Solar neutrino detection in a large volume double–phase liquid argon experiment

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APC

Magellan Workshop
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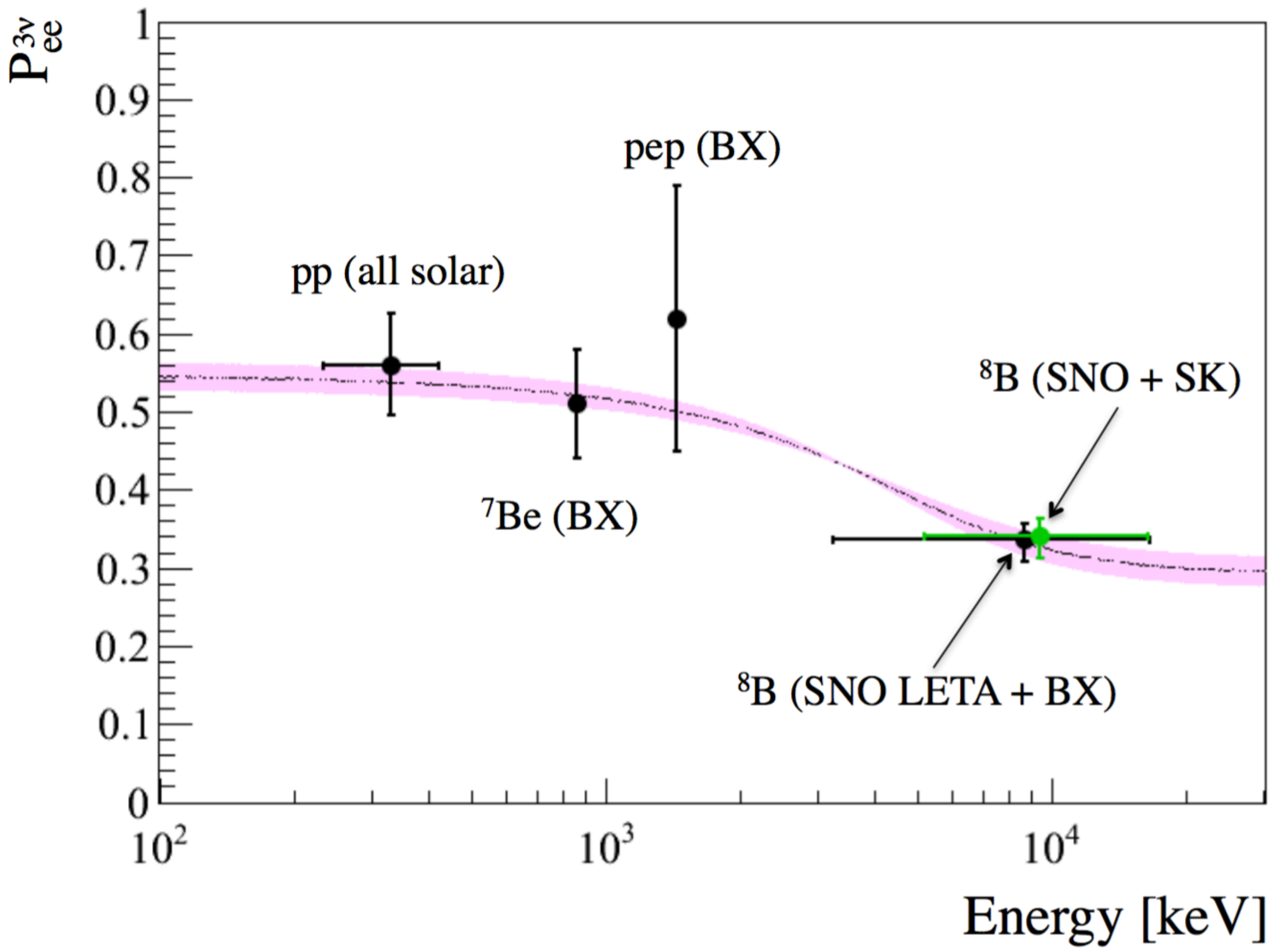
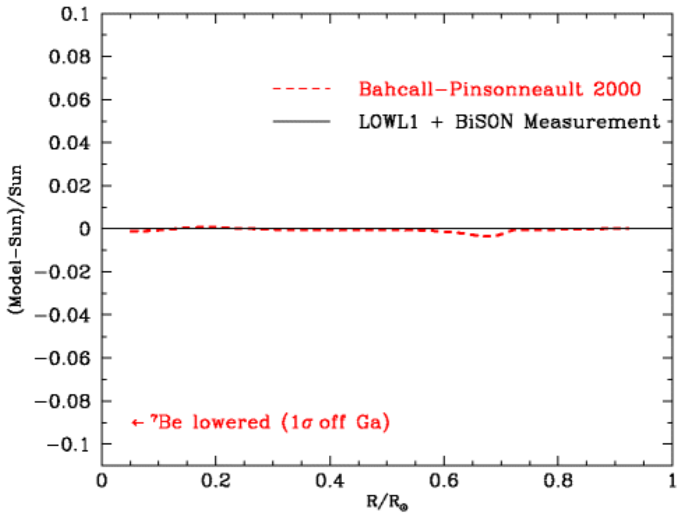
The experimental status



The metallicity problem

The Standard Solar Model, based on the old metallicity derived by Grevesse and Sauval (Space Sci. Rev. **85**, 161 (1998)), was in **agreement within 0.5 in %** with the solar sound speed measured by helioseismology.

< 2004



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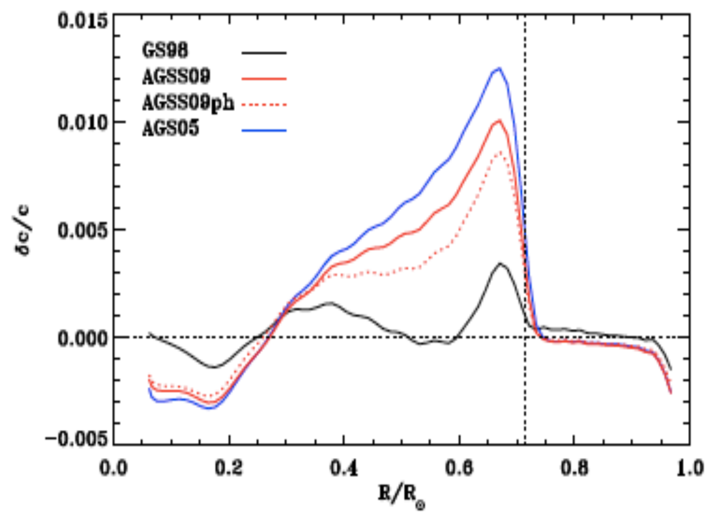
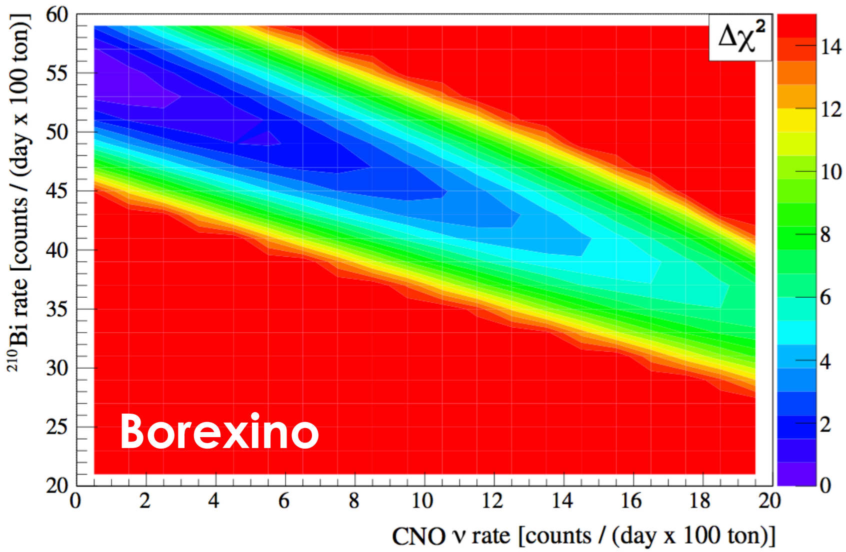


Latest work by Asplund, Grevesse and Sauval (Nucl. Phys. A **777**, 1 (2006)) indicates a **lower** metallicity **by a factor ~2**. This result destroys the agreement with helioseismology

…and the CNO component

[cm^{-2} s^{-1}]	***pp*** (10^{10})	***pep*** (10^{10})	***hep*** (10^{3})	**^{7}Be** (10^{9})	**^{8}B** (10^{6})	**^{13}N** (10^{8})	**^{15}O** (10^{8})	**^{17}F** (10^{6})
GS98	5.97	1.41	7.91	5.08	5.88	2.82	2.09	5.65
AGS09	6.03	1.44	8.18	4.64	4.85	2.07	1.47	3.48
Δ	**-1%**	**-2%**	**-3%**	**-9%**	**-18%**	**-27%**	**-30%**	**-48%**

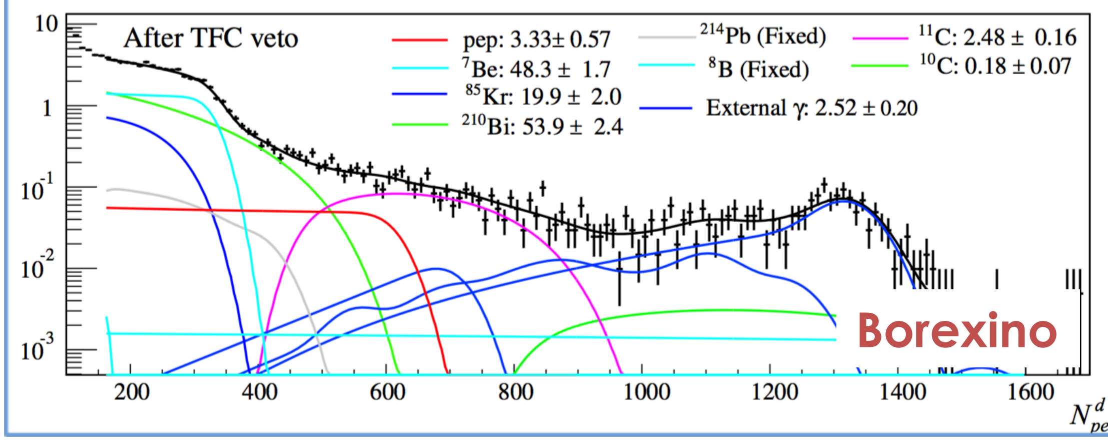


Never observed

Borexino: <7.9 10^6 cm^{-2} s^{-1}(95% CL)

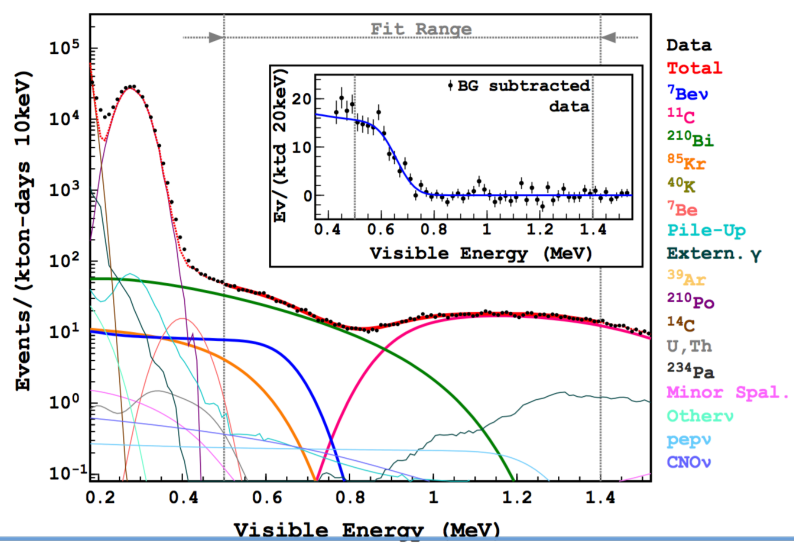
CNO neutrino (via elastic scattering) and ^{210}Bi have similar shapes: strong correlation in spectral fits

CNO and ^{210}Bi

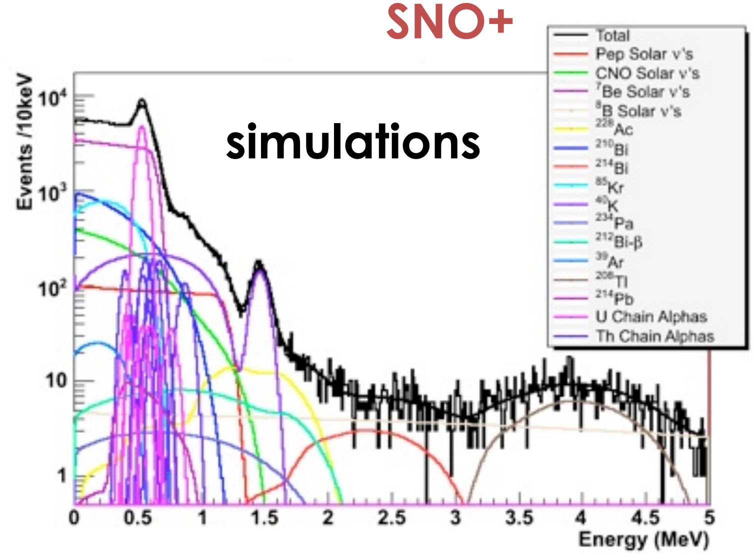


Borexino will attempt a new purification campaign to remove ^{210}Bi

KamLAND



SNO+



Difficult to reach the sensitivity to "observe" CNO and to disentangle the metallicity models with **scintillators**

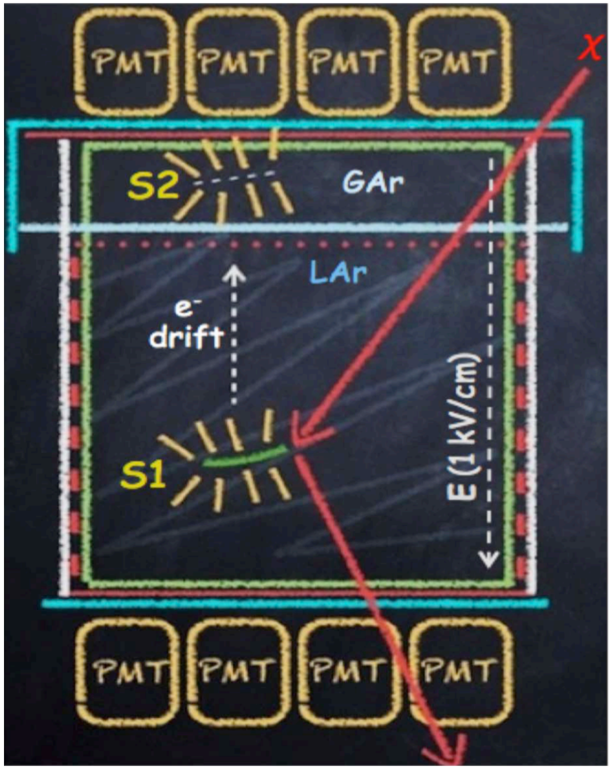
Two-Phase Liquid Argon TPC

Liquid Argon:

- Excellent **scintillator**: 40,000 photons / MeV
- It does **not bond** with chemical species
- It can be easily **purified** both in liquid and in gas phases
- Higher **intrinsic radio-purity** wrt organic liquid scintillators
- **Scalable** to multi-ton (hundreds of ton) mass targets
- Exceptional **PSD**

Two-phase TPC:

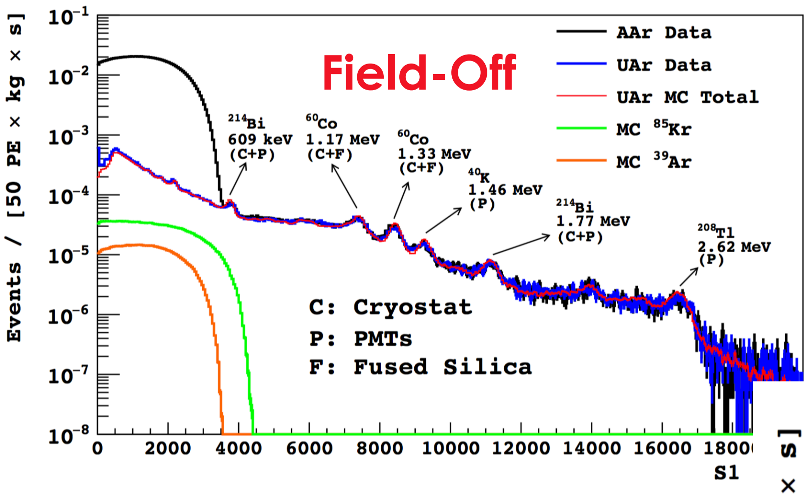
- Excellent **3D position** reconstruction
- Excellent identification and rejection of **multiple interactions**



Already planned for **Direct Dark Matter Search**

Ideal to observe **CNO neutrinos** via elastic scattering

The ^{39}Ar issue after DS50



Atmospheric Ar:

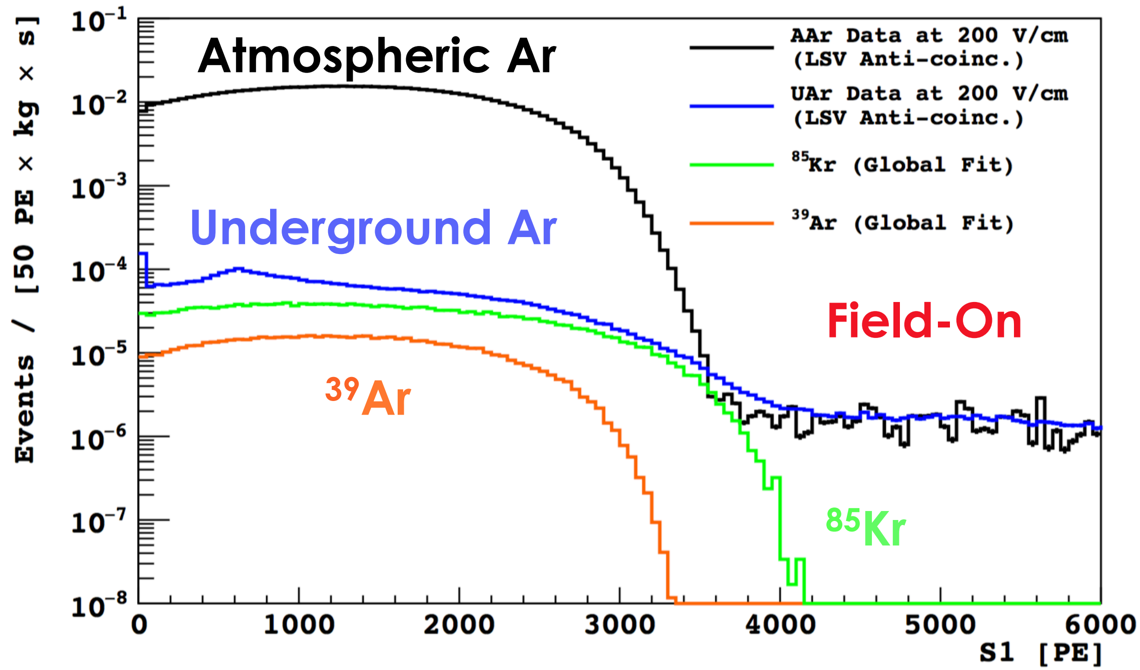
$^{39}Ar/^{40}Ar = 8 \times 10^{-16}$

Rate ~ **1 Bq/kg**

Underground Ar:

Rate ~ **0.7 mBq/kg**

Depletion factor ~ 1400



This measurement came after this work. We used the old limit of ^{39}Ar < **6.5 mBq/kg** (arXiv:1204.6011) equivalent to a depletion factor of **150**

DS Collaboration: arXiv:1510.00702

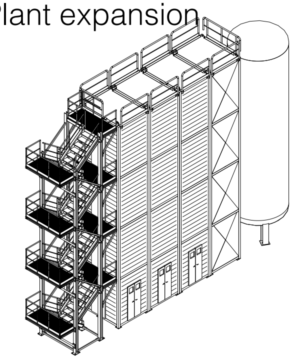
Towards Multi Tonne LAr

Depleted Ar: the **URANIA** and **ARIA** projects

URANIA

Replacement of the Ar extraction plant in Colorado to reach capacity of **100 kg/day** of UAr

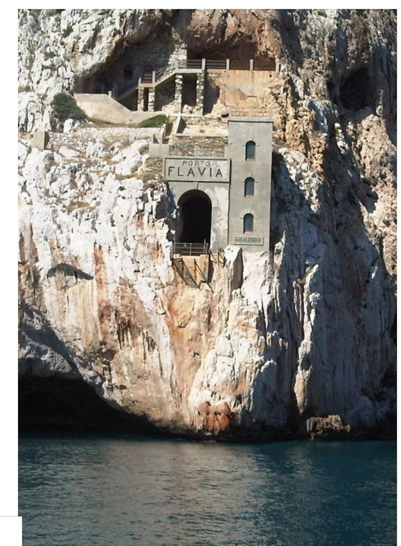
Plant expansion

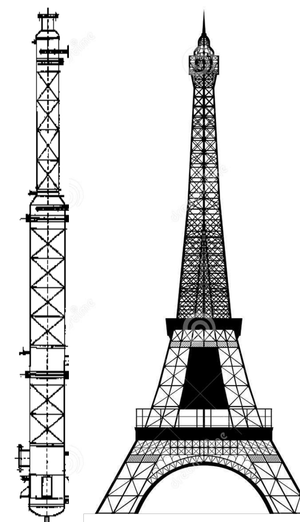


ARIA

Very tall distillation column in Seruci mine (Sardinia) for chemical and isotopic purification of UAr

Exploits finite vapor pressure difference between $^{39}Ar/^{40}Ar$: ^{39}Ar reduction factor of 10 per pass at the rate of **100 kg/day**





Detector Assumptions

Assumed ^{39}Ar activity: **6 mBq / kg** (^{39}Ar Q-value: 565 keV)

Energy resolution
DS50: ~**7,000 pe/MeV**@200 V/cm
DS50: ~**8,500 pe/MeV**@0 V/cm
MicroCLEAN: ~**6,000 pe/MeV**@0 V/cm

MicroCLEAN has demonstrated **linear energy response** within **2%** above 40 keV

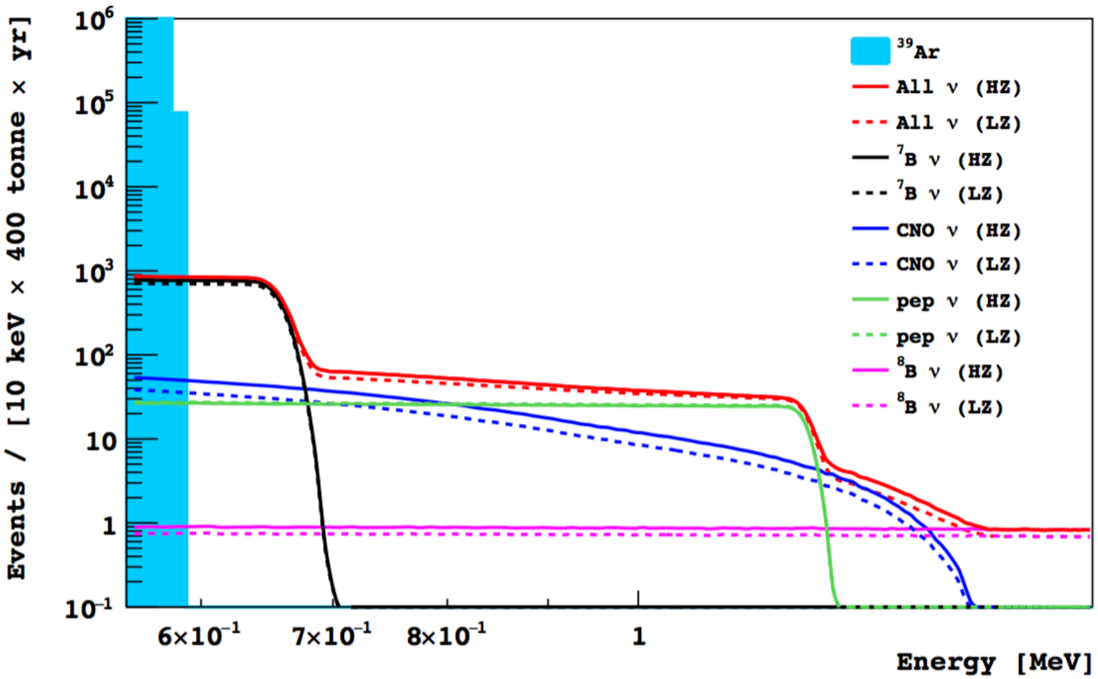
RoI: > 600 keV
(0 ^{39}Ar events expected in 400 tonne year)

Conservative LY assumed in this work: **6,000 pe/MeV** @200 V/cm

Full capability to discriminate multiple interactions if **$\Delta z > 2$ mm**

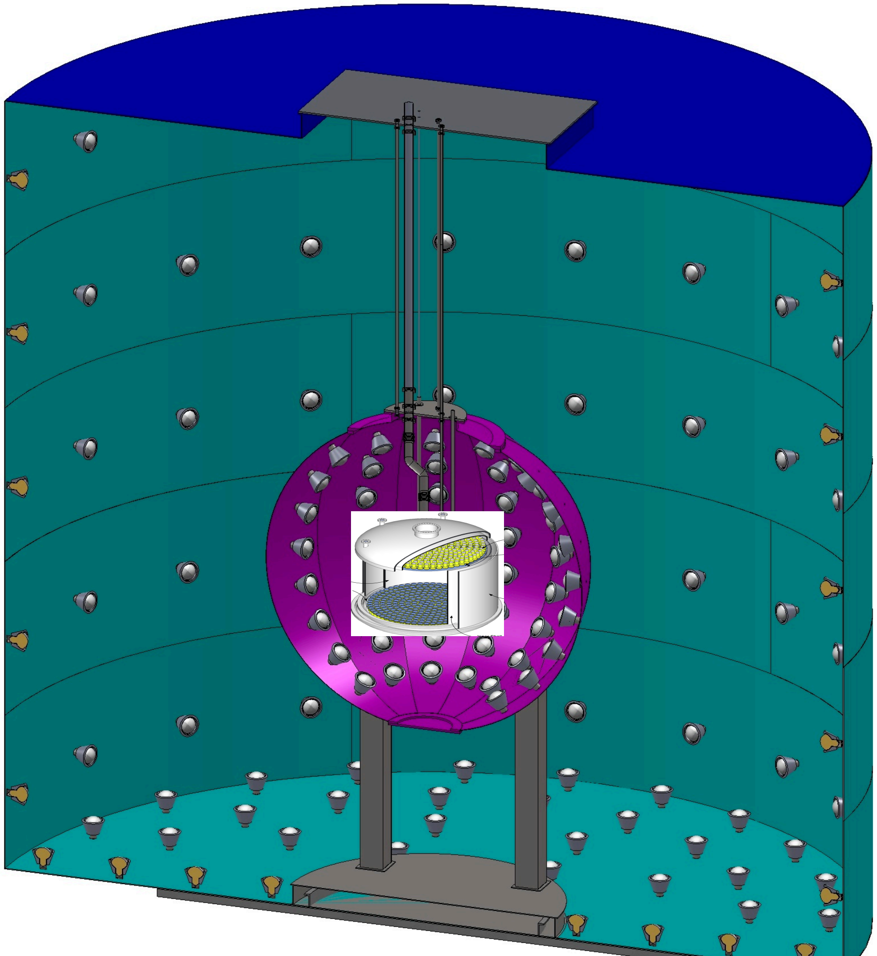
Solar Neutrino Rate

Neutrino Source	Low Metallicity (LZ) All	Low Metallicity (LZ) [0.6-1.3] MeV	High Metallicity (HZ) All	High Metallicity (HZ) [0.6-1.3] MeV
pp	107.9 ± 2.0	0	107.0 ± 2.0	0
pep	2.28 ± 0.05	1.10 ± 0.02	2.23 ± 0.05	1.07 ± 0.02
^{7}Be	36.10 ± 2.60	2.85 ± 0.21	39.58 ± 2.85	3.13 ± 0.23
CNO	3.06 ± 0.30	0.64 ± 0.06	4.28 ± 0.44	0.90 ± 0.09
^{8}B	0.30 ± 0.04	0.035 ± 0.005	0.36 ± 0.06	0.042 ± 0.007
Total	cpd / 100 tonne	4.63 ± 0.22		5.14 ± 0.25



In 400 tonne year in the RoI:
^{7}**Be**: ~**4,400** events
pep: ~**1,600** events
CNO: ~**1,100** events

The Detector



(not a scaled plot)

TPC
3 m height
3.3 m radius
150 tonne mass
3 cm thick teflon envelop
2 cm gas pocket
2 mm thick SiPM on top/bottom

Cryostat
3.2 m height
3.5 m radius
3 mm thick stainless steel

Liquid scintillator veto
6 m radius
3 mm thick stainless steel

Water veto
17 m height
8 m radius

Background Sources

Source	Origin	From	Comment
^{42}Ar-^{42}K	Anthropogenic	LAr	Not present in UAr – Observed by GERDA in AAr
^{85}Kr	Anthropogenic??	LAr	Observed (very recently) by DS50 in UAr
Induced by cosmic rays	Cosmogenic	LAr	
Radon	Natural	Liquid/gaseous argon circulation loop	
External Bg	Natural	Detector components (mostly steel and teflon)	

Cosmogenics

Isotope	Half life	Decay Mode	Q-value [keV]	Activity [cpd/100 t]
^{9}C	126.5 ms	β^+	16494.8	4.84e-03 ± 2.42e-03
^{10}C	19.290 s	β^+	2929.62	8.47e-03 ± 3.20e-03
^{11}C	1221.8 s	β^+	1982.4	5.44e-02 ± 8.11e-03
^{14}C	5700 y	β^-	156.475	8.42e-06 ± 1.11e-06
^{15}C	2.449 s	β^-	9771.7	1.21e-02 ± 3.82e-03
^{16}C	0.747 s	β^-	7891.58	1.21e-03 ± 1.21e-03
^{12}N	11.000 ms	β^+	17338.1	1.21e-03 ± 1.21e-03
^{13}N	9.965 min	β^+	2220.49	3.63e-03 ± 2.09e-03
^{16}N	7.13 s	β^-	10419.1	3.87e-02 ± 6.84e-03
^{17}N	4.173 s	β^-	8680	1.21e-02 ± 3.82e-03
^{18}N	624 ms	β^-	11916.9	1.21e-03 ± 1.21e-03
^{14}O	70.606 s	β^+	5143.04	1.21e-03 ± 1.21e-03
^{15}O	122.24 s	β^+	2754	2.06e-02 ± 4.99e-03
^{19}O	26.88 s	β^-	4819.6	1.09e-02 ± 3.63e-03
^{20}O	13.51 s	β^-	2757.45	6.05e-03 ± 2.70e-03

Isotope	Half Life	Decay Mode	Q-value [keV]	Activity [cpd/100 t]
			4812.36	4.84e-03 ± 2.42e-03
			1491.5	2.33e-01 ± 1.68e-02
			227.2	1.26e-03 ± 1.15e-04
			5845	1.69e-02 ± 4.53e-03
^{30}S	1.178 s	EC		
^{31}S	2.5534 s	EC		
^{35}S	87.37 d	β^-		
^{37}S	5.05 min	β^-		
^{38}S	170.3 min	β^-		
^{39}S	11.5 s	β^-		
^{34}Cl	1.5266 s	EC		
^{38}Cl	37.230 min	β^-		
^{39}Cl	55.6 min	β^-		
^{40}Cl	1.35 min	β^-		
^{35}Ar	1.7756 s	EC		
^{37}Ar	35.011 d	EC	813.87	1.48e+00 ± 4.16e-02
^{39}Ar	269 y	β^-	565	4.02e-02 ± 4.84e-04
^{41}Ar	109.61 min	β^-	2491.61	2.23e+01 ± 1.64e-01
^{38}K	7.636 min	EC	5913.86	7.26e-03 ± 2.96e-03

Isotope	Half Life	Decay Mode	Q-value [keV]	Activity [cpd/100 t]
^{17}F	64.49 s	β^+	2760.8	3.63e-03 ± 2.09e-03
^{18}F	109.77 min	β^+	1655.5	4.11e-02 ± 7.05e-03
^{20}F	11.163 s	β^-	7024.53	3.99e-02 ± 6.95e-03
^{30}Al	3.62 s	β^-	6325.68	2.78e-02 ± 5.80e-03
^{31}Al	644 ms	β^-	5205.97	2.42e-03 ± 1.71e-03
^{32}Al	33.0 ms	β^-	13020	1.21e-03 ± 1.21e-03

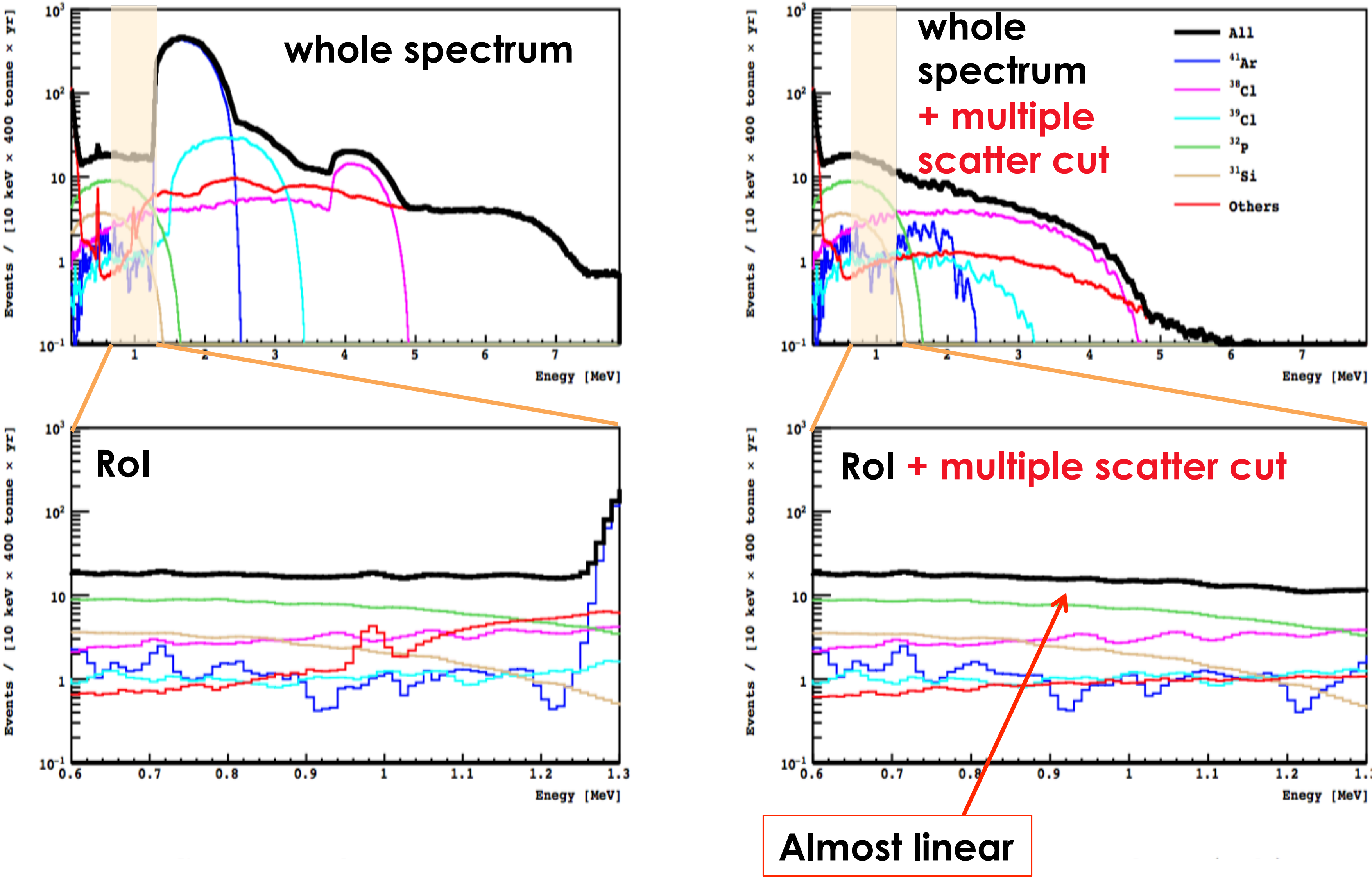
Cosmic muons at LNGS:

- 3800 mwe depth
- 283 GeV mean energy
- Energy and angular distributions from MACRO
- Flux: 1.14 μ / hr / m^2
- μ^+/μ^- = 1.38

Simulations:

- Isotopes production with **FLUKA: known to be accurate within a factor 2**
- Generated 3 m above the tank, through 0.7 m of rock
- Muon showers and short lived isotopes (<1 ms) vetoed
- Production of **84 isotopes**
- Each of them **tracked with Geant4**

Cosmogenics



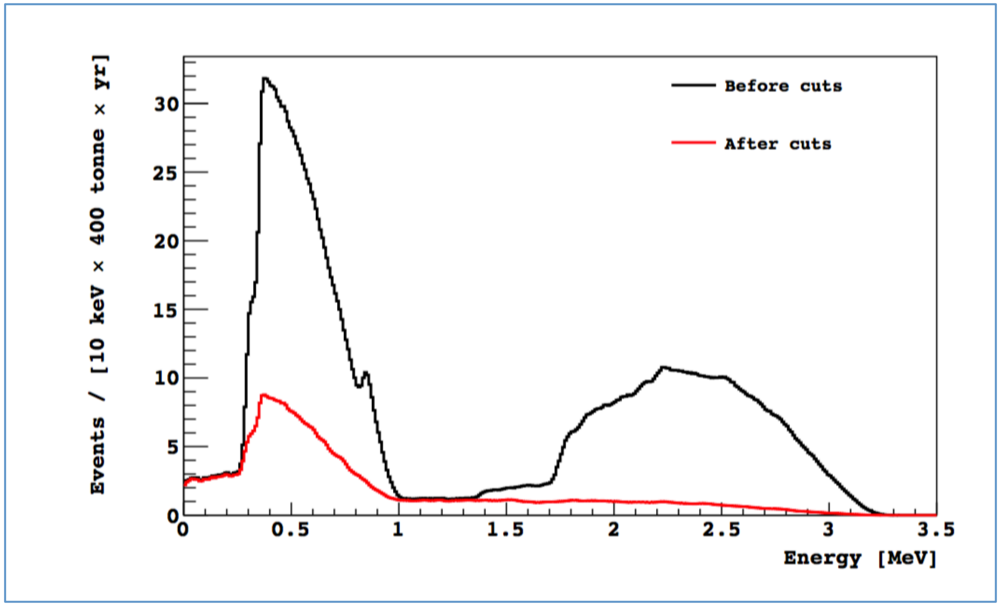
Cosmogenics: a summary

Isotope	Half Life	Decay Mode	Q-value [MeV]	Rate Entire Range	Rate [0.6-1.3] MeV
^{41}Ar	109.61 min	β^-	2.492	0.213	0.054
^{38}Cl	37.230 min	β^-	4.917	0.815	0.147
^{39}Cl	55.6 min	β^-	3.442	0.173	0.051
^{32}P	14.268 d	β^-	1.711	0.636	0.332
^{34}P	12.43 s	β^-	5.383	0.145	0.021
^{31}Si	157.36 min	β^-	1.492	0.229	0.106
Others				1.897	0.022
Total	cpd / 100 tonne			4.108	0.733

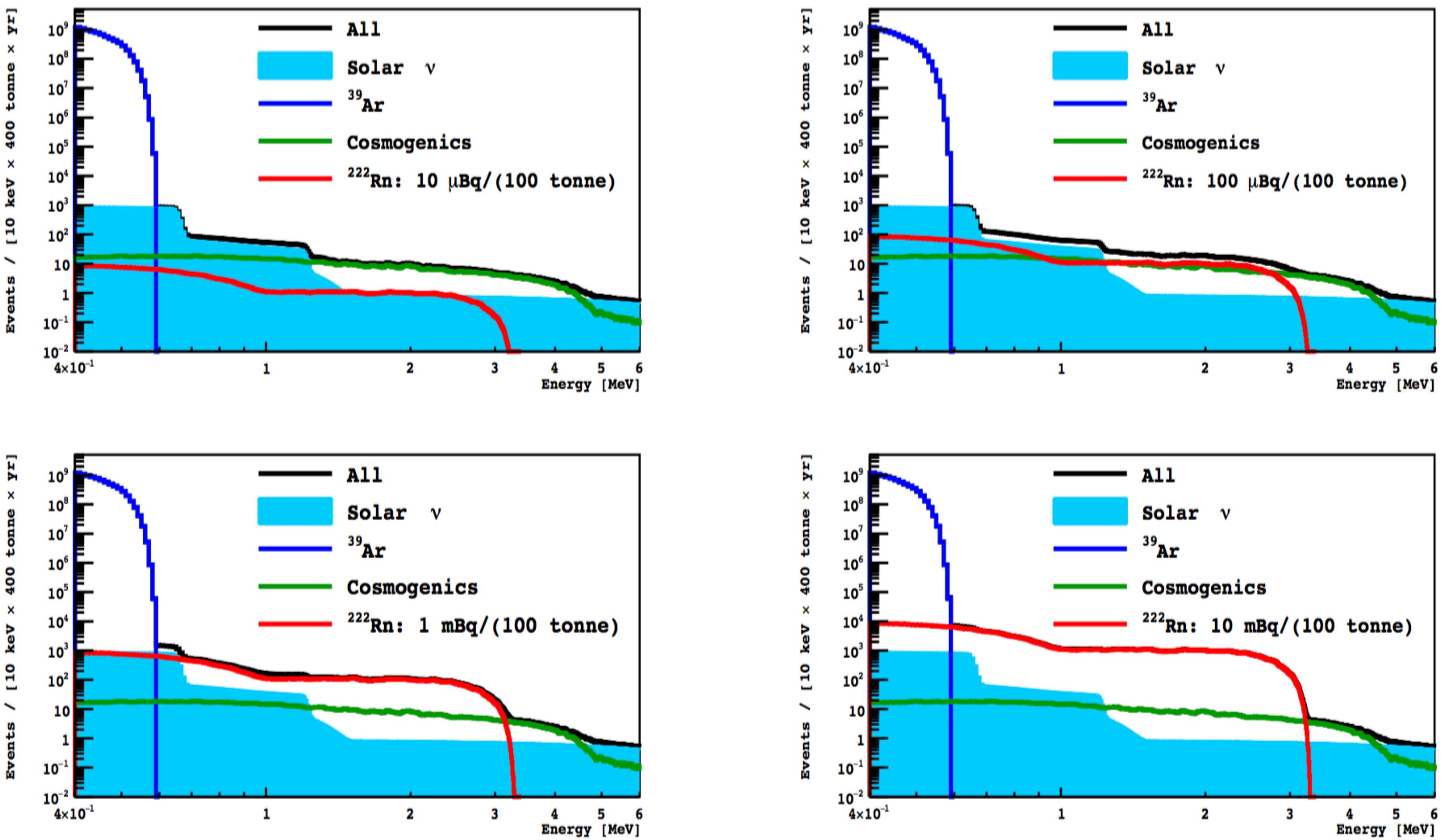
S/B ~ 7

Radon

- ^{222}**Rn** diffuses by **purification loop** of the cryogenic and gas handling system
- Cold-charcoal traps: fractions of the μBq in 1 m^3 in GAr
- Potentially, with **cryogenic adsorption** technique: **< 1 mBq/100 tonne**
- Alpha's efficiently rejected with **PSD**
- **6.9%** of ^{214}**Pb** and **5.9%** of ^{214}**Bi survive** to the cuts
- ^{214}**Bi-Po** coincidence is here assumed with **60%** efficiency



Radon


All
Solar ν
^{39}Ar
Cosmogenics
^{222}Rn: 10 μBq/(100 tonne)
^{222}Rn: 100 μBq/(100 tonne)
^{222}Rn: 1 mBq/(100 tonne)
^{222}Rn: 10 mBq/(100 tonne)
Events / [10 keV × 400 tonne × yr]
Energy [MeV]
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
4×10^{-1}
1
2
3
4
5
6

External Background

Source	Origin	Attenuation length [cm]	Survived Fraction without FV	Survived Fraction with FV
^{40}K	Photosensors	3.9	0.3×10^{-2}	1×10^{-6}
^{214}Bi	Photosensors	4.2	1.1×10^{-2}	9×10^{-6}
^{208}Tl	Photosensors	3.6	0.7×10^{-2}	2×10^{-6}
^{60}Co	Cryostat	5.1	0.1×10^{-2}	3×10^{-6}

FV = 30 cm cut from the TPC walls

Only ^{60}Co is an issue

Assuming the lowest ^{60}Co activity in literature in stainless steel (6.6 mBq/kg) => 1.7 cpd / tonne expected in the FV after the cuts

Definitive solution to ^{60}Co is a **titanium cryostat**

External background is here considered negligible

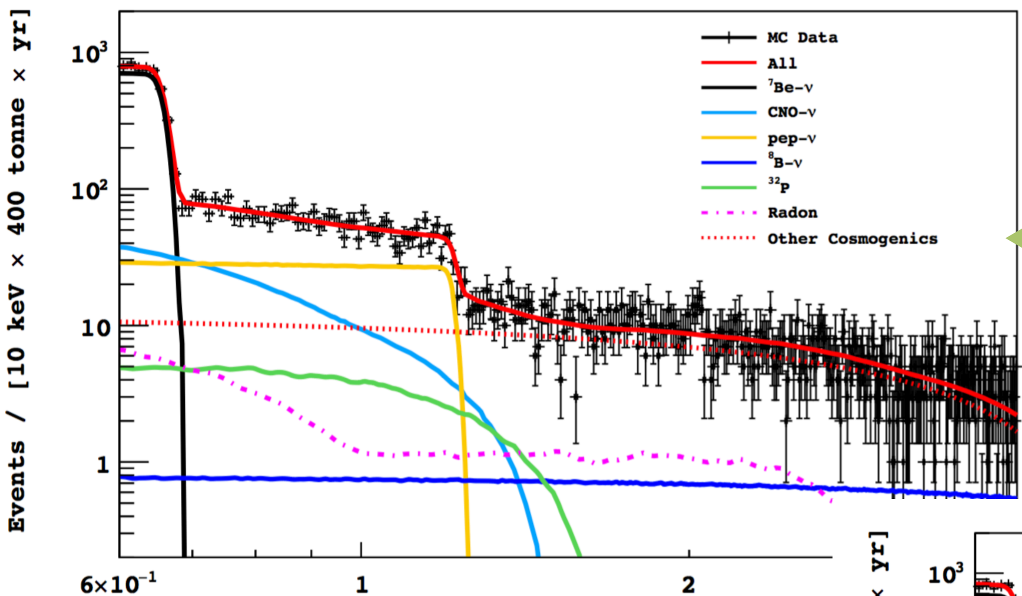
Toy MC Strategy

- **10,000** samples of simulated data for each radon activity
- Poisson statistics corresponding to a **400 tonne yr exposure**
- Each signal and bg component **independently** generated
- Repeated for each **metallicity** model
- detector resolution for a light yield of **6,000 pe/MeV**

Fit Strategy

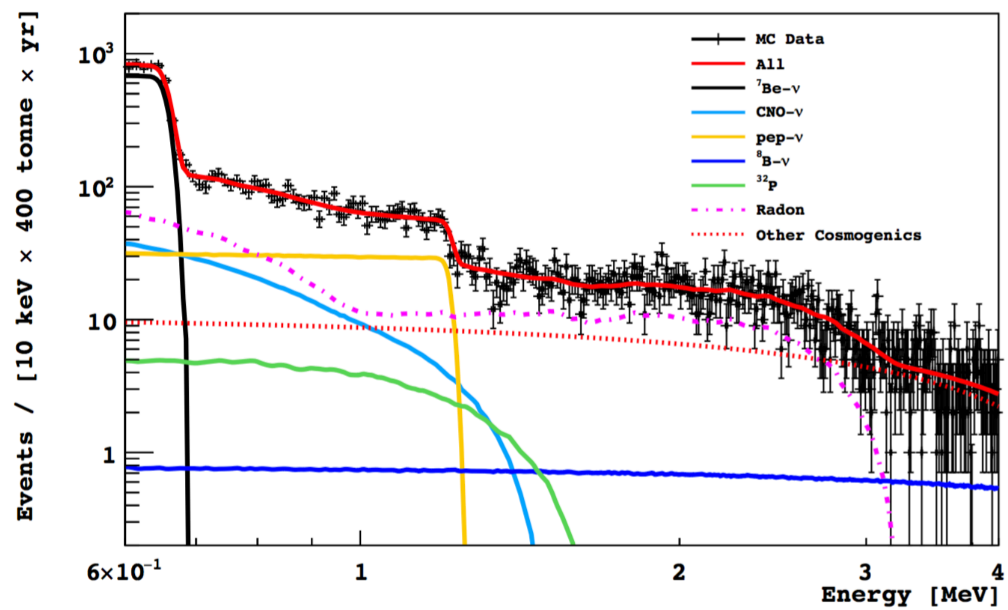
- binned likelihood with **ROOFIT**
- Radon activity varied from **10 to 200 μBq / 100 tonne**
- **Radon** amplitude **weighted** by the uncertainty on the BiPo coincidences (60% efficiency)
- Cosmogenics modeled with **1st degree polynomial** (2 free parameters) + **^{32}P**

Fit to the toy MC samples

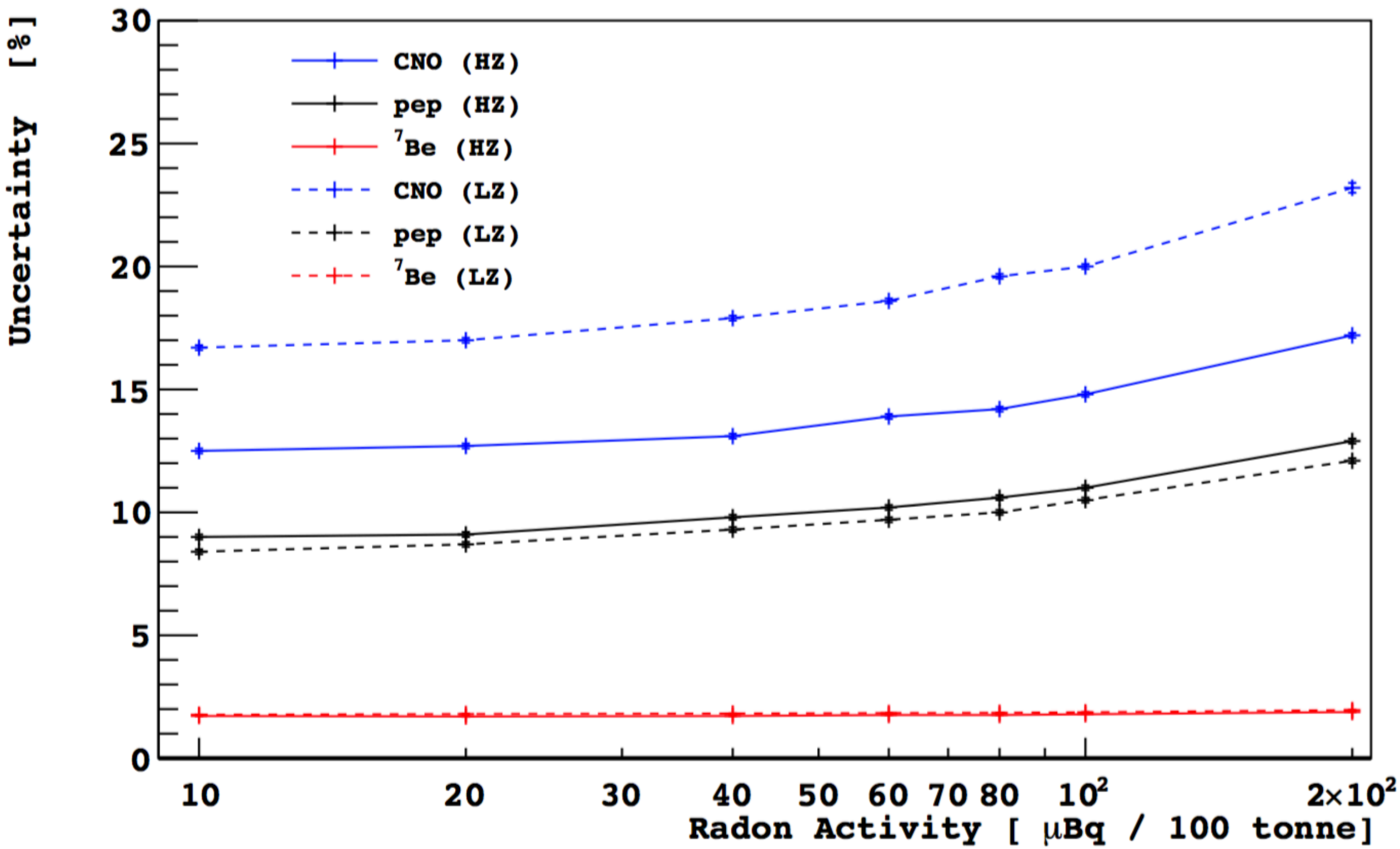


Radon
10 μBq/100 tonne

Radon
100 μBq/100 tonne

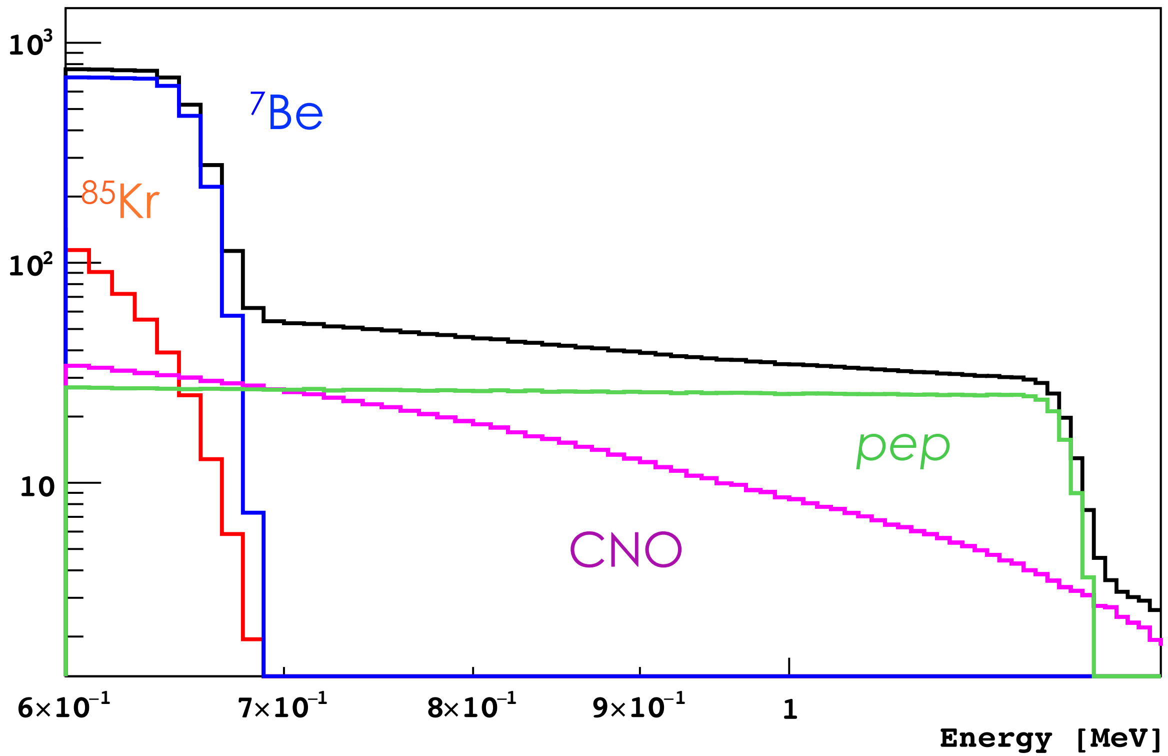


Fit Results



CNO amplitude dominated by systematics >200 μBq /100 tonne

^{85}Kr affects only the ^{7}Be measurement (Q-value: 687 keV)



Fixing radon activity to 10 μBq/100 tonne, we tested 85Kr contamination at **1, 10 and 100 μBq/100 tonne**: ^{7}Be uncertainty changes to **2%, 3.5%, and 5%**, respectively

Systematics

High accuracy on the energy scale and on the position reconstruction (systematics at percent level) -> **Only ^{7}Be affected**

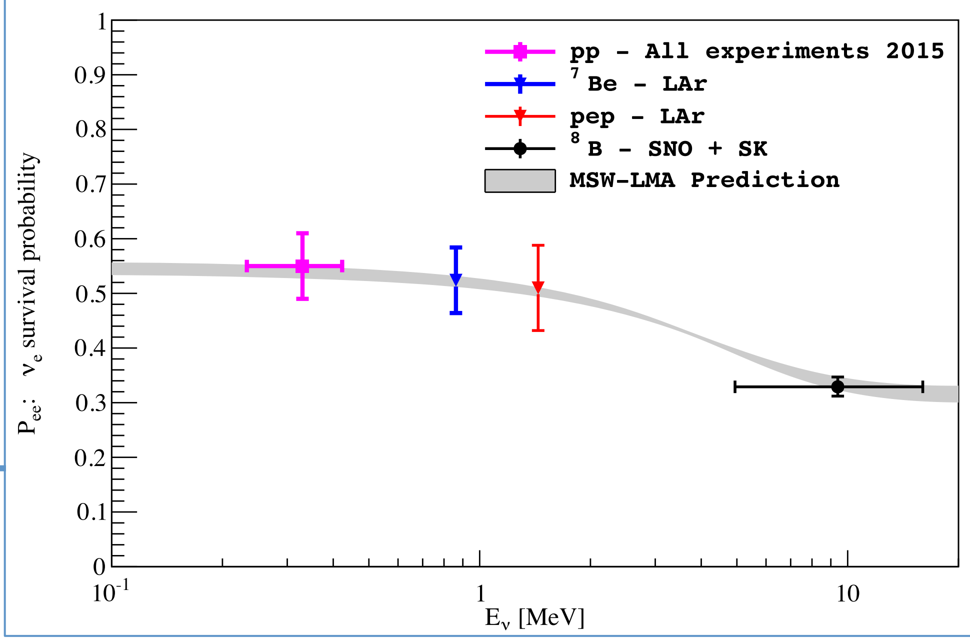
Main systematics from the cosmogenic fitting model

To test the model, **each cosmogenic** component activity was **randomly varied within a factor 2**. The toy MC and fitting procedure was then repeated for two cases: radon contaminations at 10 and 100 μBq/100 tonne.

No differences with respect to the already quoted results

Percent level overall systematic: achievable

Impact of the results



Assuming accuracies at:
- ^{7}Be: 2%
- *pep*: 10%
- CNO: 15%

Potential Goals:

- **Observation of CNO (>5σ)**
- Determination of the **C and N** content **in the Sun** at 16.5% level (currently at 25%)
- S17 (**^{7}Be(p,γ)^{8}B**) precision from 12% to 8% (one of the input parameters of the SSM)
- Good potential in discriminating between **metallicity** models

Conclusions

Two-phase LAr TPC with 100 tonne fiducial mass already on the DarkSide roadmap (**ARGO**) for direct dark matter search

Exceptional **radio-purity** and **resolutions**

Strong potential in solar neutrino physics

Background can be kept under control. **Need some effort** especially for radon and external background.

More details in **arXiv:1510.04196**

Solar neutrino detection in a large volume double–phase liquid argon experiment

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