Neutrino Research at ADS Facilities

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Outline

- ADS
- IsoDAR
- μDAR
- Conclusions

ADS

The main purposes of an Accelerator Driven Subcritical System (ADS), of the kind being developed in China (C-ADS), are

- recycle the used nuclear fuel
- produce electricity

The byproducts of nuclear fission are still radioactive but cannot sustain a chain reaction. In the C-ADS nuclear reactor the additional neutrons will be provided by a linear accelerator, where the energy of the beam will be gradually increased up to 1.5 GeV.

Z.H. Li *et al.*, **Phys.Rev.ST Accel.Beams 16 (2013) 8, 080101**

ADS time-schedule			
R&D: 2017	CIADS: 2022	Demo Facility: 2030	Industrial Facility: 203x
12 mA, 26 MeV	10 mA, 250-500 MeV	10 mA 1GeV	15 mA 1.5 GeV

Also Europe is working on the development of an ADS system: MYRRHA

Neutrino Research at ADS

Even in the earlier phases of ADS, neutrinos can be produced first via Isotope Decay At Rest (IsoDAR), then via muon Decay At Rest (μDAR).

- **IsoDAR**: the accelerator is used as source of spallation neutrons. They are absorbed in a ^{7}Li converter placed around the target, producing ^{8}Li $\Rightarrow$ β-decay $\Rightarrow$ $\bar{\nu}_e$.
  Possible to search for **sterile neutrinos** in the **disappearance channel** (energy higher than reactor neutrinos)
- **μDAR**: when the energy is higher ($>$ 400 MeV), $\bar{\nu}_\mu$ can be created via μDAR, using the process

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

  Studying $P_{e\mu}$ is it possible to search for **sterile neutrinos** in the **appearance channel** and to **measure δ_{CP}**

IsoDAR

Comparison with Reactor Neutrino Experiments

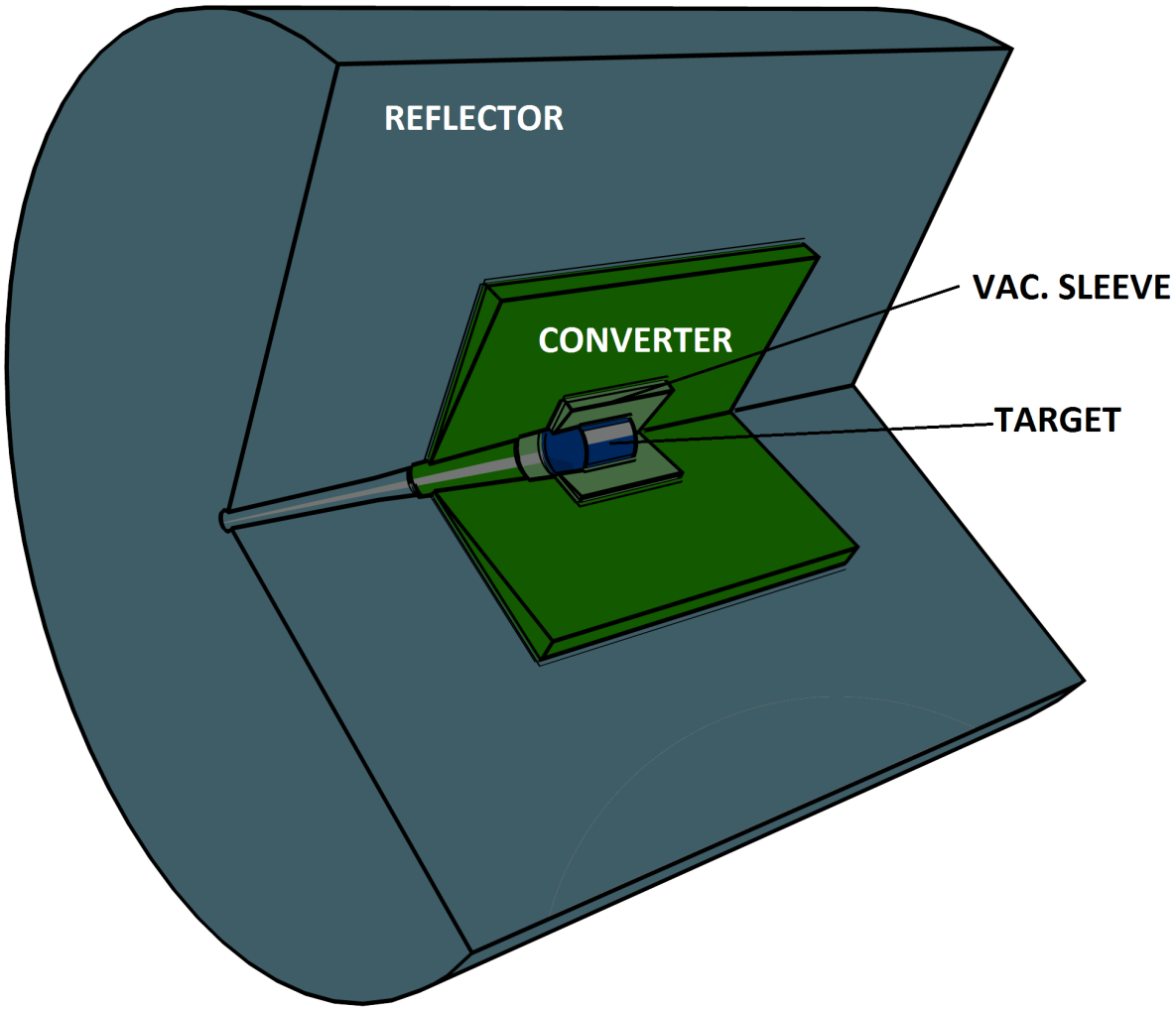
Many other proposed experiments using $\overline{\nu}_e$ from nuclear reactors to search for the same effect.

- Shape of the expected spectrum is known more precisely (uncertainties for reactor neutrino spectrum)
- Due to our higher energy:
  A) Longer baselines (for the same oscillations) $\Rightarrow$ easier for near detector
  B) More shielding *and* sensitive to higher ΔM^2
  C) Different energy range $\Rightarrow$ complementary to reactor neutrino experiments

However

- Reactor neutrino experiments will get an higher neutrino flux
- No need of additional facilities to produce neutrinos

Target Station



IsoDAR - Converters

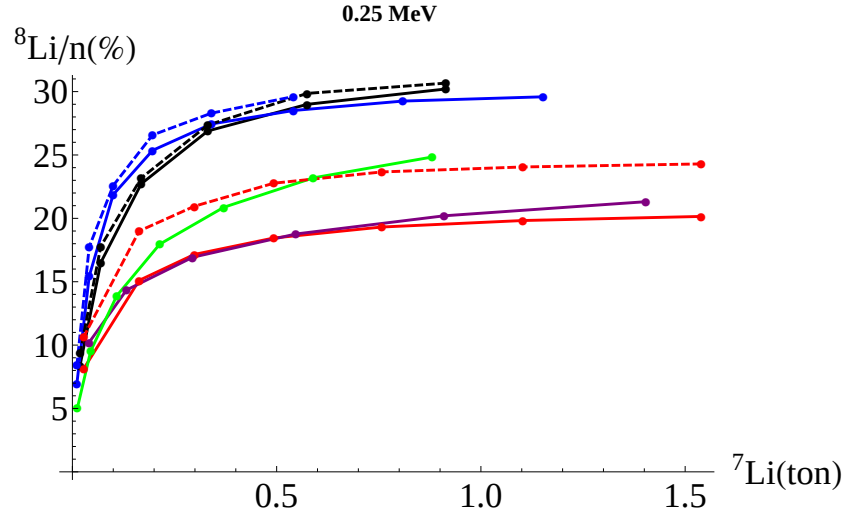
^{8}Li production from the reaction $^7Li + n \rightarrow {}^8Li$
The neutrons from the spallation target must be slowed down by a moderator

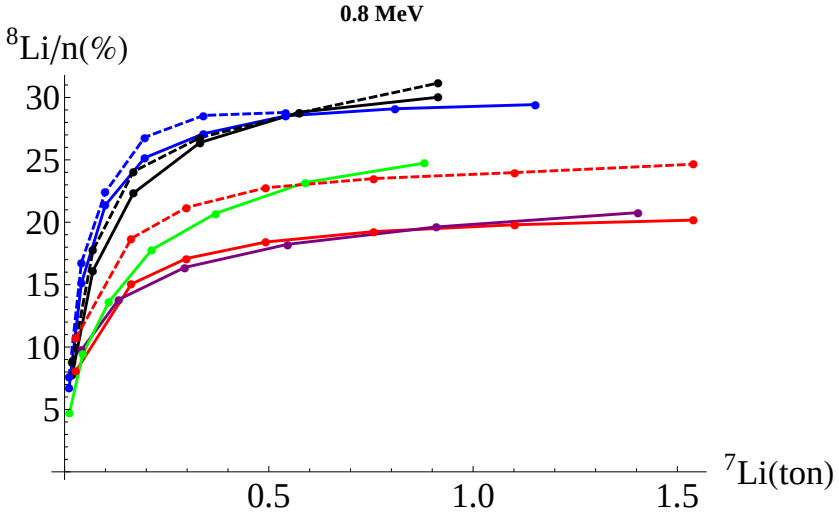
We considered several possibilities for the converter

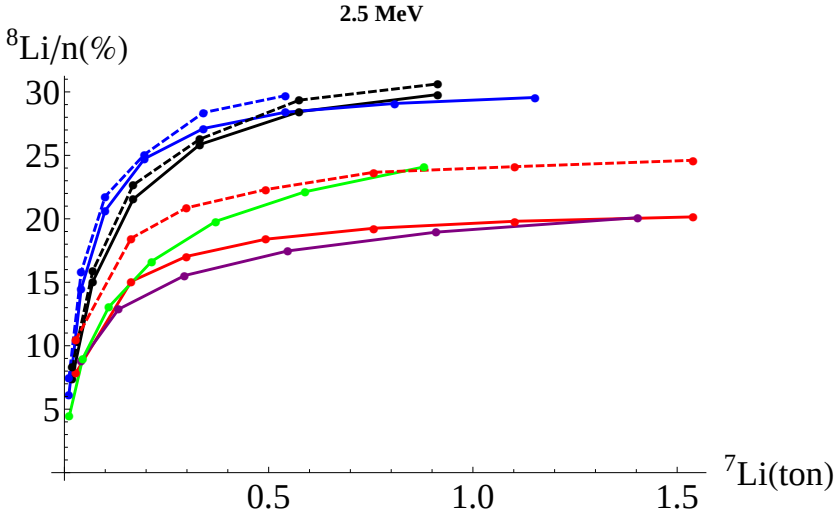
E. Ciuffoli *et al.*, **arXiv:1606.09451 [physics.ins-det]**

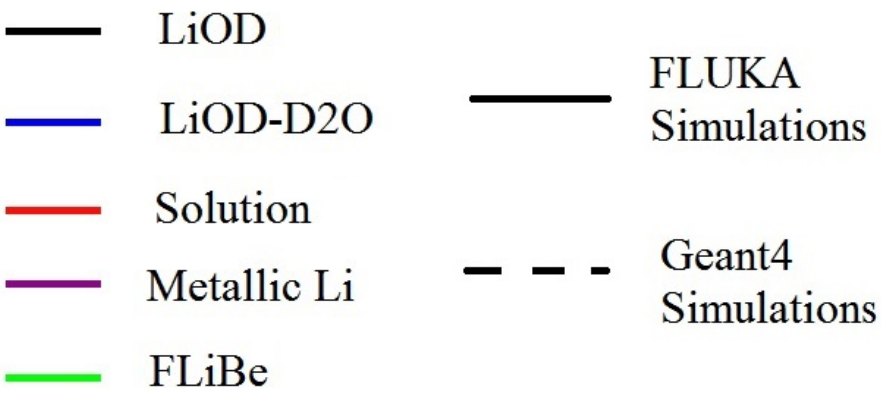
- **Metallic Lithium**: the neutrons are moderated by a heavy water sleeve around the target.
- Lithium deuteroxide anhydrate (**LiOD**) and monohydrate (**LiOD-D_2O**): they offer the highest neutrino yields because they act also as a moderator for the neutrons due to the presence of D in the converter. Another advantage is that the converter is reasonably compact ($\Rightarrow$ reduce the uncertainty on the baseline).
- 9.5% **LiOD solution** in heavy water: lower conversion efficiency due to the higher amount of H present in the compound.
- **FLiBe**: converter proposed for IsoDAR@KamLAND
  M. Abs *et al.*, **arXiv:1511.05130 [physics.acc-ph]**

Converter Efficiency

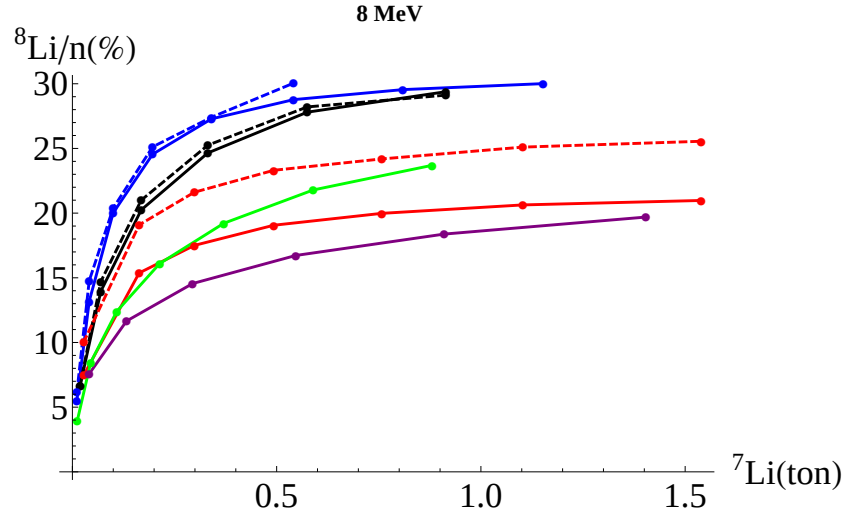


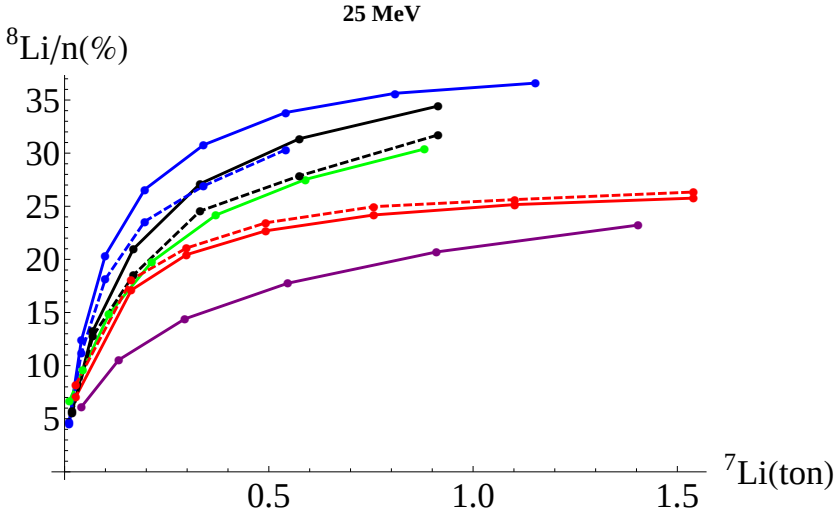


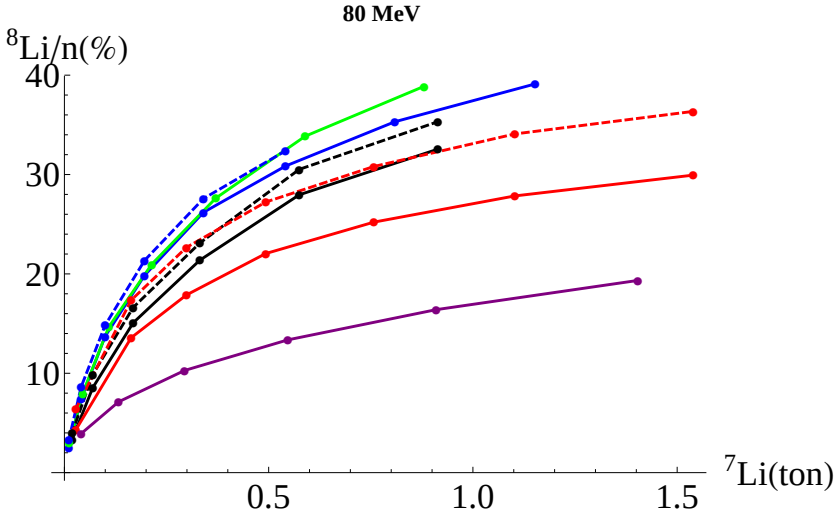


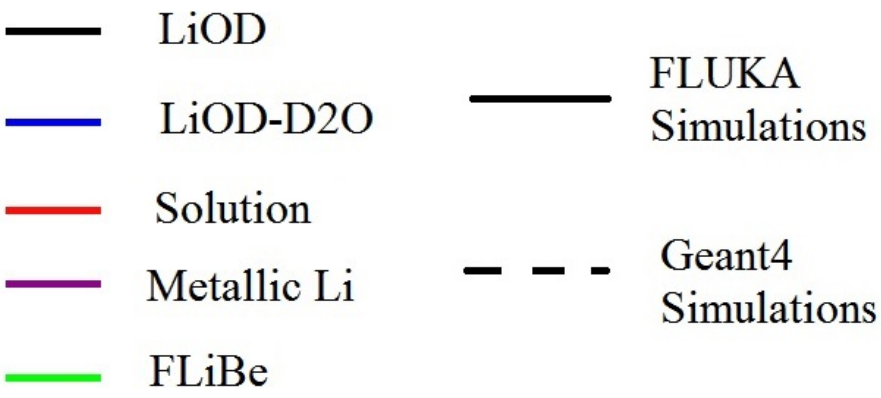


Converter Efficiency









Complete Simulations

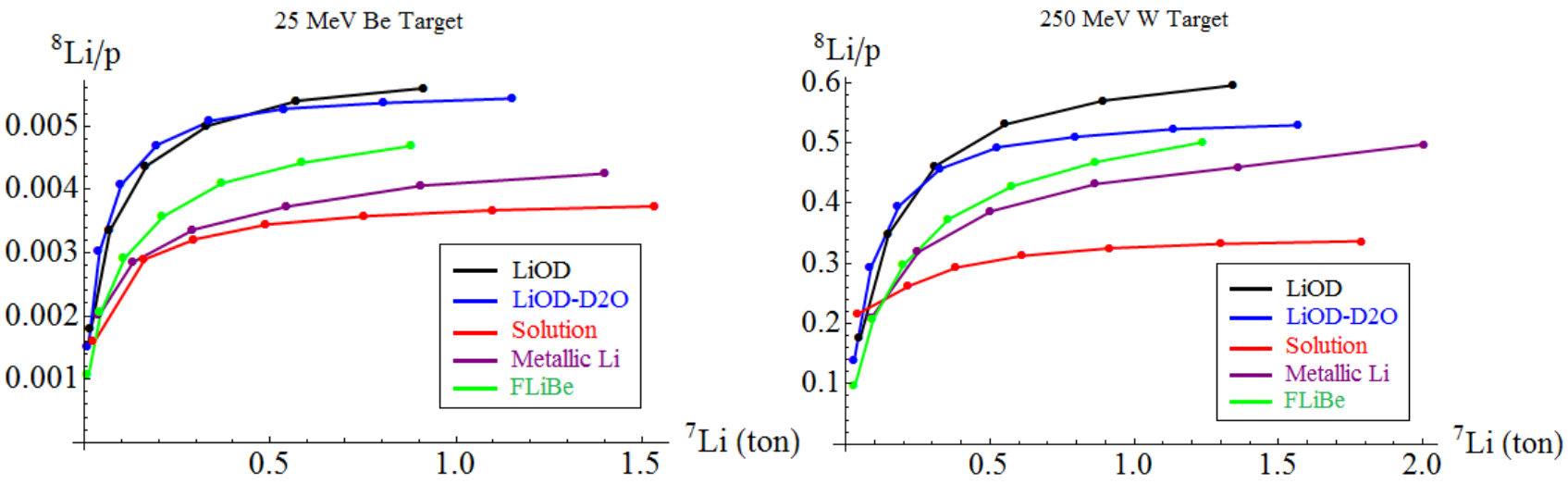
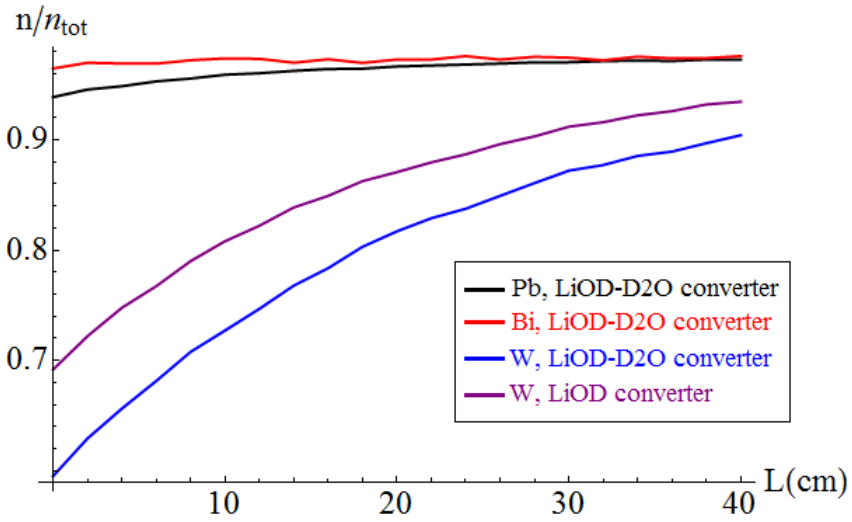


Figure: ^{8}Li yield for different proton beam energies, using a Be target (25 MeV) or W target (250 MeV)

Vacuum Sleeve

When the target is surrounded by other materials (ex: converter, heavy water sleeve, etc...), some of the neutrons can bounce back and be absorbed inside the target. This effect is particularly important in case of W targets. If the target is surrounded by a vacuum sleeve, it will increase the probability for the bounced-back neutrons to avoid the target, reducing the neutron loss.



- 25 MeV: Be target preferred
- 250 MeV heavy metal targets give better performances (used W in the current simulations, however also depleted U under study)

Sterile Neutrinos

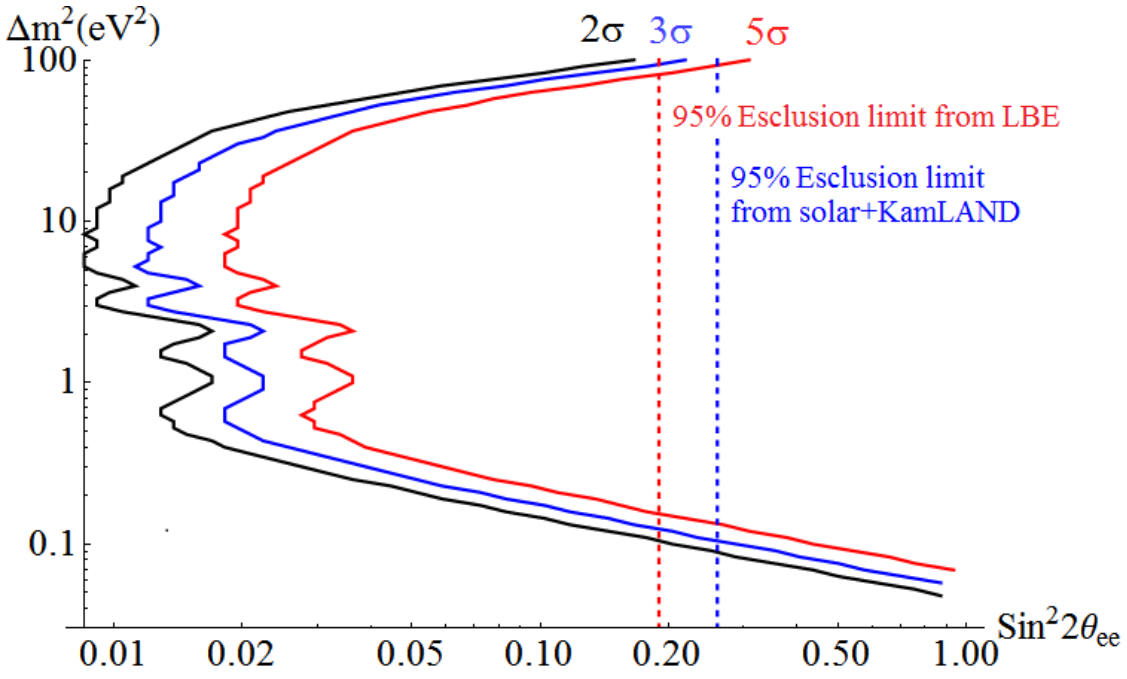


Figure: Exclusion contours in the disappearance channel using IsoDAR

EC, J. Evslin, F.Y. Zhao, JHEP 1601 (2016) 004

μDAR

Neutrinos from μDAR

Using μDAR it is possible to measure precisely δ_{CP}.
Advantages:

- Spectrum (Michel) and cross section (IBD) known very well
- Using two detectors, no degeneracy between δ_{CP} and $\pi - \delta_{CP}$
- Synergy with other experiments, like T2K and NOνA. Exploiting this synergy, even only one detector achieves a good determination of δ_{CP} ($\simeq$15-35 degrees)
- Low background in this energy range (30-55 MeV)

μDARTS

The first proposal along these lines was the DAEδALUS project.

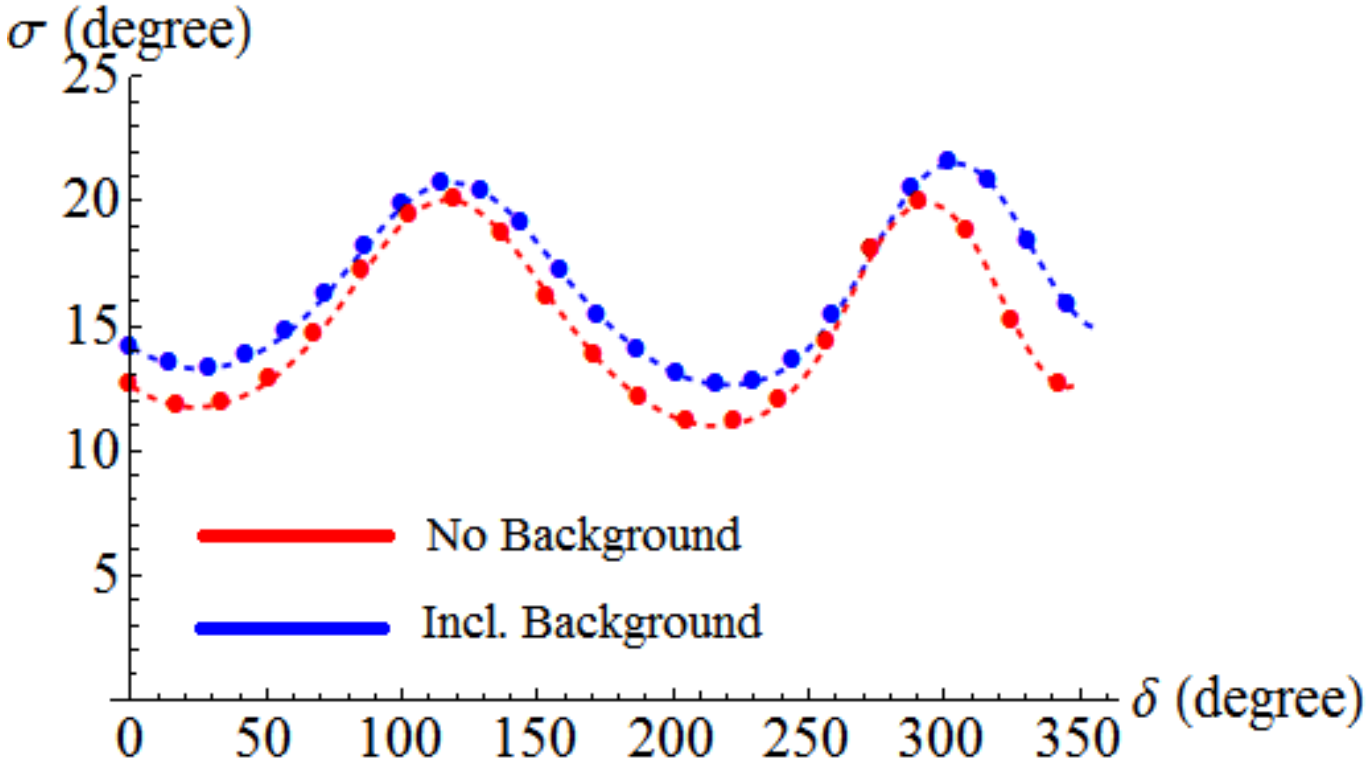
J. Alsonso *et al.*, **arXiv:1006.0260 [physics.ins-det]**

μ Decay At Rest with Two Liquid Scintillators (μDARTS)

- Our idea is to use a single accelerator to produce neutrinos and two detectors at different baselines.
- With one small detector near the accelerator it is possible to fix the flux normalization (and test LSND anomaly).
- In our simulations, we considered 20 ktons liquid scintillators, and a neutrino flux equivalent to the one generated by a 10 mA, 800 MeV proton beam.
- This is equivalent to 650 IBD events expected a 10 km with $\delta_{CP} = 0$

NOTE: Exploiting the synergy with LBNE it is also possible to obtain a reasonable precision even with just one detector

Expected Precision



Summary

- ADS facilities will be able to produce a large amount of neutrinos
- Even from the first phases of the project it will be possible to produce $\bar{\nu}_e$ via IsoDAR, searching for experimental signs of the presence of sterile neutrinos
- LiOD and LiOD-D_2O give the best ^{8}Li yield in most of the cases
- Using heavy metal target, bounce back can significantly decrease neutron yield (reduced with vacuum sleeve)
- When the energy is higher, $\bar{\nu}_\mu$ can be produced via μDAR and be used to determine δ_{CP} with good precision

Backup Slides

IsoDAR: Converter Efficiency

If almost all the neutrons are absorbed inside the converter, the expected ratio $^8Li/n$ can be calculated analytically.

ρ_i = fraction of atoms of the isotope i present in the compound

σ_i = absorption cross section for thermal neutrons

$$P_{Li8} = \frac{\sigma_{Li7}\rho_{Li7}}{\sum \sigma i \rho_i}$$

	H	D	^{6}Li	^{7}Li	Be	O	F
σ_{abs}	0.33	5.2×10^{-4}	940	0.045	0.008	1.9×10^{-4}	0.01

	Li	LiOD	LiOD·D_2O	solution	FLiBe
P_{Li8}	0.326	0.317	0.300	0.208	0.280

NOTE

Since $\sigma_{Li6} \gg \sigma_{Li7}$ ($\simeq 2 \times 10^4 \sigma_{Li7}$), the main limiting factor in the ^{8}Li yield is the isotopic purity of Li

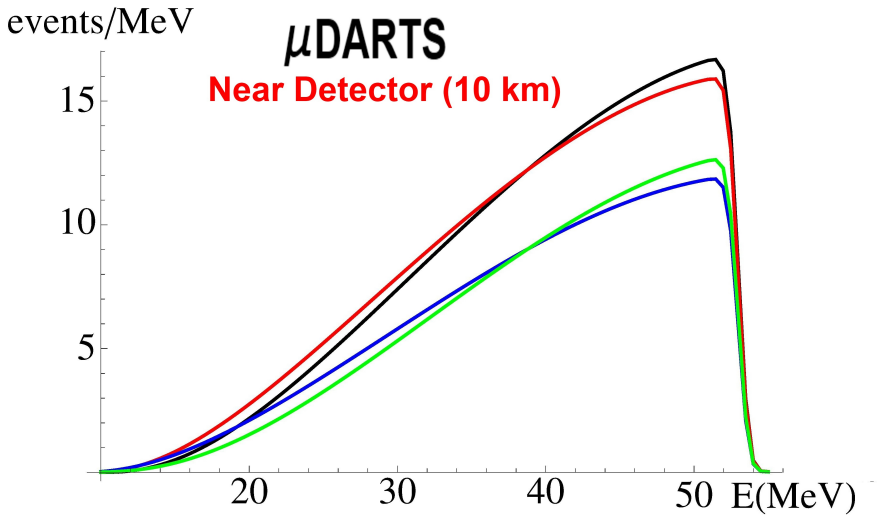
μDAR: CP Violation

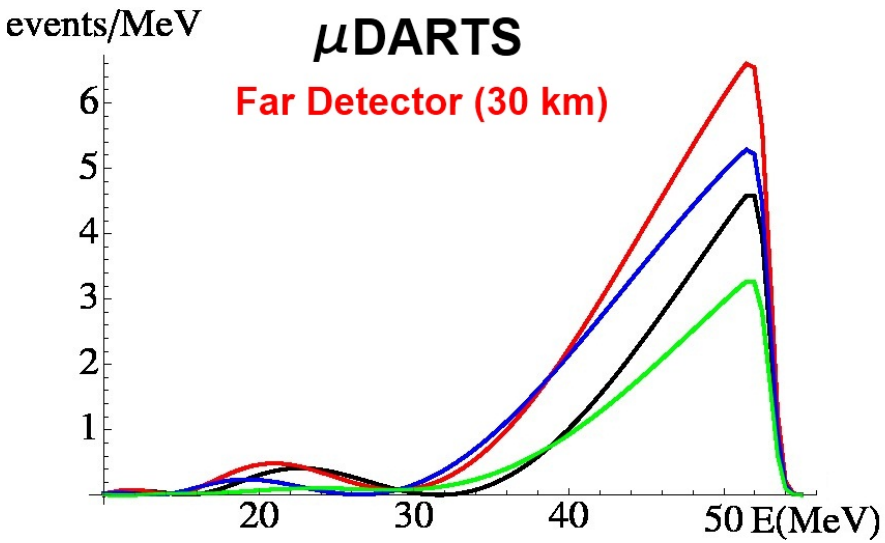
The CP-violating angle δ_{CP} appears only in the oscillation probability (no δ_{CP} in the disappearance channel); *e.g.*:

$$
\begin{aligned}
&P_{\mu\to e} = \\
&\sin^2(\theta_{23})\sin^2(\theta_{13})\sin^2(\Delta_{31}) \\
&\pm\sin(\delta_{CP})\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin^2(\Delta_{31})\sin(\Delta_{21}) \\
&+\cos(\delta_{CP})\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin(\Delta_{31})\cos(\Delta_{31})\sin(\Delta_{21}) \\
&\cos^2(\theta_{23})\sin^2(\theta_{13})\sin^2(\Delta_{21})
\end{aligned}
$$

$\Delta_{ij} = 1.27\Delta m^2_{ij}L/E$; + (-) for antineutrinos (neutrinos).

μDAR: Expected Signal

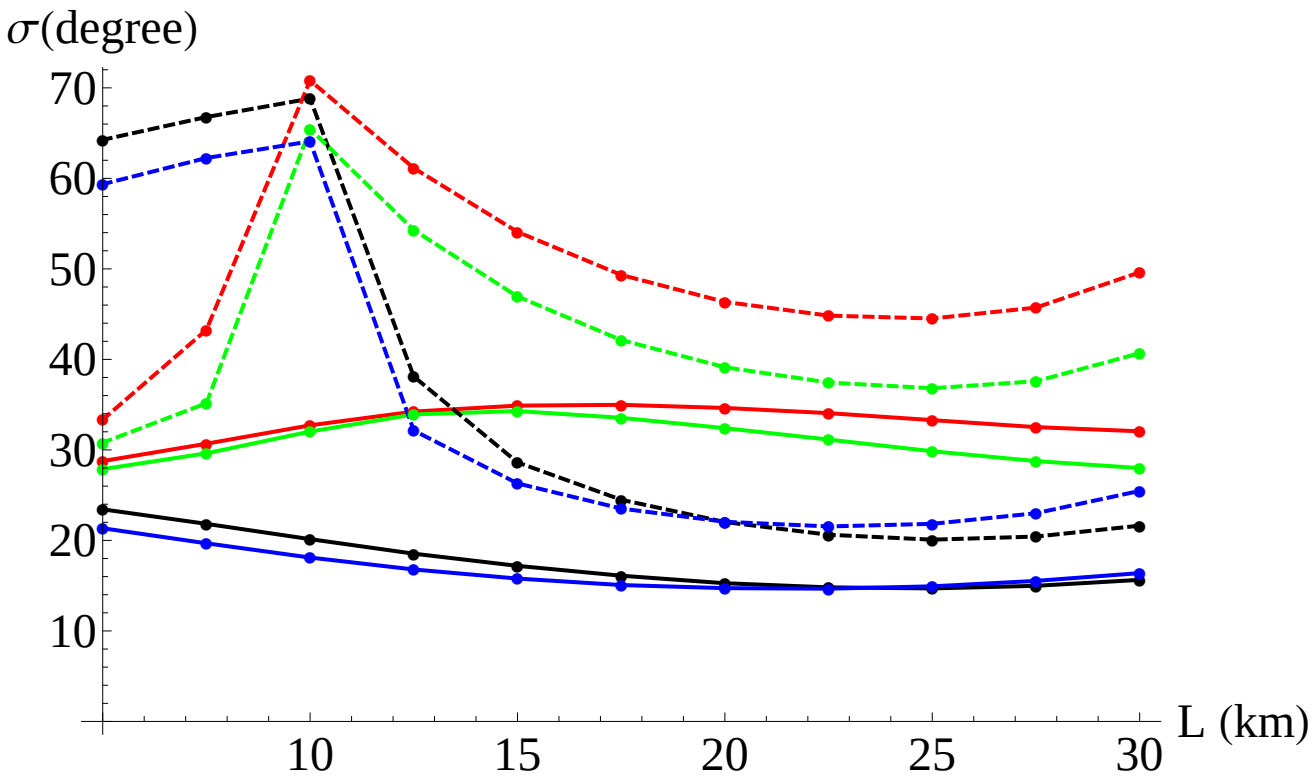




Expected spectra at near and far detectors for $\delta_{CP} = 0°$, $90°$, $180°$, $270°$; normal hierarchy, 10 years lifetime.

With $\delta_{CP} = 0$, 650 expected events between 30 and 55 MeV

μDAR: One Detector



Sensitivity to δ_{CP} for $\delta_{CP} = 0°$, $90°$, $180°$, $270°$.

Solid curves: synergy with NOνA is taken into account.

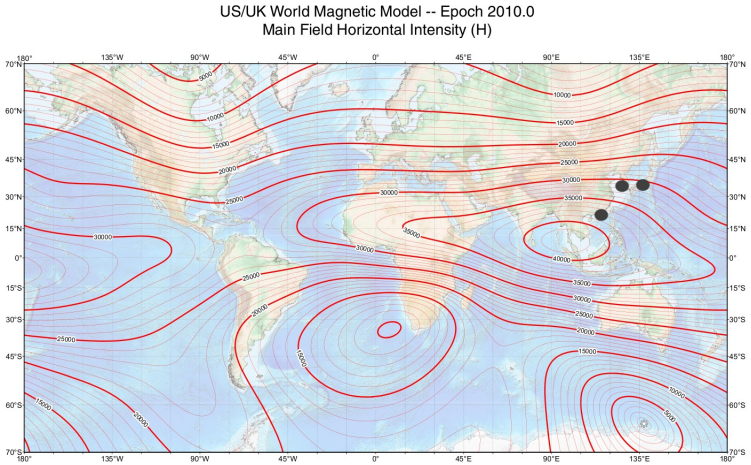
μDAR: Atmospheric Neutrinos

In our energy range (30-55 MeV) we can neglect the spallation, reactor or geoneutrinos background $\Rightarrow$ main source of background: atmospheric neutrinos.
A strong horizontal geomagnetic field defects low energy cosmic rays, reducing the low energy atmospheric flux.

China (0.38 G), RENO
50/Kamioka mines (0.31 G)

vs

DUNE (0.17 G), LENA in the Pyhasalmi mine (0.13 G)



Low background: $\simeq$ 50 events in 10 years (compared to 650 events at 10 km wth $\delta_{CP} = 0$)

J. Evslin, S.F. Ge, K. Hagiwara; arXiv:1506.05023