Future Dark Matter Detectors at LNGS

Water and Liquid Scintillator Shielding Concepts to Suppress Neutron Backgrounds

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Future of DM Searches

- Current sensitivity (CDMS, Xenon): ~10^{-44} cm^2
- Desired sensitivity & exposure for xenon/argon detectors:
  - 10^{-47} cm^2: 1 ton-yr Xe, 10 ton-yr Ar
  - 10^{-48} cm^2: 10 ton-yr Xe, 100 ton-yr Ar
- Fundamental backgrounds limit ultimate sensitivity to 10^{-48} - 10^{-49} cm^2
  - Solar pp neutrino-electron scattering for Xe
  - Atmospheric neutrino-nuclear coherent scattering Xe/Ar
- Need multi-ton detectors, negligible background, low threshold energy.

Future DM Detectors at LNGS

- DM detectors with exposures < 100 kg-yr are relatively safe from cosmogenic neutrons at LNGS, even with modest shielding.
- Multi-ton-yr exposures at LNGS face serious backgrounds from cosmogenic neutrons produced in the rock and passive shields, due to the shallow depth.
- Merging the successful Borexino technology of water and liquid scintillator shields with DM detectors can render cosmogenic neutrons harmless at LNGS.
- This talk evaluates the water-scintillator shields for dark matter detectors and suggests a straightforward program to develop them at LNGS.
- In addition to mitigation of cosmogenic neutrons, the choice of an active liquid scintillator veto can provide extremely powerful rejection of radiogenic neutrons.
  - Key is the adoption on novel scheme in neutron detection: $^{10}B(n,\alpha)^{7}Li$

Borexino Concepts Applied to Dark Matter

- Borexino is a 300-ton liquid scintillator designed to detect solar neutrinos.
- Borexino achieved unique, unprecedented low backgrounds with active water and liquid scintillator shields.
- Successful measurements include:
  - ^{7}Be and ^{8}B solar neutrinos
  - Geo-neutrinos
  - Nuclear reactor anti-neutrinos from sites > 1000 km away.
  - More on the way…

The Borexino Detector

Outer Water Detector

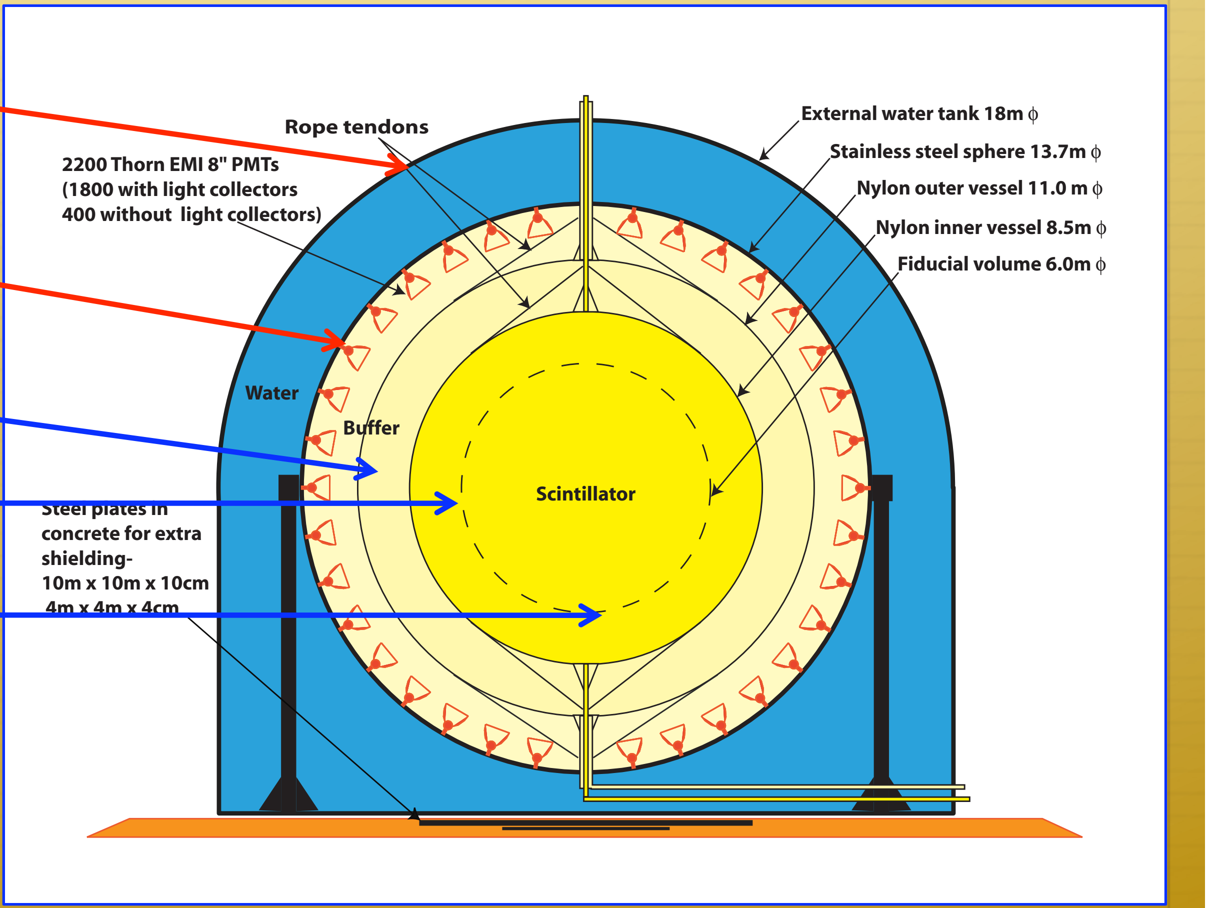
Inner Detector

Buffer

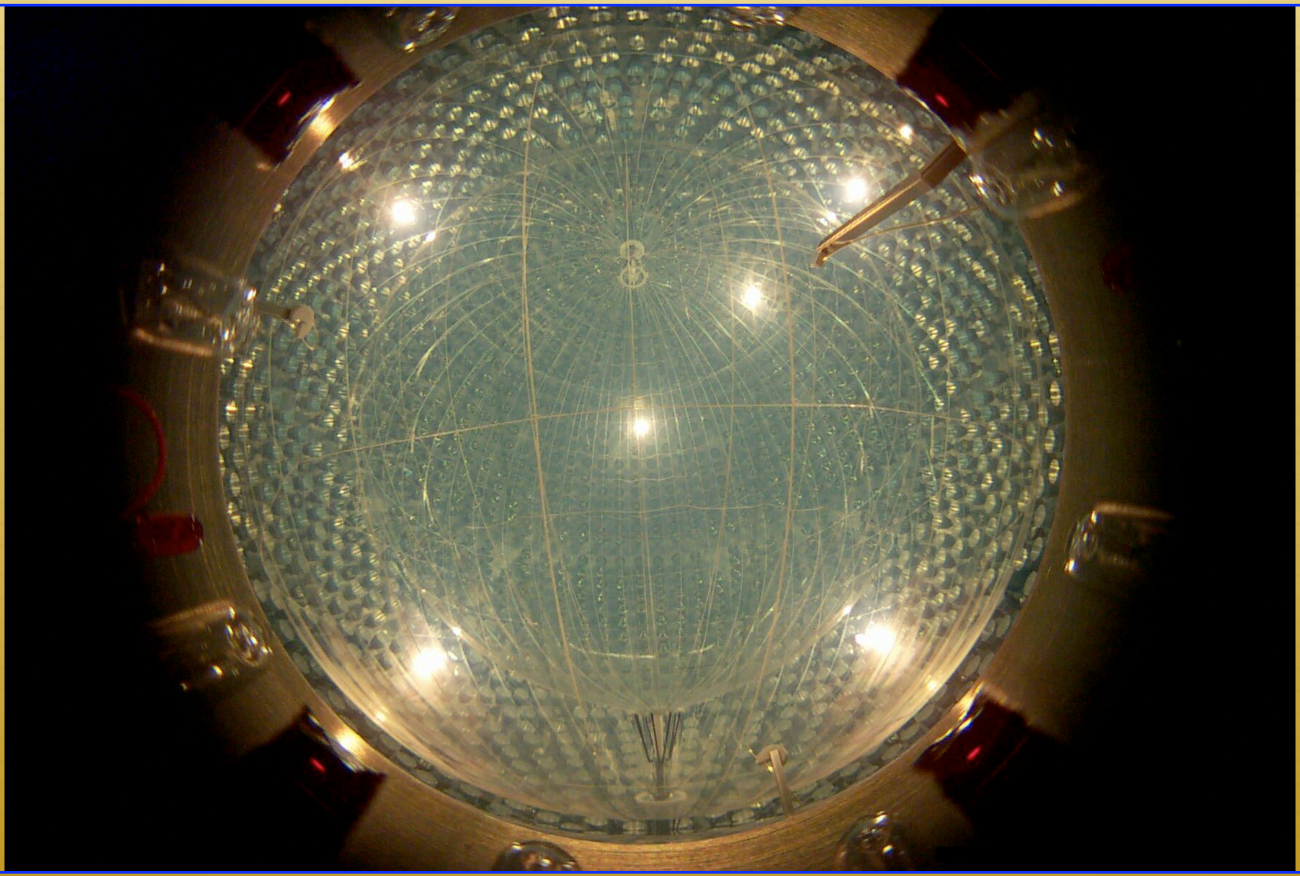
Scintillator

Fiducial Volume

(100 tons)

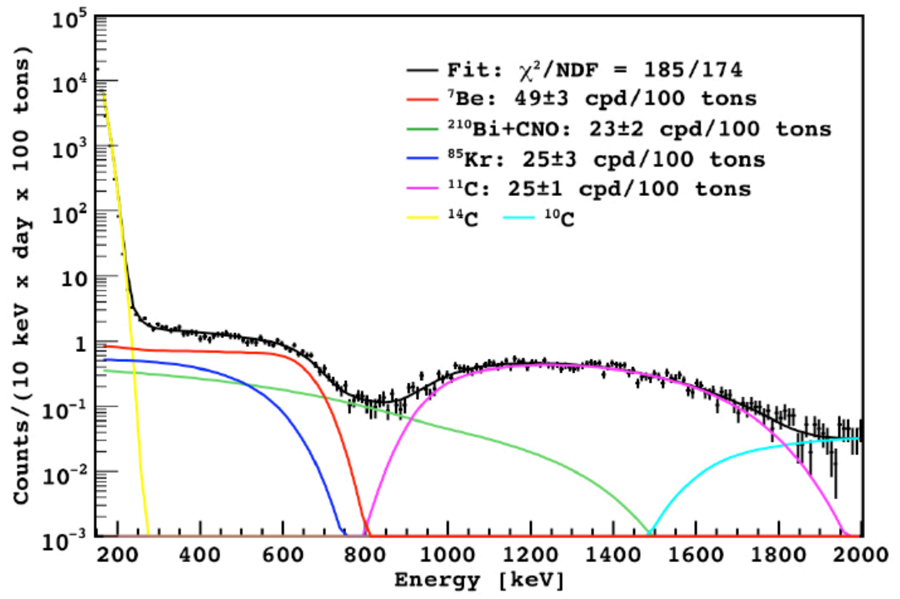


Borexino Filled 2007

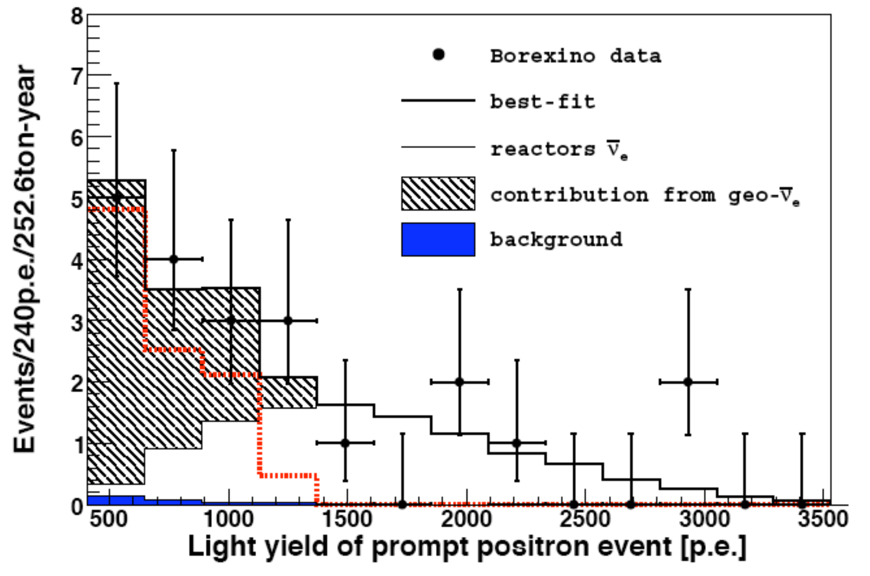


Borexino Results

- ^{7}Be Solar Neutrinos (2008)



- Geo-neutrinos (2010)



- ~4 geo-neutrinos/(100 ton-yr) with negligible neutron background
- Defeated neutron-related background (<<1 background event/(250 ton-yr))

Borated Liquid Scintillator *Best Active Veto for Radiogenic Neutrons*

- Radiogenic neutrons major background issue for all dark matter experiments:
  - Radiogenic neutrons emitted from detector parts.
    - (α,n) reactions and fission from U, Th in PMT's, cryostat,…
    - surfaces contaminated with ^{210}Po
    - External neutrons
  - (n,n') mimics WIMP events (W,W')
- Borated scintillator was studied for BOREX to measure charged and neutral current solar neutrino rates (Raghavan).
- Suppress radiogenic neutrons with active veto made of boron loaded scintillator:
  - Detect charged particles: $^{10}B(n,\alpha)^{7}Li$: $\sigma_{thermal} = 3800$ b

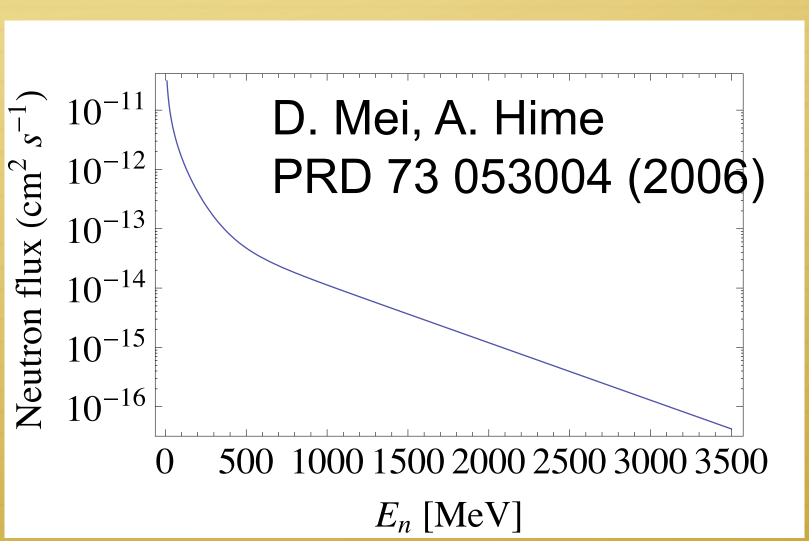
Neutron Capture on Boron

- $^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha$, $^{7}Li^{*} \rightarrow {}^{7}Li + \gamma$ (480 keV) 94%
  $\rightarrow {}^{7}Li$ (g.s.)$+ \alpha$ 6.7%
- Q-value: + 2.79 MeV
  - Excited state: E(α) = 1471 keV; E(^{7}Li) = 839 keV
  - Ground state: E(α) = 1775 keV; E(^{7}Li) = 1014 keV
- Quenching of reaction products: ~ 60 keVee. (~1/40)
- Neutrons travel less than 20 cm before capture.
- Unlike (n,γ) capture, detection of charged particle products is very efficient:
  - Neutron veto efficiency: ~99.8% for 1-m thick scintillator.
  - Limited by invisible capture on inert detector materials: many 9's possible for neutrons not captured within detector.

Liquid Scintillator

Veto for external cosmogenic neutron

- Most serious background comes from cosmogenic neutrons generated in the rock by muons.
- Above a few hundred Mev, the neutrons flux decreases and contributes little to background.
- At lower energies the neutrons are more easily absorbed by shielding.



$$E_n \approx 90 \text{ MeV}$$

$$\approx \text{ mean energy of neutrons}$$

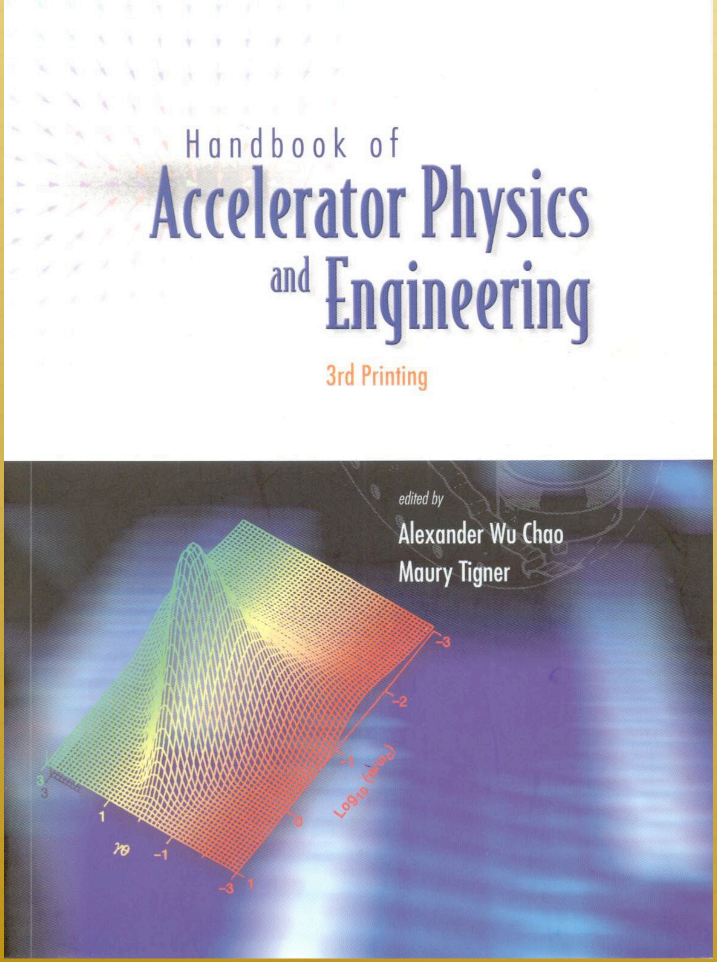
Liquid Scintillator

External Cosmogenic Neutron Veto

Neutron Energy	Mean Free Path in Liquid Scintillator	Attenuation Length in Water
10 MeV	~ 30 cm	~25 cm
50 MeV	~50 cm	~50 cm
100 MeV	~55 cm	~80 cm
>200 MeV	~70 cm	~120 cm

- Fast neutrons with E ~ 100 MeV are difficult to stop in passive shield of water.
- Liquid scintillator of same thickness is more effective than water because it offers a veto signal based on mean free path, in addition to absorbing the neutrons.
    - Scintillator thickness effectively doubled by requirement that neutron must pass through the scintillator twice (in and out) to mimic WIMP signal.

Neutron Attenuation



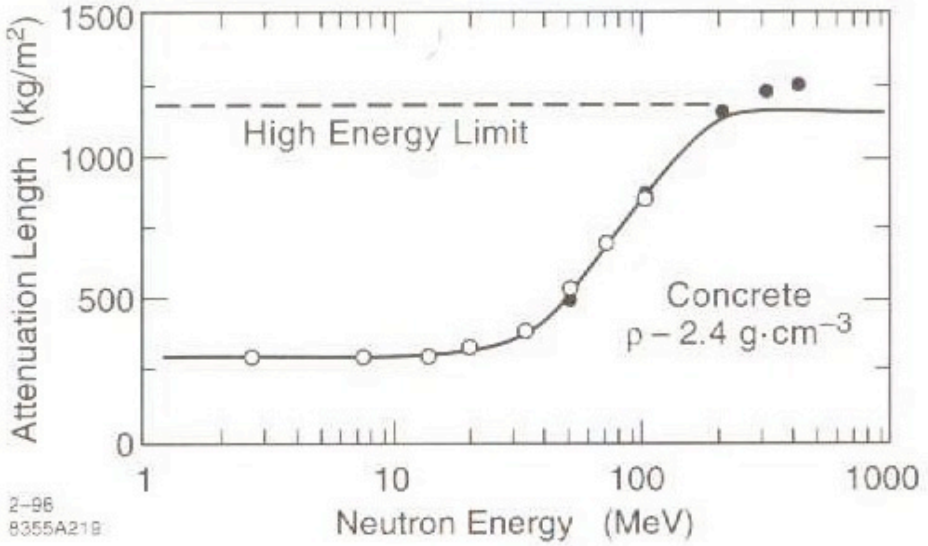


Figure 4: λ for neutrons in concrete vs energy. Full circles and open circles are data from [2] and [3]. The solid line shows recommended values of λ and dashed line shows the high energy limiting value of 1170 kg/m^2.

Muon Flux versus Depth

- SNO-Lab at Sudbury is at depth of ~6000 mwe.
- Muon flux at SNO-Lab:
    - ~70 times lower than LNGS.
- Shallower depth of LNGS can be overcome with water or scintillator shielding equivalent to 4-5 attenuation lengths.
- For 100 MeV neutrons this is ~ 4-5 meters of water or scintillator.
- Detailed simulations are needed for better estimates.

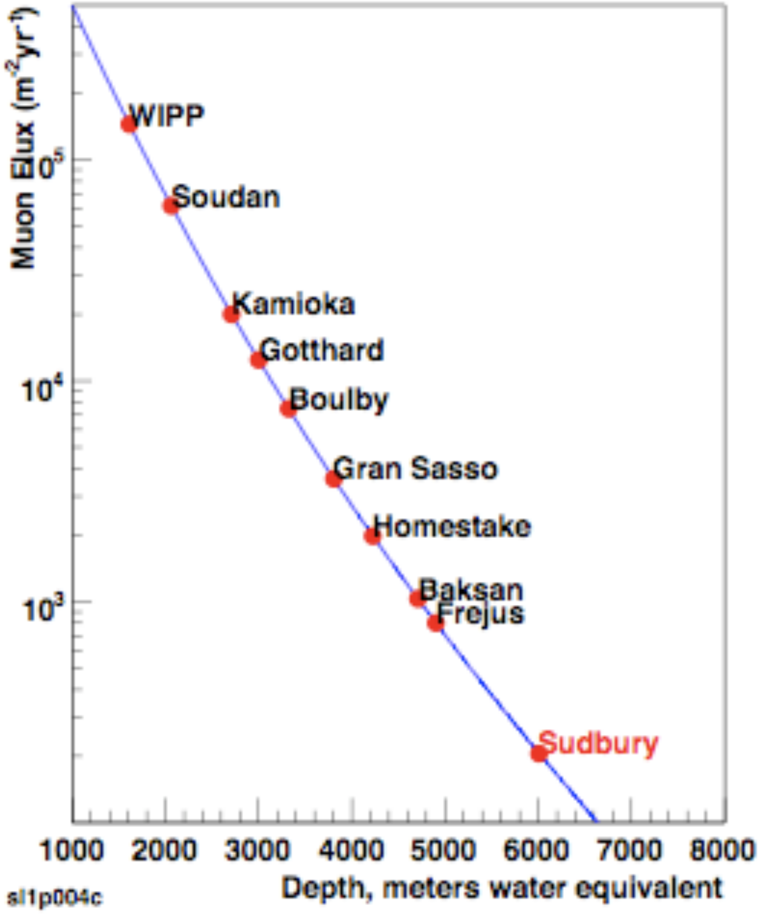


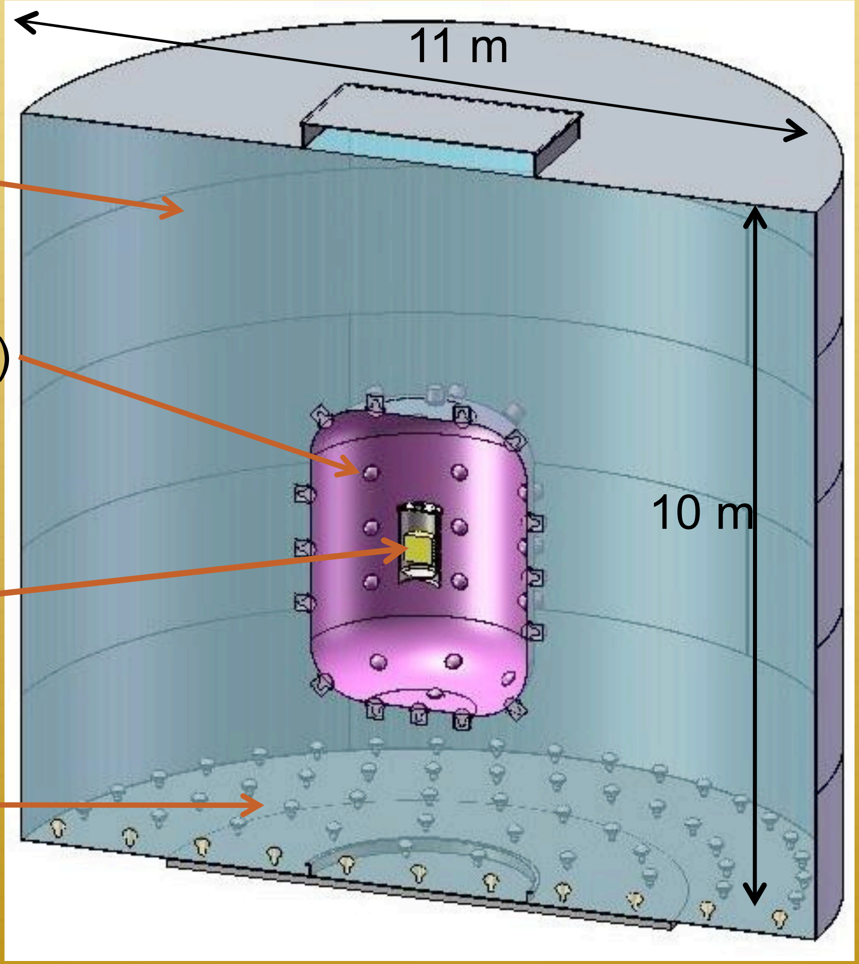
Figure 3.4: Muon Flux as a function of Depth.

A Case Study: Dark Matter with DAr

- A DAr detector with depleted argon has been proposed as the prototype of a series of a large-scale dark matter detectors (See talk of C. Galbiati tomorrow.)

- Novel low background features make this a powerful instrument to search for dark matter, as well as a prototype for new technology.
  - Underground argon depleted in ^{39}Ar
  - Low background high quantum efficiency photo-detectors
  - Boron-loaded scintillator for efficient rejection of neutron backgrounds.
  - Two-phase TPC detector with double discrimination against β/γ events, based on pulse shape and ionization/scintillation ratio

DAr Detector in Water and Scintillator

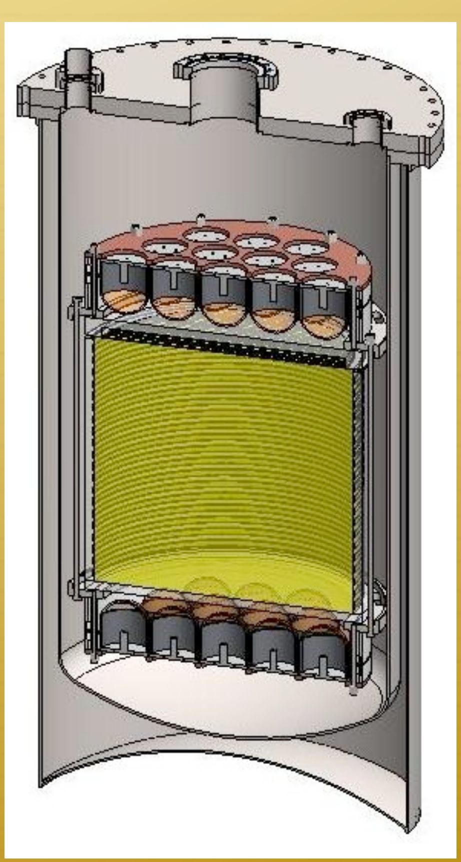


CTF Water Tank
(11 mϕ x 10 mH)

Borated Liq. Scint.
3 mϕ x 4 mH (25 tons)
with 50 PMT’s

Xe/Ar detector

PMTs for Cerenkov
Detection of Muons



Depleted Ar Detector
in cryostat

Cosmogenic Neutrons

- With passive shielding:
    - 40 cm polyethylene. + 20 cm Pb + 15 cm Steel:
    - ~3,000 background events/(ton-yr)
- With active (muon) shielding accomplished with 1 m of liquid scintillator or 5 m of water:
    - ~2 events/(ton-yr) (10^{-46} cm^2 in 1 ton-year of DAr)
- With active shielding, 4 m water + 1 m borated scintillator:
    - <0.1 events/(ton-yr) (10^{-47} cm^2 in 10 ton-years of DAr)
- With 5 m scintillator:
    - Background is tiny!

Background and possible reach with Borexino size water/scintillator

- MEASURED: Dark matter background can also be measured by Borexino
  - Muon crossing BX, WT, fast cosmogenic neutron enters BX IV, induces proton recoil, then captures in BX IV
  - Distinctive signal of proton recoils in BX scintillator: excellent pulse shape discrimination
  - First experimental indication from geo-anti-nue analysis: <<1 event/(10 ton-yr) when extrapolated to a Xe/Ar recoil [nominally equivalent 10^{-47} cm^2 for Ar, 10^{-48} for Xe]
- ESTIMATED: Cosmogenic neutron-induced background calculated in Borexino (geo-anti-nue paper):
  - Fast cosmogenic neutron enters BX IV, induces proton recoil, then captures on ^{1}H
  - Background estimate in geo-neutrino paper is <<1 antinue-background event/(250 ton-yr) [nominally equivalent 5×10^{-49} cm^2 for Ar, 5×10^{-50} cm^2 for Xe]

Conclusions

- Large liquid scintillators are very effective in vetoing both radiogenic and cosmogenic neutrons.
- Water/scintillator shields can reduce cosmogenics to the levels of the deepest underground laboratories and enable ultimate dark matter experiments at LNGS.
- Possibility of achieving a background of ~10^{-48}-10^{-49} cm^2 at shallow LNGS depth can be evaluated experimentally using current Borexino data.