A High Efficiency Neutron Veto Based on Boron-Loaded Liquid Scintillator

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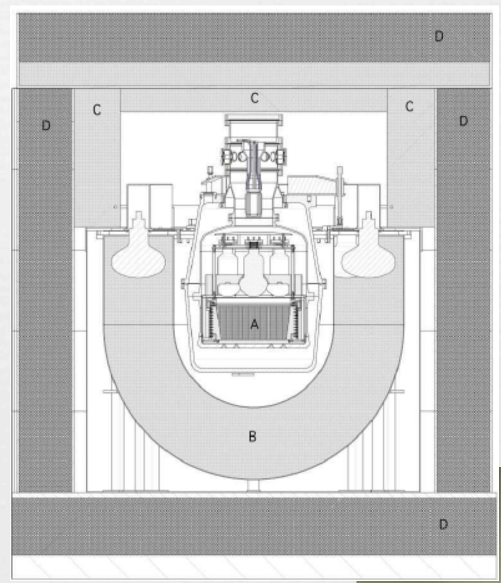
Neutron Vetoes in Dark Matter Experiments

- Single scatter neutron events are a "perfect background" for direct detection dark matter experiments
- Vetoing these events with high efficiency can significantly increase the sensitivity of an experiment
- Also provides an in-situ measurement of the neutron environment
  - Significantly strengthen any claim of a dark matter detection

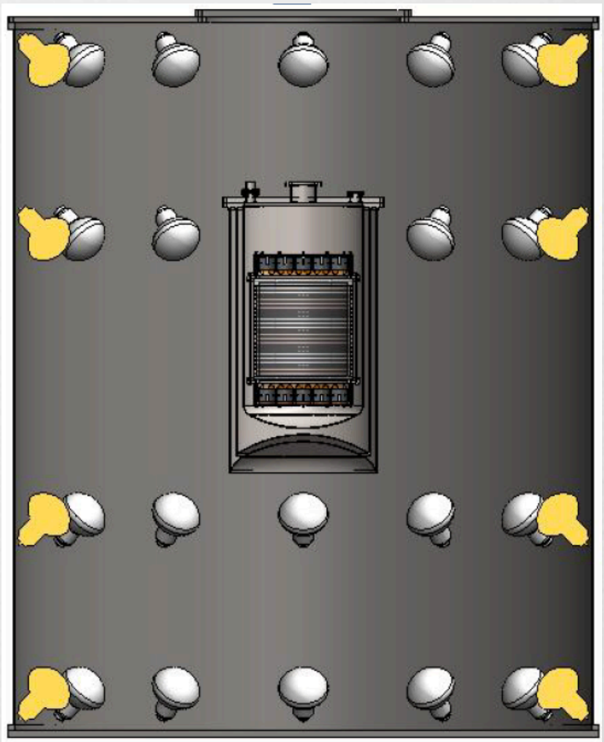


Zeplin II, from astro-ph/0701858v2

WARP, from L.Grandi PhD. Thesis, University of Pavia

A Neutron Veto Using Boron-Loaded Liquid Scintillator

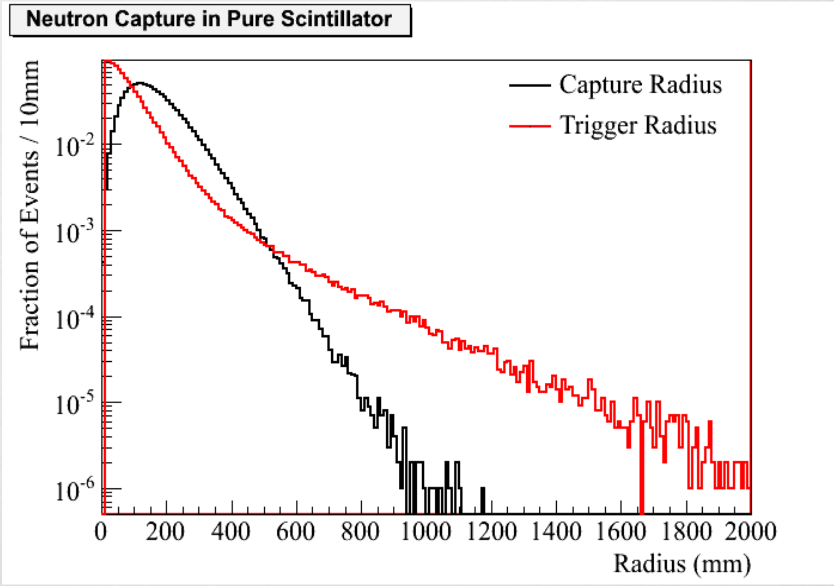
- Immerse the dark matter detector in boron-loaded liquid scintillator
  - Baseline: 1 m thick liquid scintillator loaded with 5.2% w/w natural boron
- Veto efficiency simulations with Geant4
- Practical considerations:
  - Light yield
  - Veto-induced deadtime



Pure Scintillator

- In pure scintillator, the mean neutron capture time is long (~250 μs) so long veto windows are required to get high efficiency
  - Very low background rates are required in the veto to avoid large deadtimes
- Neutron capture on protons produces gamma rays, which can propagate some distance before interacting

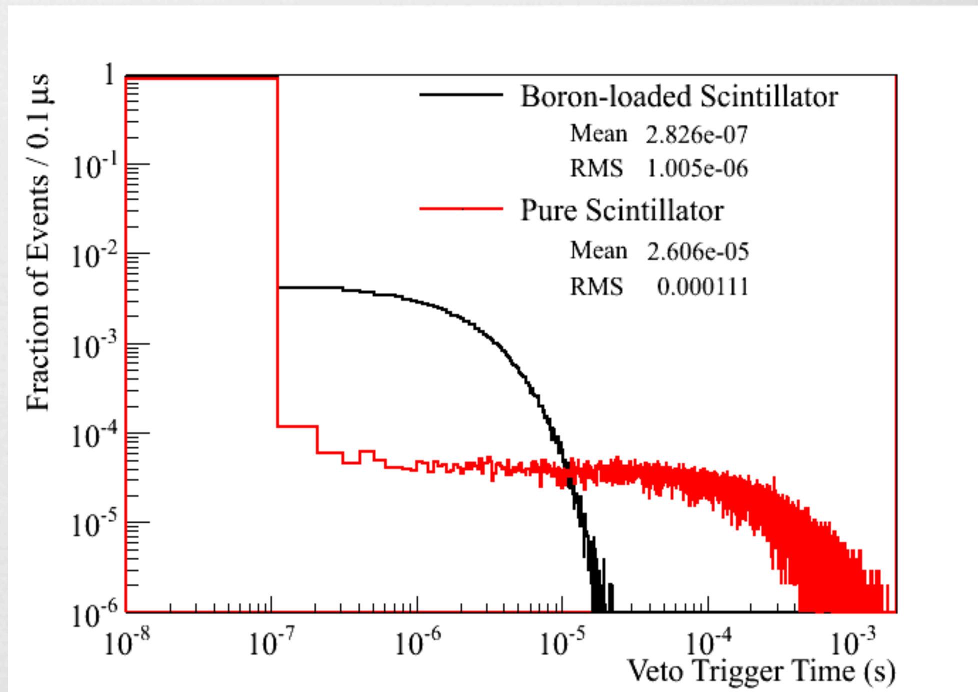
Veto Window	Veto Rate for 5% Deadtime
10 μs	5,100 Hz
100 μs	510Hz
1 ms	51 Hz



Boron Loading

- High ^{10}B capture cross section (3837(9)b) reduces neutron capture time

Detection Efficiency	Time in Pure Scintillator (μs)	Time in Boron Scintillator (μs)
70%	0.08	0.08
90%	7.8	0.1
95%	185	1.7
98%	421	3.8
99%	603	5.4
99.5%	788	7.0
99.9%	1282	10.9
99.99%	–	22.0



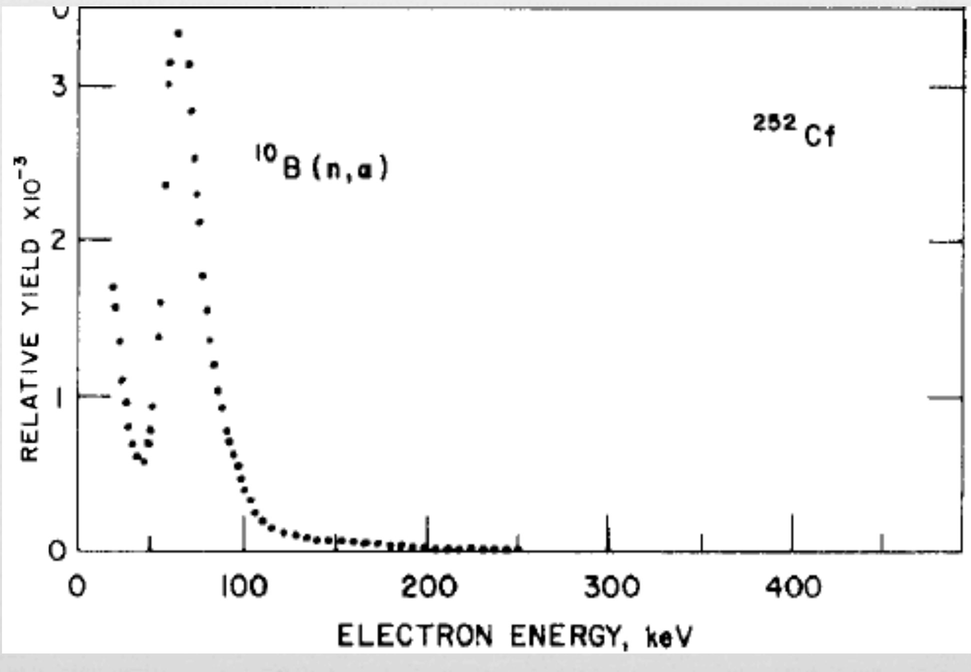
("Boron scintillator" has 5.2% w/w natural boron)

Boron Loading

$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha \rightarrow {}^{7}Li + \alpha + 478\ \text{keV}\ \gamma$ (93.7%)

$\rightarrow {}^{7}Li + \alpha$ (6.4%)

- Recoil fragments have ~2 MeV kinetic energy, quenched to 50-65 keV_{ee}
  - Detecting the recoil particles eliminates gamma-propagation



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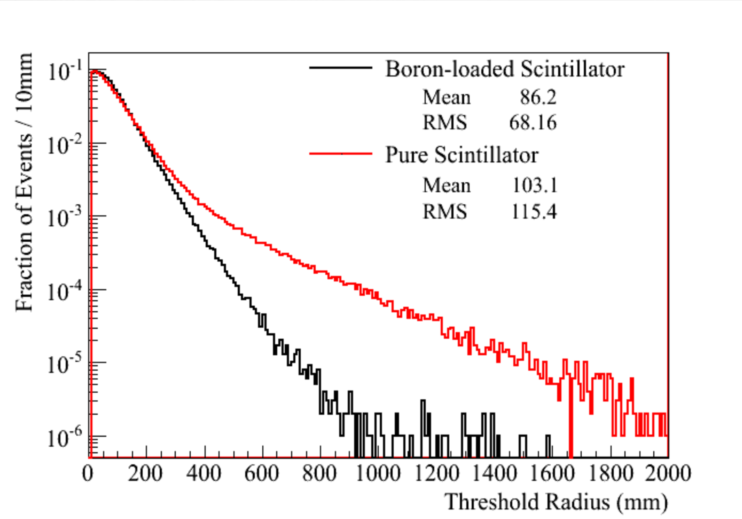
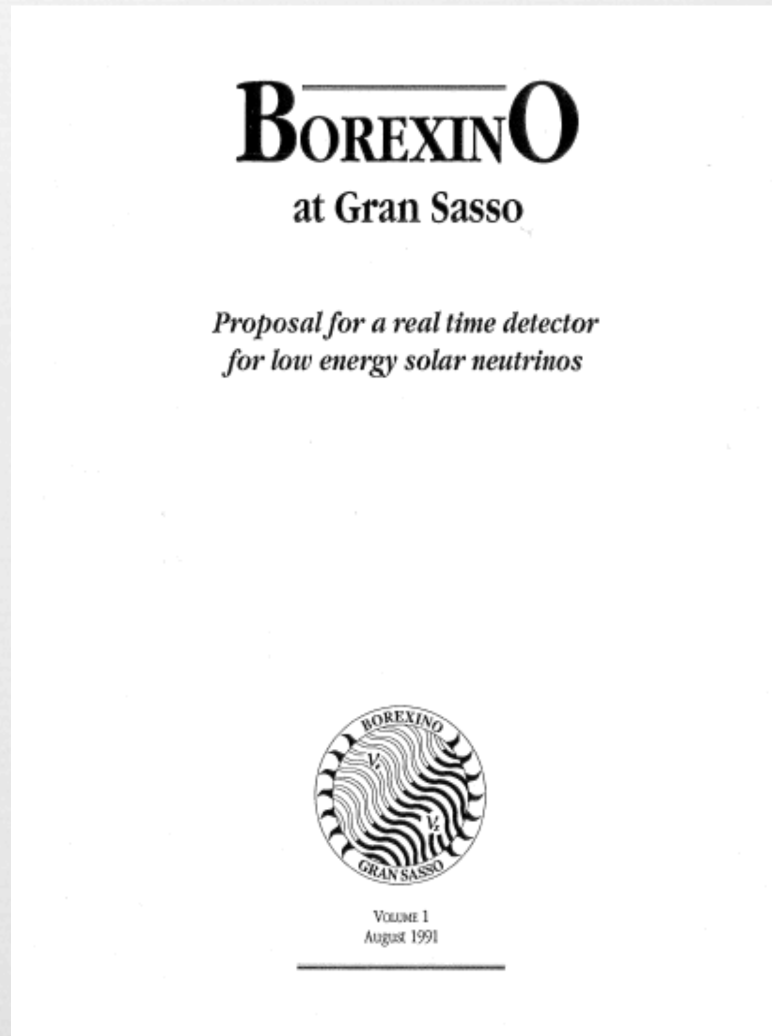


Containment Probability	Pure Scintillator Radius (cm)	Boron Scintillator Radius (cm)
70%	11.1	10.2
90%	21.0	17.2
95%	29.1	21.7
98%	44.8	28.0
99%	60.4	32.9
99.5%	78.0	38.1
99.9%	129.7	51.6
99.99%	–	136.5

Boron Loaded Scintillator

- Trimethyl borate (TMB) is miscible in pseudocumene
  - 50% w/w TMB gives 5.2% boron
- TMB loading investigated in the context of BOREX (and, for small detectors, elsewhere)
  - After distillation, TMB radiopurity and optical transmission as good or better than PC
  - Light output of 6000 photons/MeV achieved at 80% v/v TMB



BOREXINO
at Gran Sasso

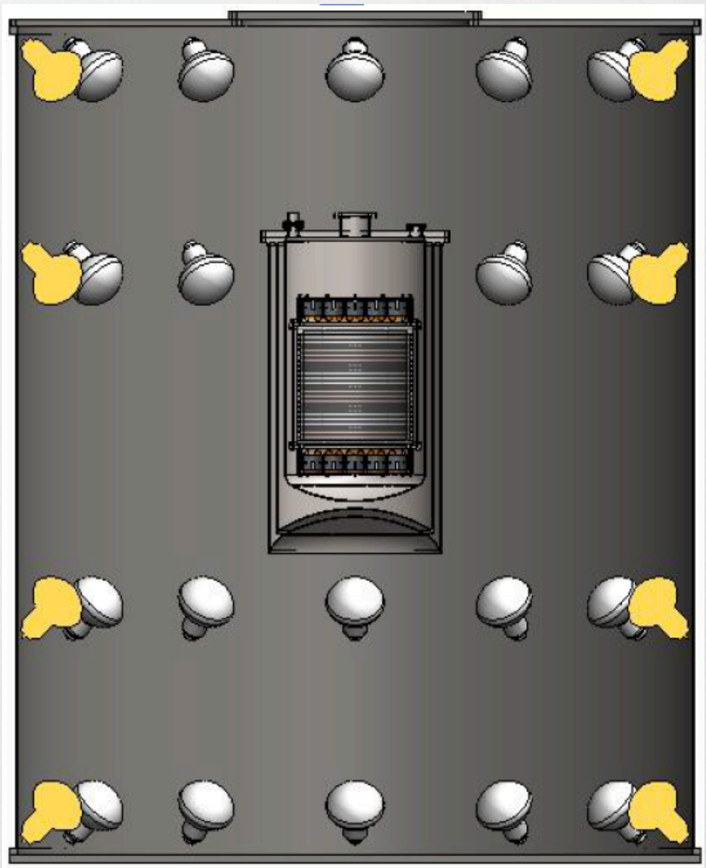
Proposal for a real time detector for low energy solar neutrinos

BOREXINO GRAN SASSO

VOLUME 1
August 1991

Efficiency Studies

- Study veto efficiency using Geant4
  - 1 m 50% (w/w) TMB scintillator around the DarkSide-50 dewar
  - Simplified cylindrical geometry
  - 10 cm diameter air-filled feed-through with dogleg penetrates the veto
  - Radiogenic neutron energy spectrum from SOURCES4A



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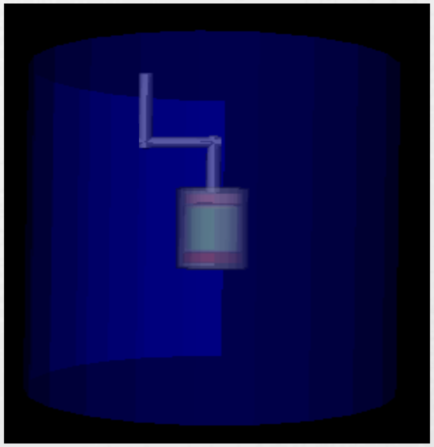
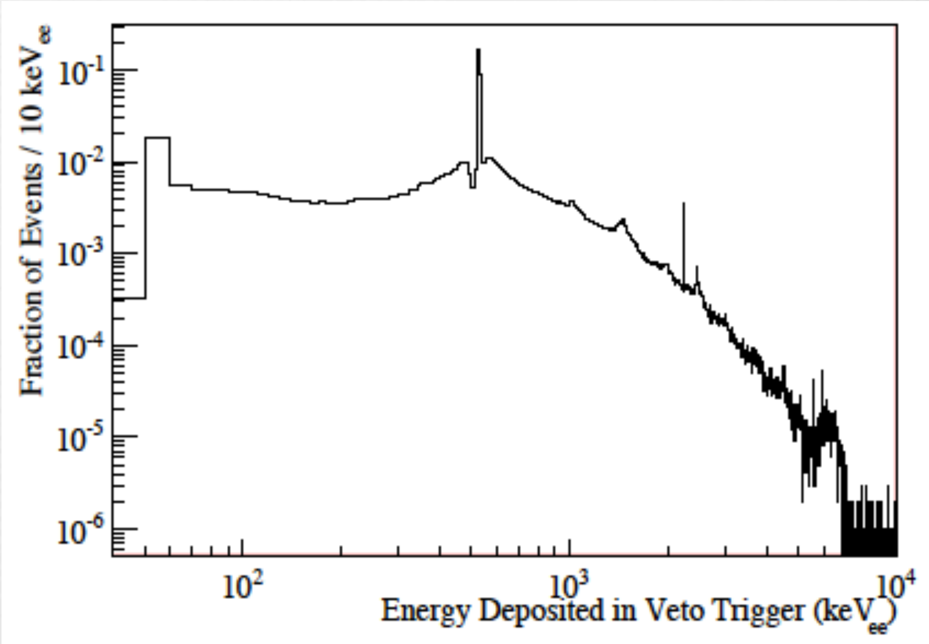


Component	Material	Mass (kg)
Active Volume	Liquid Argon	52.7
Inner vessel + photo-sensors	Fused Silica	25.4
Passive Buffer	Liquid Argon	74.1
Dewar + Internal Mechanics	Titanium	78.6
Neutron Veto	Boron-Loaded Scintillator	11,500

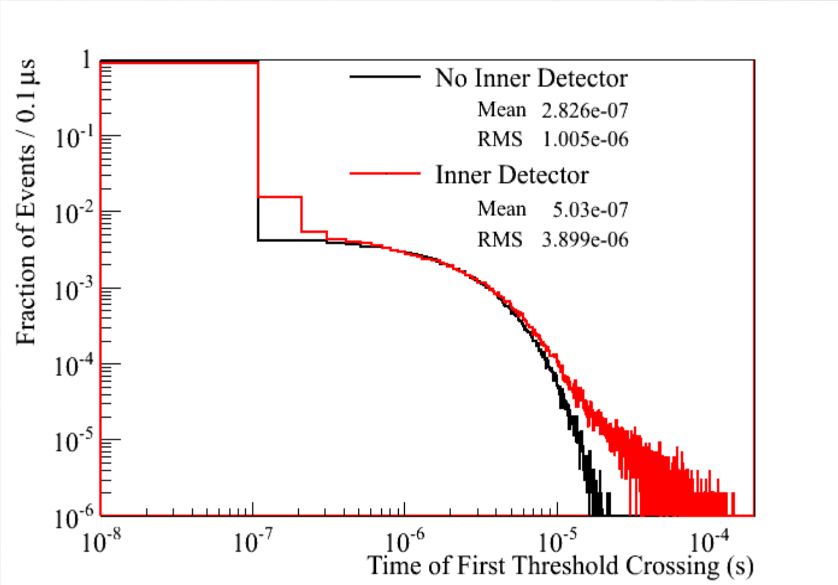
Internal Radiogenic Neutrons

- 99.8% of internal radiogenic neutrons produced a "veto trigger" (>40 keV_{ee} deposited in the veto within 1 μ s)
- ~20% of the neutrons were captured by inner vessel components
  - Detected in the veto either through proton recoils or gamma rays from the capture
  - To have high veto efficiency avoid gamma shielding around the inner detector



Internal Radiogenic Neutrons

- The distribution of veto times is lengthened by the presence of the inner detector



Detection Efficiency	Time Required (μs) Inner Det.	No Inner Det.
70%	0.08	0.08
90%	0.37	0.1
95%	2.3	1.7
98%	5.5	3.8
99%	9.3	5.4
99.5%	21.5	7.0
99.8%	57.7	10.9

Internal Radiogenic Neutrons

- Veto efficiency is degraded (and the timing further worsened) by hydrogenous material in the inner detector
  - Changing the fused silica vessel to acrylic reduced the veto efficiency to ~98%
  - The increase in veto efficiency from removing neutron shielding more than offsets the increase in neutron rate

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Cosmogenic Neutrons

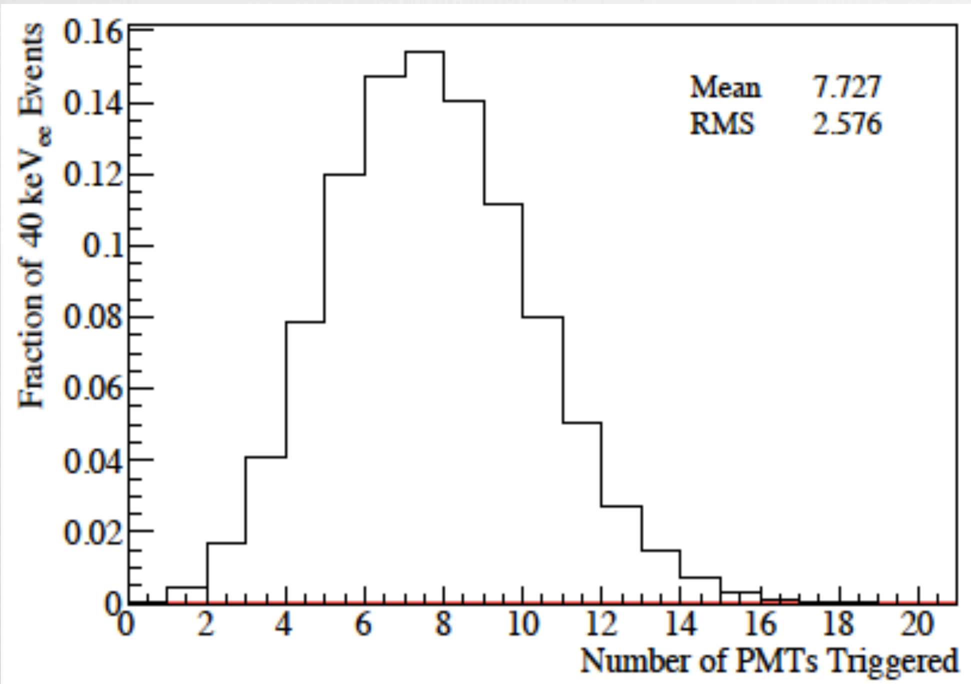
- Simulate external cosmogenic neutrons individually, using the energy spectrum from Mei & Hime (PRD 73, 053004, 2006)
  - Should underestimate veto efficiency
- With 1 m scintillator, recoil backgrounds from external cosmogenic neutrons are reduced by a factor of 40
- Internal cosmogenics are tiny due to very high efficiency of detecting primary muon

Thickness of Veto (m)	Interaction Rate in DarkSide50 (after veto)
0	1.0
1	0.027
2	0.0024
3	0.0005

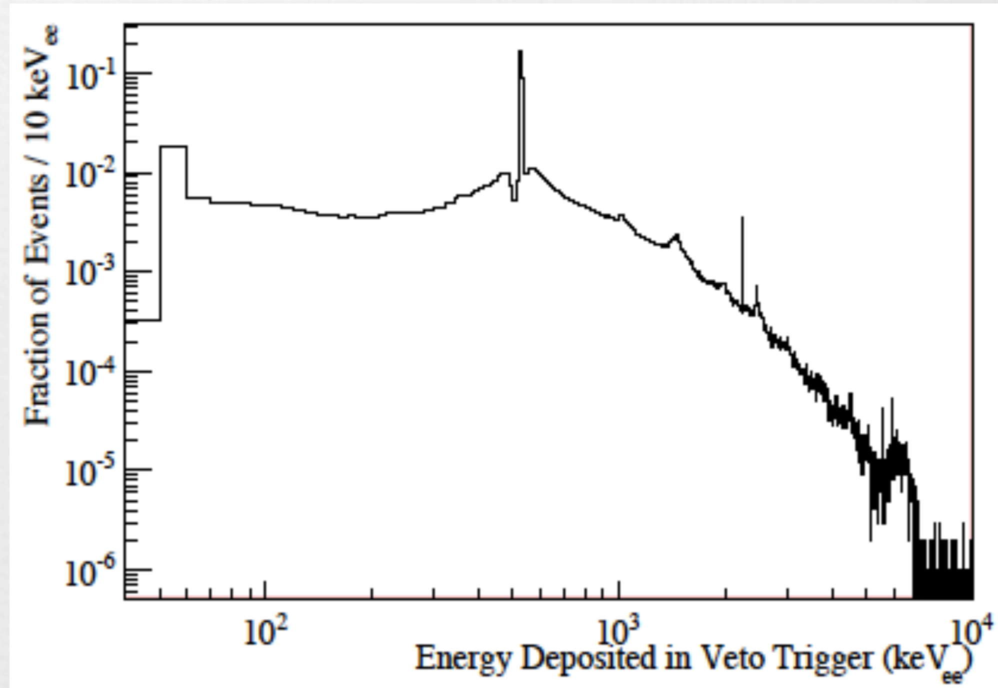
Is a 40 keV_{ee} Veto Threshold Achievable?

- Assume 80 8'' PMTs in veto
  - With 1 kHz dark rate, a 3 hit threshold gives a reasonable random rate
- Optical simulation:
  - 6000 photons/MeV
  - 20% PMT Q.E.
  - 95% reflection from walls/surfaces
  - 5m attenuation length
  - 2m scattering length

Is a 40 keV_{ee} Veto Threshold Achievable?



98% of uniformly distributed 40 keV_{ee} events in the veto give 3 or more hits



Only a small fraction of veto events fall below 100 keV_{ee}

40 keV_{ee} seems to be a feasible threshold!

Deadtime from Veto Backgrounds

- Estimate background rates (primarily γ's) in the veto for a 'typical' underground lab

Background Source	Veto Rate (Hz)
Inner Detector	<1
Scintillator Background	<1
PMTs	200
External Backgrounds with 25 cm steel	150
Steel Backgrounds	65
Random Veto Triggers (1 kHz dark rate)	80
Total Veto Rate	495

- 500 Hz corresponds to ~3% deadtime with a 60 μs trigger window

Conclusions

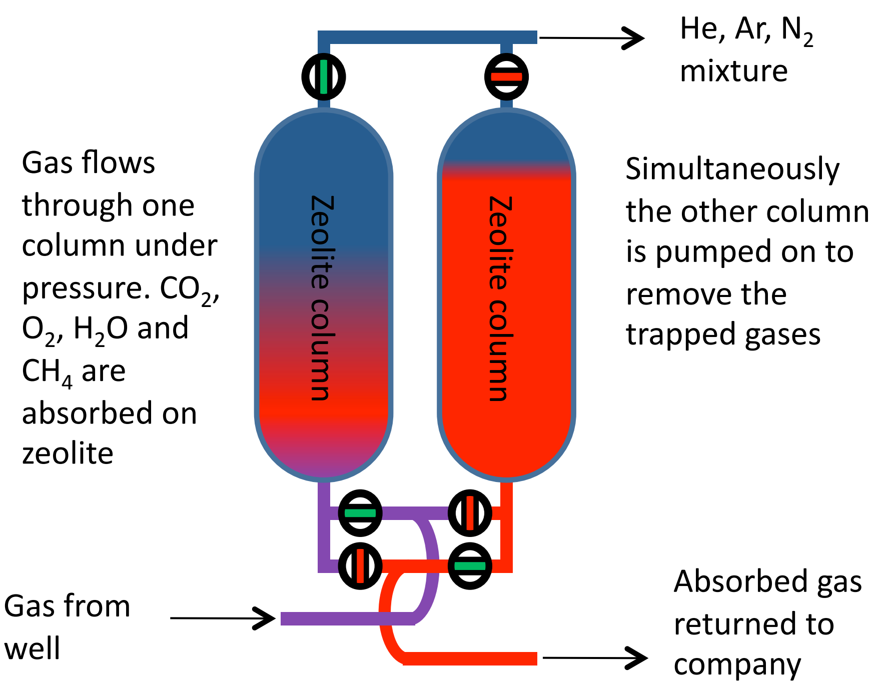
- Simulations suggest that very high efficiency for both radiogenic and cosmogenic neutrons are realizable using boron loaded liquid scintillators
  - 1 m veto gives >99.5% and >95% efficiency, respectively
- Acceptable veto light outputs and backgrounds rates seem practically realizable
- Simulations are nice but…
  - DarkSide-50 will deploy a scintillator veto and test its performance

DEPLETED ARGON FROM UNDERGROUND

Gas extraction

Chromatographic Gas Separation

- Underground Argon is not exposed to cosmic rays and is depleted in ^{39}Ar
  - (factor of 25 lower than atmospheric Ar)
- CO_2 well in southwestern Colorado identified with 600 ppm of Argon
- CO_2, O_2, H_2O and CH_4 can be trapped into zeolite (1st Stage)
- N_2 is partially trapped due to the high He content (2nd Stage)
- Absorption is pressure dependent
  - Higher pressure = greater absorption
  - Lower pressure = lower absorption



Vacuum-Pressure swing absorption unit in Colorado

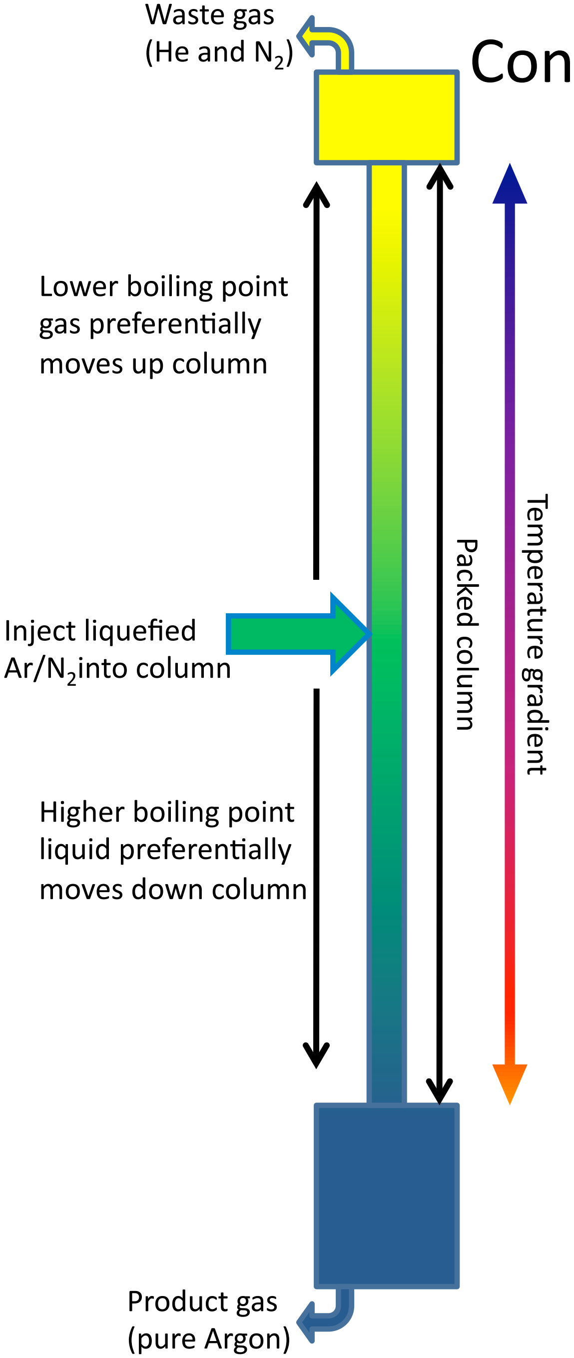
- Gas from well
  - 96% - CO_2
  - 2.4% - N_2
  - 5,700 ppm - CH_4
  - 4,300 ppm - He
  - 2,100 ppm - Other hydrocarbons
  - 1,000 ppm - H_2O
  - **600 ppm - Ar**
  - Below sensitivity - O_2
- Output gas:
  - 70% - N_2, 27.5% - He, and 2.5% - Ar
- 52 higher pressure cylinders collected

➢ **26 kg of Depleted Argon**

Fermilab

Gas purification

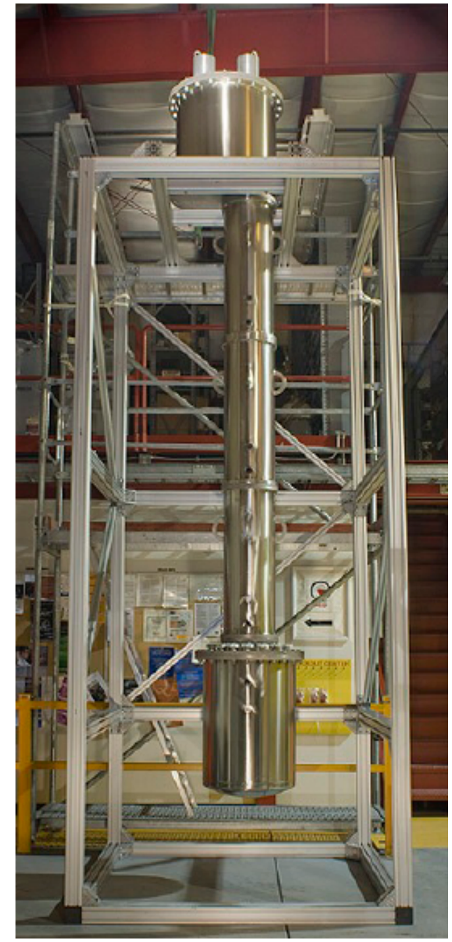
Continuous Distillation Gas Separation



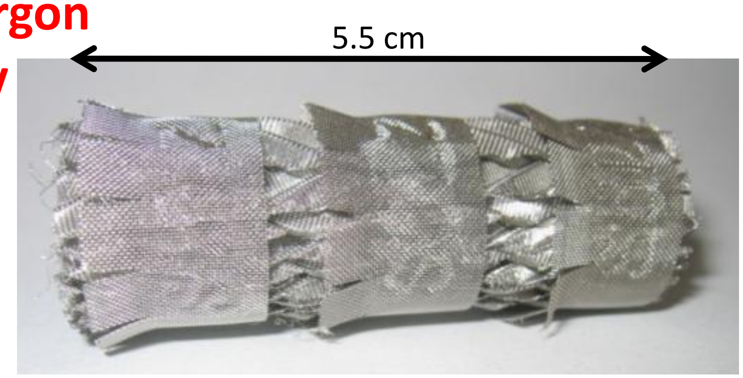
- Continuous boiling of liquid and recondensing of gas allow efficient continuous separation of liquids with different boiling points
- Boiling and recondensing occur in the column on custom made packing material
- Our column:
  - Packed column
  - Diameter~ 2 cm
  - Length ~ 320 cm
- Equivalent to 40 theoretical stages
- Expected performance:

➢ **Purity – 99.9999% pure Argon**

➢ **Production rate – 5kg/day**



Cryogenic Distillation Column at Fermilab



Column packing material

Does It Have to be Boron?

- In our simulations, loading with 0.6% (w/w) Gd gave similar performance
  - Multiple gammas helps to mitigate the gamma propagation effect

Active vs. Passive Shielding of Cosmogenics

- Active scintillator shield is about 4 times as effective as the same thickness of "passive" water
  - Factor of 2 from detecting recoil neutron
  - Factor of 2 from "mean free path" rather than "attenuation length"

Neutron Energy (MeV)	Mean Free Path (cm)	Most Distant Recoil (cm)
10	11	28
20	14	33
50	30	63
100	47	103
200	71	170

Internal Radiogenic Neutrons

- Veto performance seems to be surprisingly independent of energy deposition in the active volume