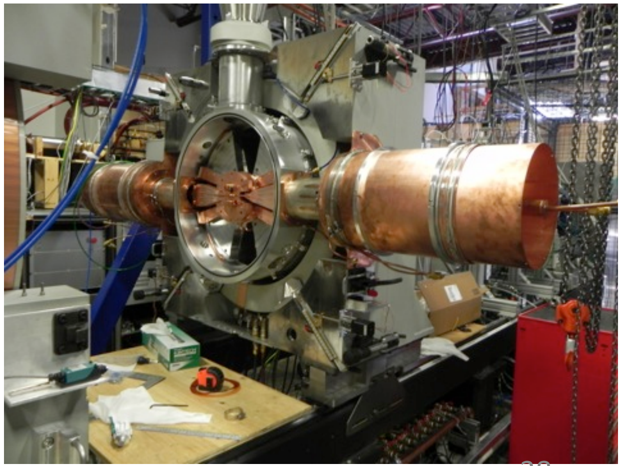
# DAEδALUS/IsoDAR Status

See also J. Spitz's talk on Friday

- Installed ion source from INFN Catania at development lab of Best Cyclotron Systems Inc, Vancouver
  - Demonstrated 40 mA protons
  - Re-optimizing for $H_2^+$
    - Initial output: 12 mA (summer 2014)
    - Upgrade with new plasma chambers Sept 2014
      - Anticipate 20-30 mA $H_2^+$
- Beam successfully inflected and accelerated 3.5 turns in test cyclotron (600 keV energy)







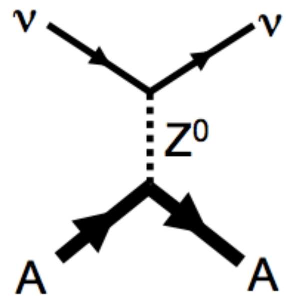
# Status of π/μ/K DAR Sterile ν Searches

- OscSNS
  - Preferred location at SNS identified
  - Neutron measurements currently being performed on site
- J-PARC MLF
  - Third floor of MLF building identified as preferred site
  - Neutron measurements performed on site
- KDAR
  - J-PARC MLF is a possible site

# Physics of DAR Neutrino Sources

- CP violation searches
  - DAEδALUS
- Sterile neutrino searches
  - IsoDAR, OscSNS, J-PARC MLF, KDAR
- Coherent elastic neutrino-nucleus scattering
  - COHERENT, CENNS
- Neutrino non-standard interactions
  - IsoDAR, COHERENT, CENNS
  -
- Standard Model tests (e.g. weak mixing angle)
  - IsoDAR, COHERENT, CENNS
- Charged current cross section measurements
  - IsoDAR, OscSNS, KDAR, CAPTAIN

# Coherent elastic neutrino-nucleus scattering




$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

Well-predicted in the SM but never observed

Measuring it is a test of SM and a probe of BSM physics (e.g. neutrino non-standard interactions)

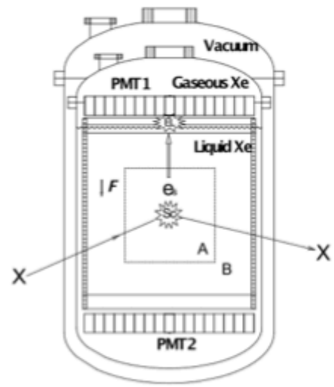
- Need $Q \lesssim 1/R$. True for many nuclei at DAR energies.
- Need $E_{th} < 2E_\nu^2/M$. At DAR energies, this is in the range $\mathcal{O}(10 - 100\mathrm{keV})$.

Beyond what neutrino detectors can achieve…

# WIMP Detectors To Measure Coherent Elastic Neutrino-nucleus Scattering at DAR ν source

arXiv:1310.0125

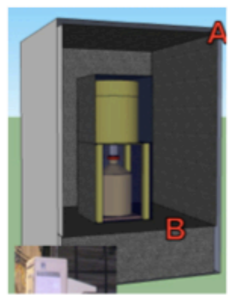
**Two-phase LXe**

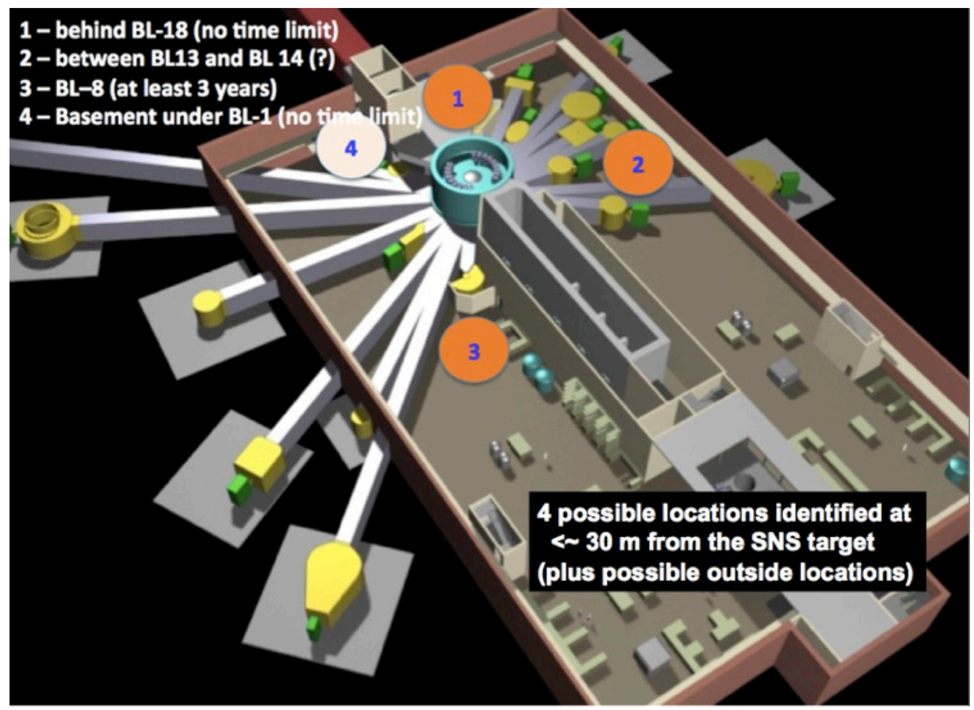



**CsI**

Neutrino flux:
few times $10^7$ /s/cm$^2$ at 20 m

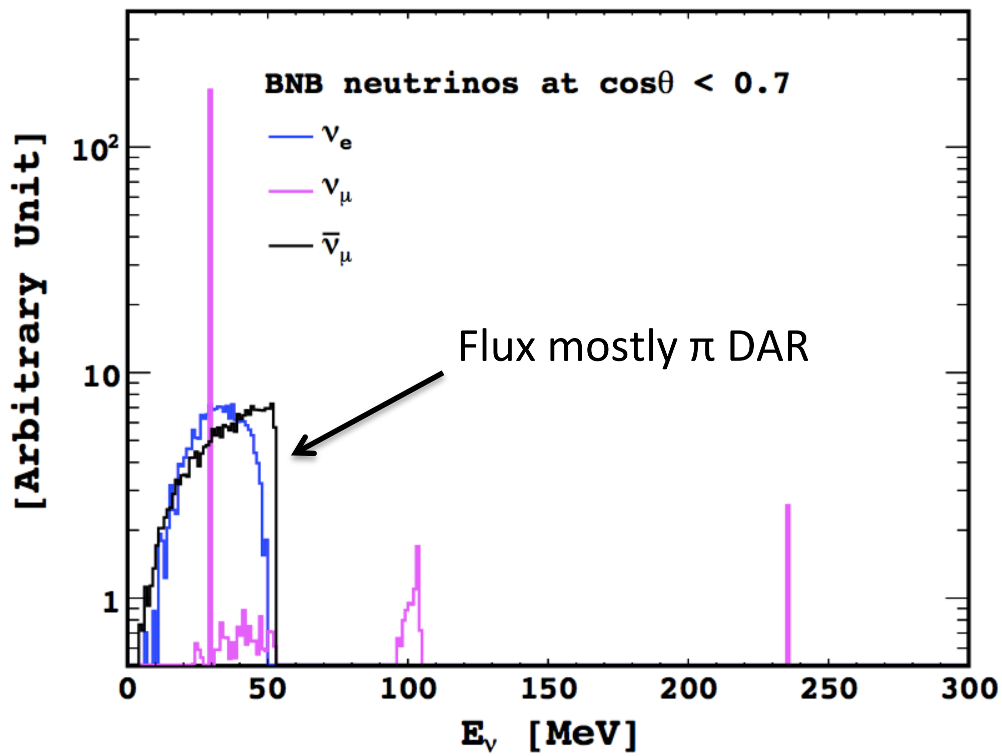
**HPGe PPC**

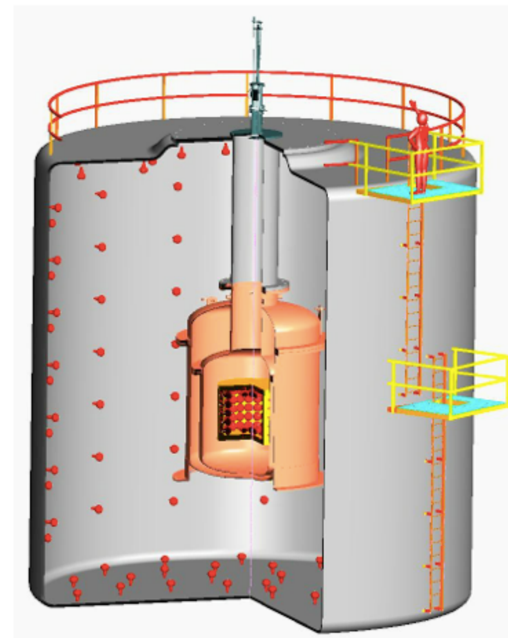


# WIMP Detectors To Measure Coherent Elastic Neutrino-nucleus Scattering at DAR ν source

Phys. Rev. D **89**, 072004



**Ton-scale single phase LAr detector**

<u>CENNS Collaboration</u>

# Status of coherent elastic neutrino-nucleus scattering searches at DAR ν sources

- COHERENT
  - Identified a preferred site at the SNS
    - Measured to have a low neutron background
  - Recent progress on candidate detector technology
    - See arXiv:1407.7524v2
- CENNS
  - Neutron measurements performed near BNB target at preferred FNAL site location
  - Low energy threshold LAr detector development

# Concluding Remarks

- Rich physics program associated with DAR ν's
- There exists a new generation of intense, short duty factor DAR ν sources that are currently completely untapped by our community
- In addition, the DAEδALUS program is developing new small sized, relatively inexpensive, but quite intense cyclotron-based decay-at-rest ν sources for the field
- A low energy DAR ν beam program complements quite well the traditional high energy DIF ν beam program