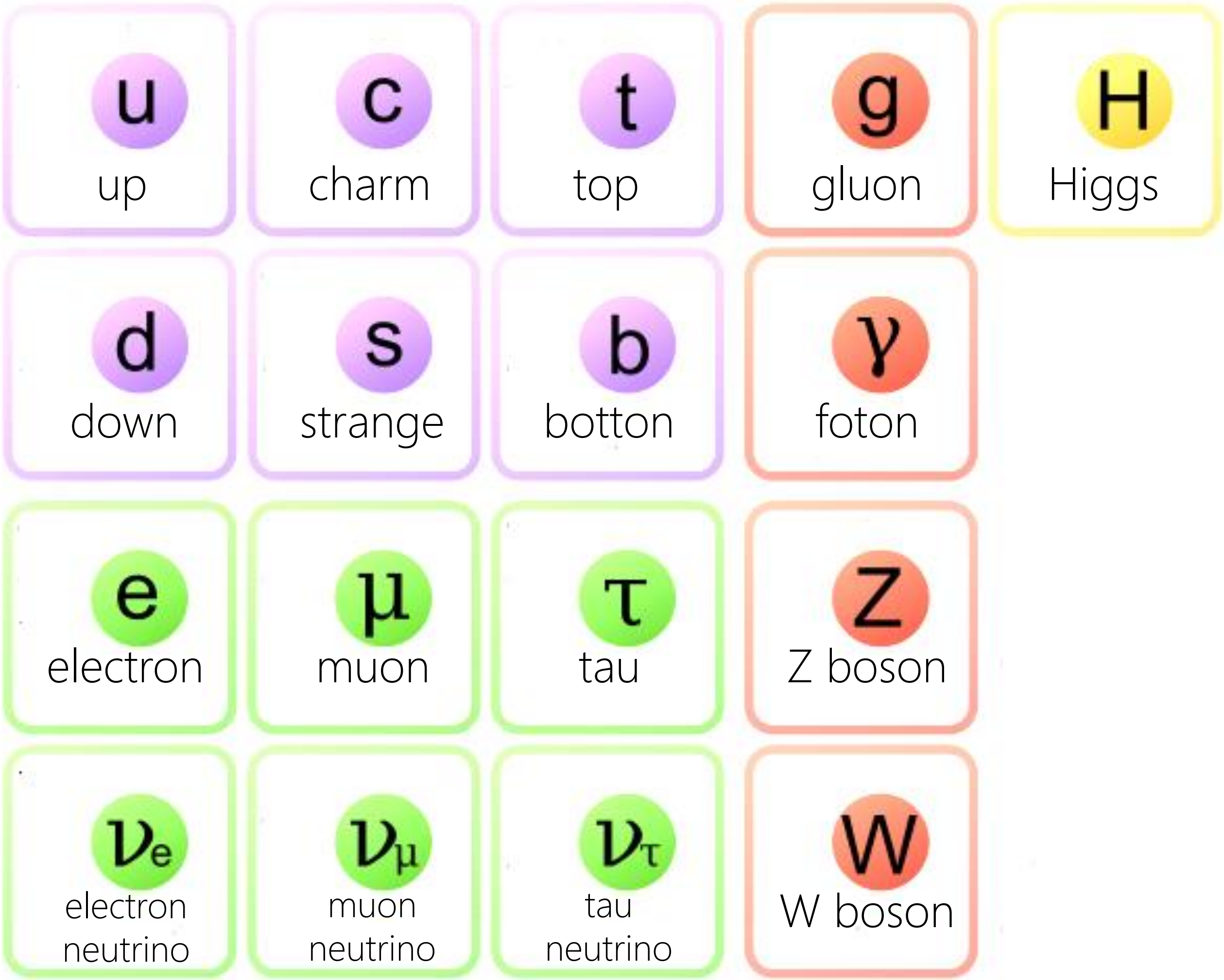
External and internal neutron backgrounds in the SNO+ experiment

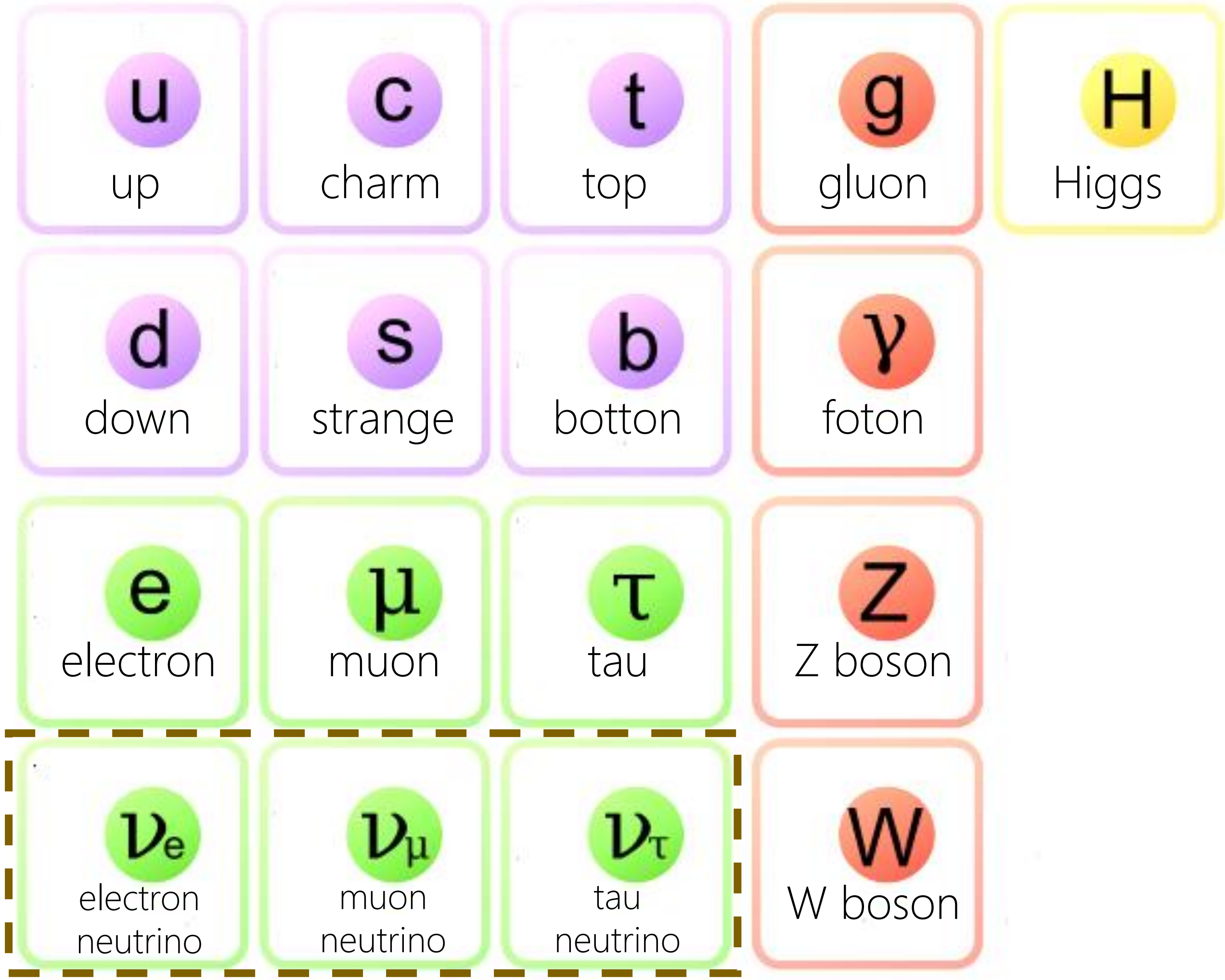
Luis Hernández Hernández
Instituto de Física
Universidad Nacional Autónoma de México

Meeting of the Cosmic Rays Division of the Mexican Physical Society
Friday, October 5th, 2018

Outline

- The SNO+ experiment: overview
- The SNO+ detector, run plan and physics program
- Backgrounds in the SNO+ experiment
- Neutron backgrounds in the SNO+ experiment
- Final remarks


u
up
c
charm
t
top
g
gluon
H
Higgs
d
down
s
strange
b
botton
γ
foton
e
electron
μ
muon
τ
tau
Z
Z boson
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
W
W boson


u
up
c
charm
t
top
g
gluon
H
Higgs
d
down
s
strange
b
botton
γ
foton
e
electron
μ
muon
τ
tau
Z
Z boson
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
W
W boson


ν_e
electron
neutrino
ν_μ
muon
neutrino
ν_τ
tau
neutrino

Neutrinos are massive particles and interact with matter not only through gravitational force, but also through weak nuclear force with a **very** small cross section.

Neutrinos are massive particles and interact with matter not only through gravitational force, but also through weak nuclear force with a **very** small cross section.

. Currently we know that the sum of their masses is less than 0.2 eV approximately.

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

An understanding of their properties can help us to explain open questions in fundamental physics like the matter-antimatter asymmetry, even we can get meaningful information of their sources.

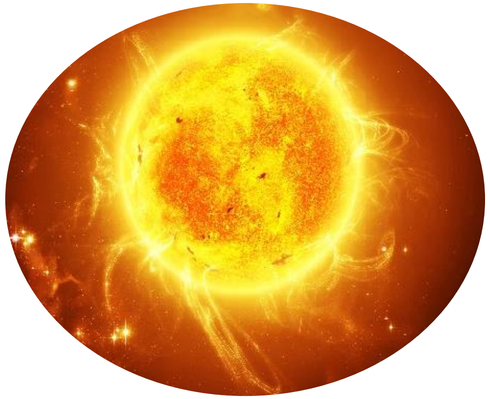
An understanding of their properties can help us to explain open questions in fundamental physics like the matter-antimatter asymmetry, even we can get meaningful information of their sources.

Neutrinos are naturally occurring or can be produced through man-made processes:

An understanding of their properties can help us to explain open questions in fundamental physics like the matter-antimatter asymmetry, even we can get meaningful information of their sources.

Neutrinos are naturally occurring or can be produced through man-made processes:

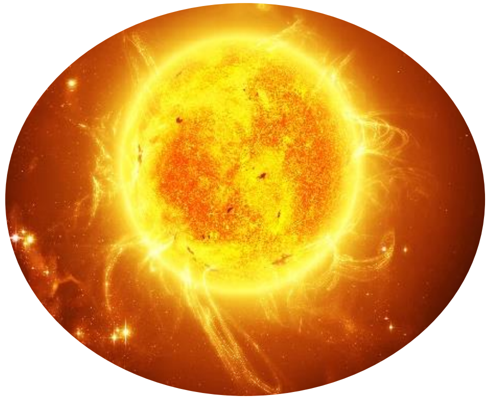
Solar neutrinos



An understanding of their properties can help us to explain open questions in fundamental physics like the matter-antimatter asymmetry, even we can get meaningful information of their sources.

Neutrinos are naturally occurring or can be produced through man-made processes:

Solar neutrinos

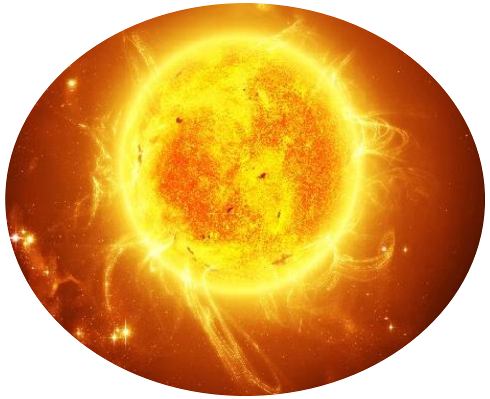


Atmospheric neutrinos

An understanding of their properties can help us to explain open questions in fundamental physics like the matter-antimatter asymmetry, even we can get meaningful information of their sources.

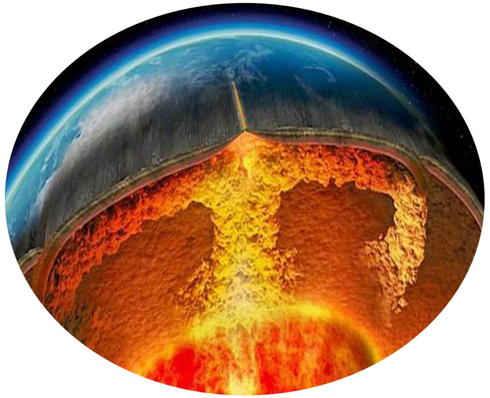
Neutrinos are naturally occurring or can be produced through man-made processes:

Solar neutrinos



Atmospheric neutrinos

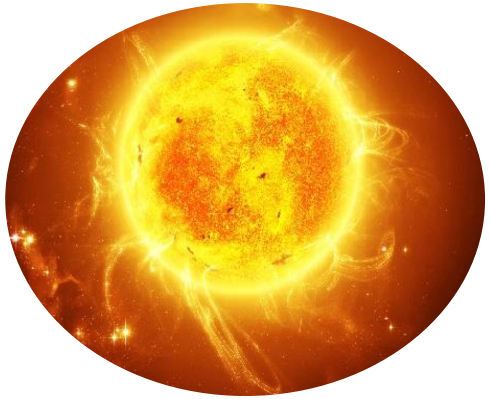
Geoneutrinos



An understanding of their properties can help us to explain open questions in fundamental physics like the matter-antimatter asymmetry, even we can get meaningful information of their sources.

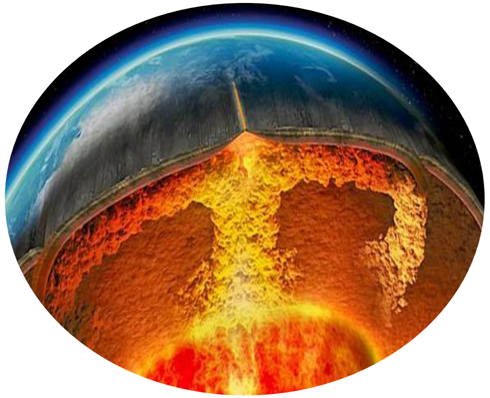
Neutrinos are naturally occurring or can be produced through man-made processes:

Solar neutrinos



Atmospheric neutrinos

Geoneutrinos

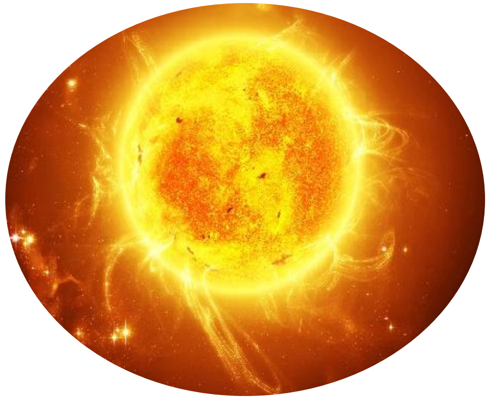


Supernova neutrinos

An understanding of their properties can help us to explain open questions in fundamental physics like the matter-antimatter asymmetry, even we can get meaningful information of their sources.

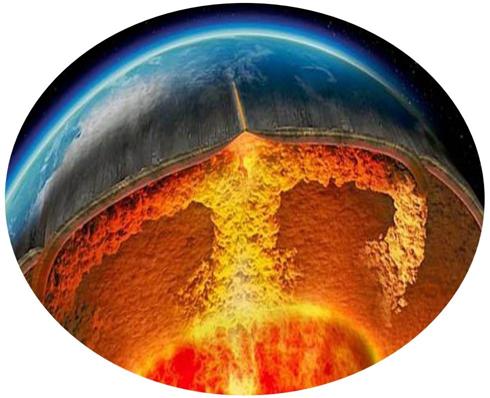
Neutrinos are naturally occurring or can be produced through man-made processes:

Solar neutrinos



Atmospheric neutrinos

Geoneutrinos



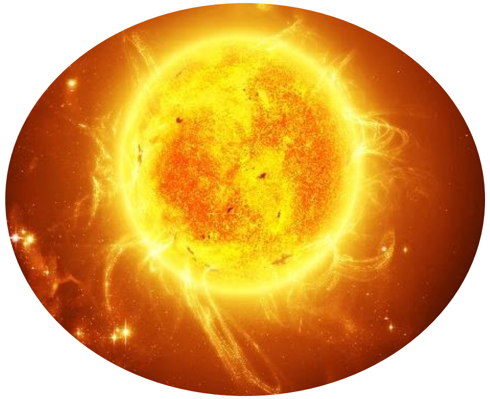
Supernova neutrinos

Reactor neutrinos

An understanding of their properties can help us to explain open questions in fundamental physics like the matter-antimatter asymmetry, even we can get meaningful information of their sources.

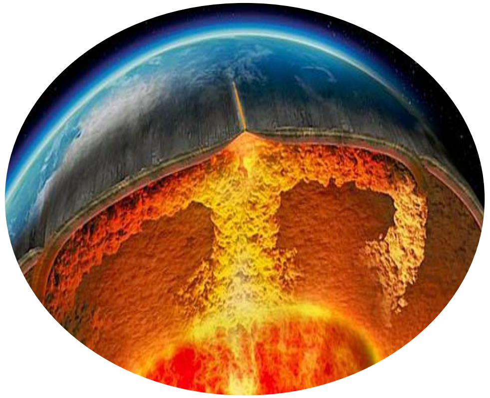
Neutrinos are naturally occurring or can be produced through man-made processes:

Solar neutrinos



Atmospheric neutrinos

Geoneutrinos

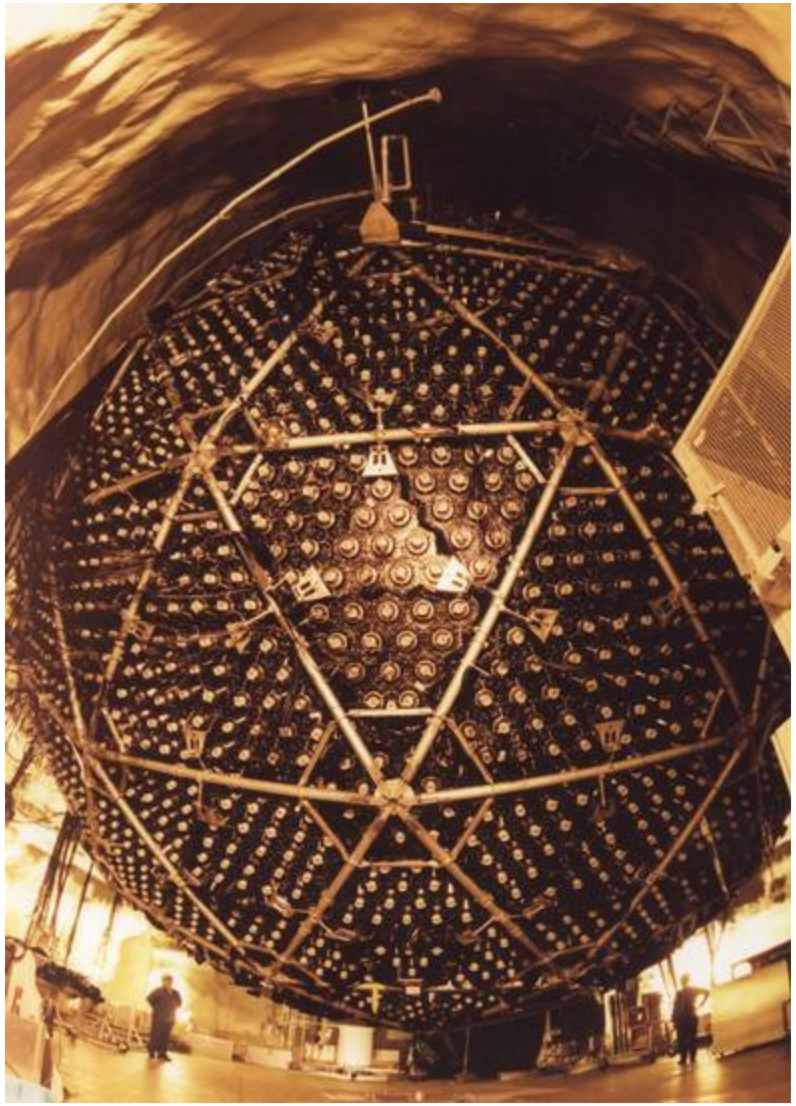


Supernova neutrinos

Reactor neutrinos

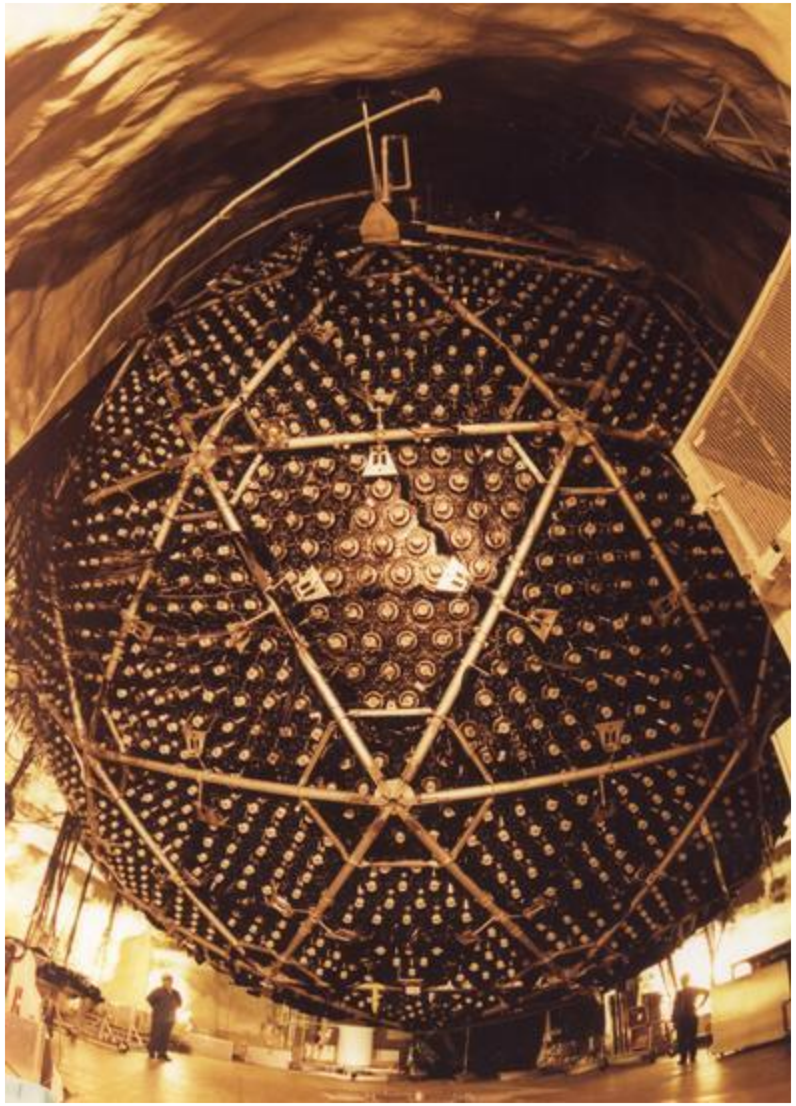
Accelerator neutrinos

The SNO+ experiment



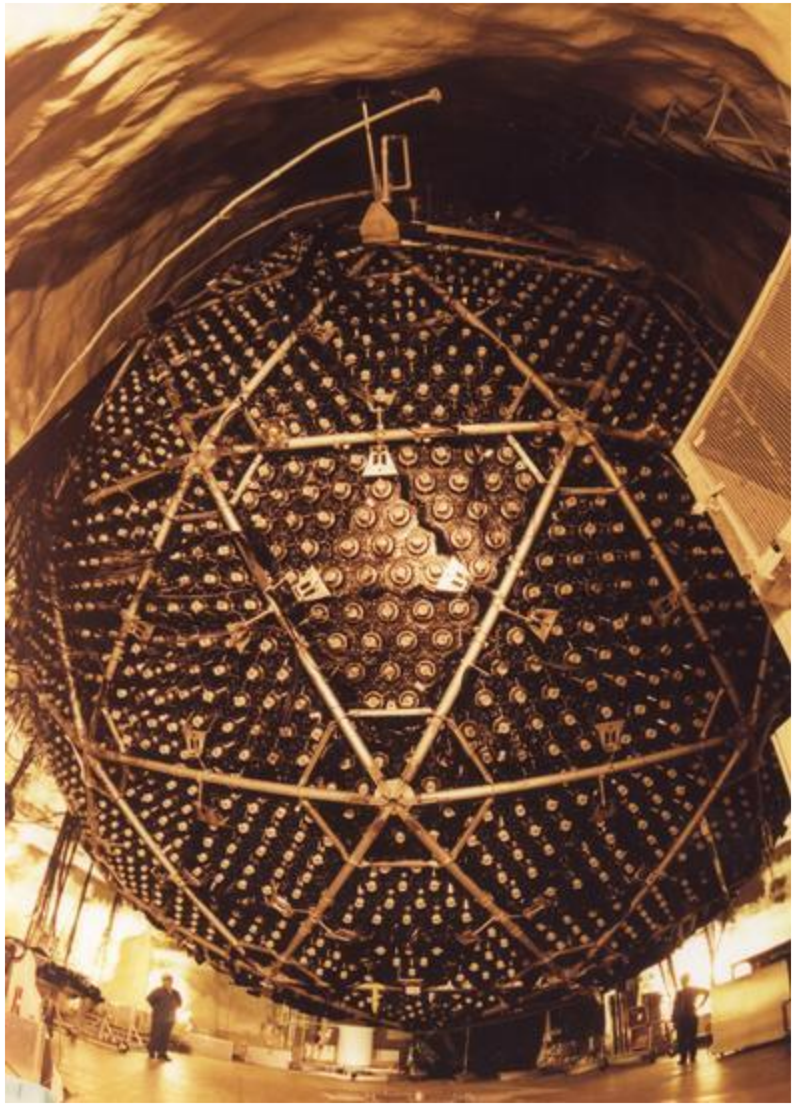
- The SNO+ experiment is a large scale neutrino experiment located at a depth of 2 km in Vale's Creighton Mine in Sudbury, Canada.

The SNO+ experiment



- The SNO+ experiment is a large scale neutrino experiment located at a depth of 2 km in Vale's Creighton Mine in Sudbury, Canada.
- Large volume and high purity of the materials.

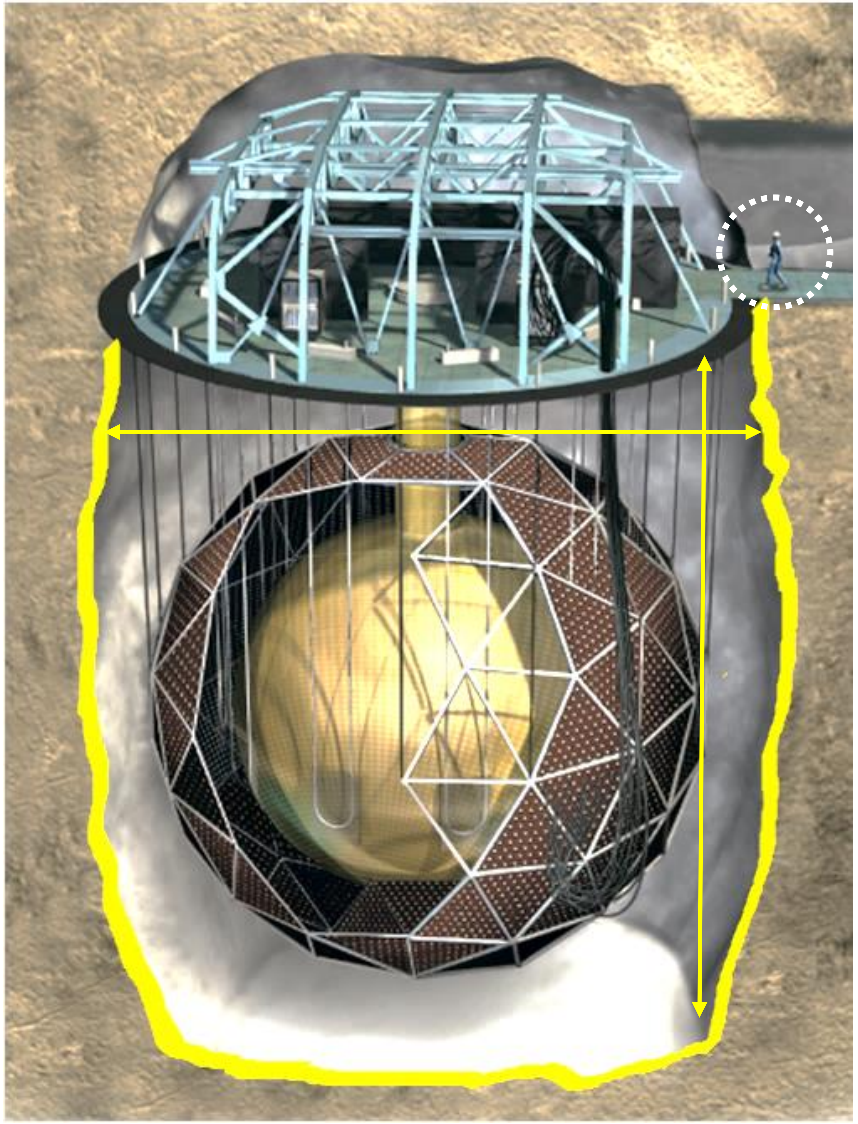
The SNO+ experiment



- The SNO+ experiment is a large scale neutrino experiment located at a depth of 2 km in Vale's Creighton Mine in Sudbury, Canada.
- Large volume and high purity of the materials.
- Physics program:
  - Search for neutrinoless double-beta decay with ^{130}Te.
  - Low energy pep and CNO solar neutrinos.
  - Geoneutrinos.
  - Reactor antineutrinos.
  - Supernova neutrinos and antineutrinos
  - Nucleon decay

The SNO+ detector

Rock cavern



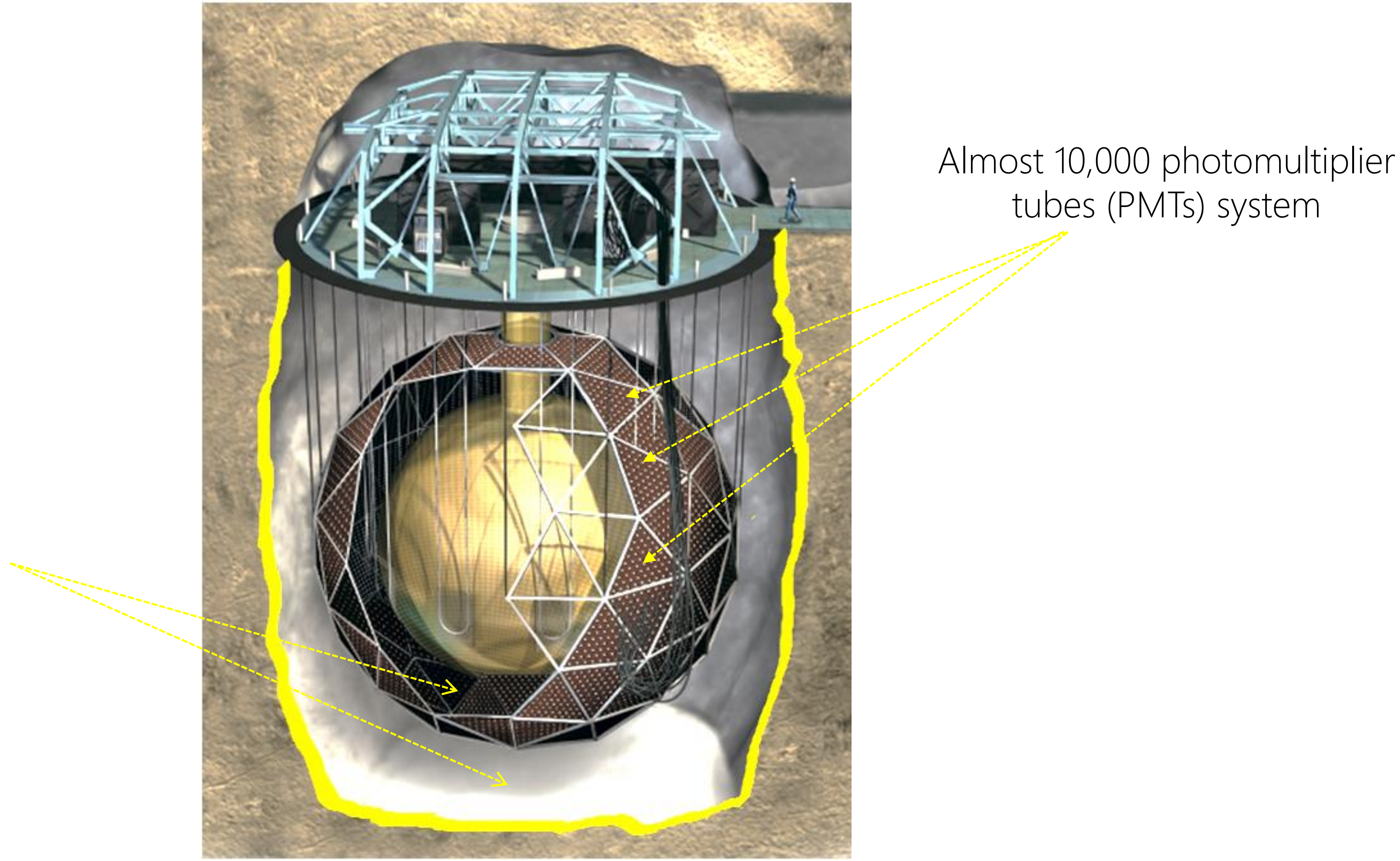
< 2 m

Diameter: 11 m

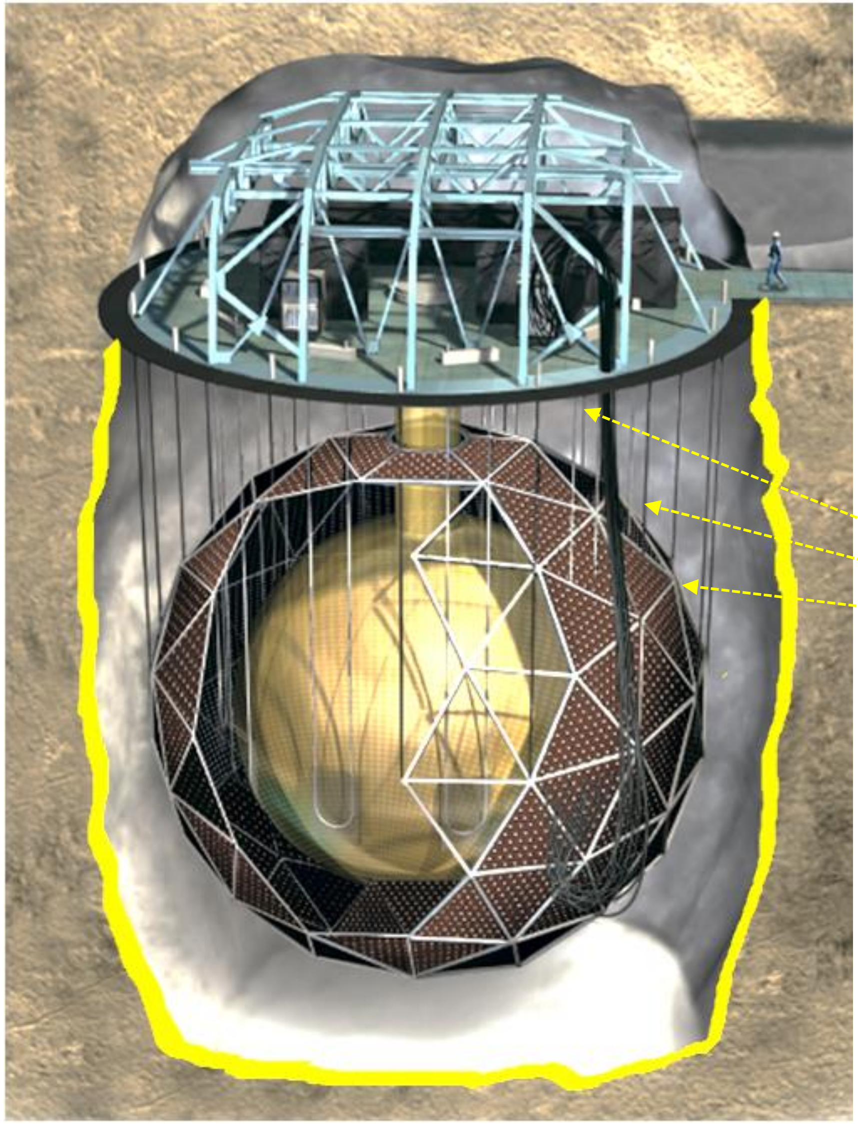
Height: 30 m

The SNO+ detector

The SNO+ detector

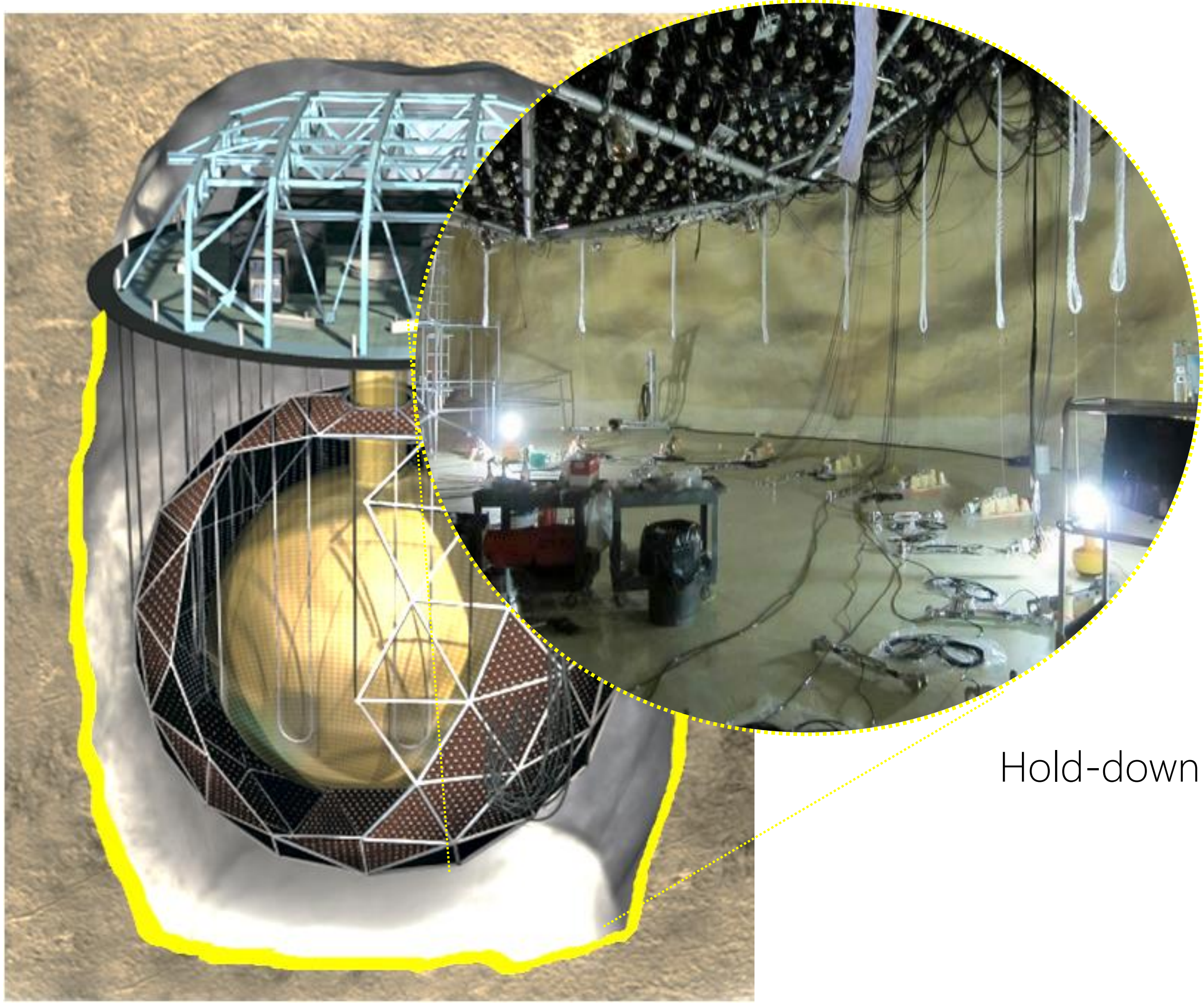


The SNO+ detector



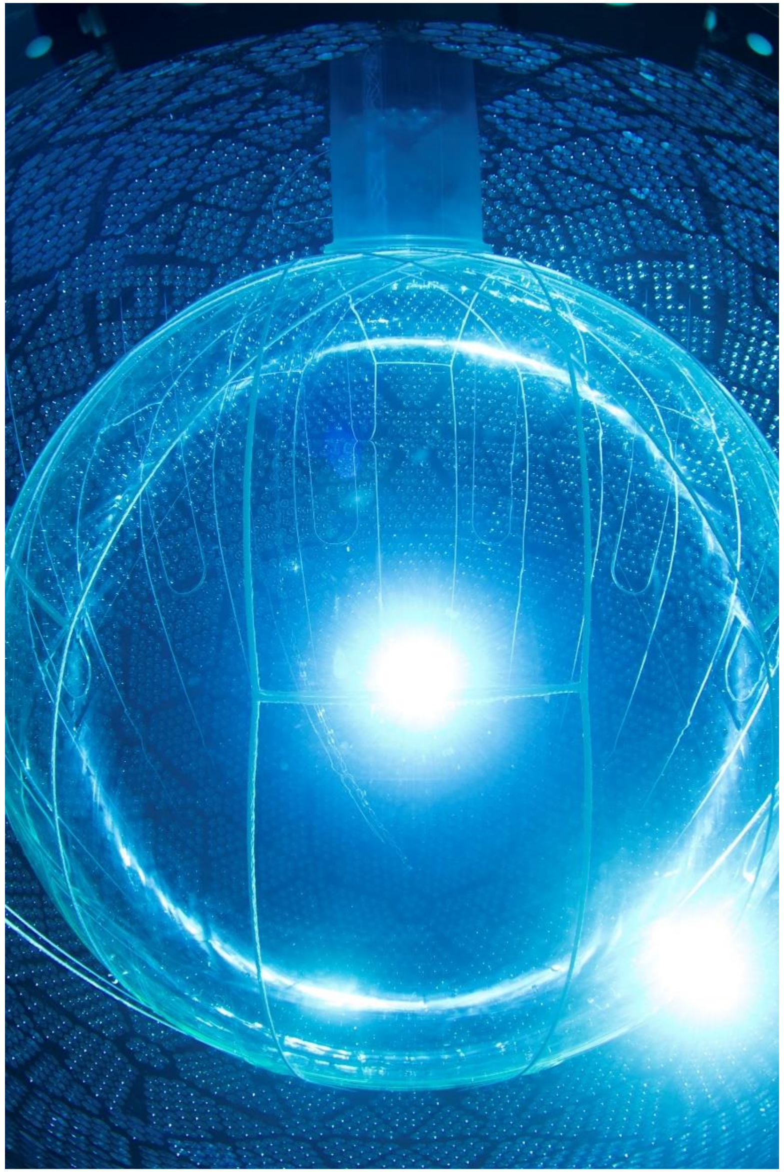
Hold-up ropes system

The SNO+ detector



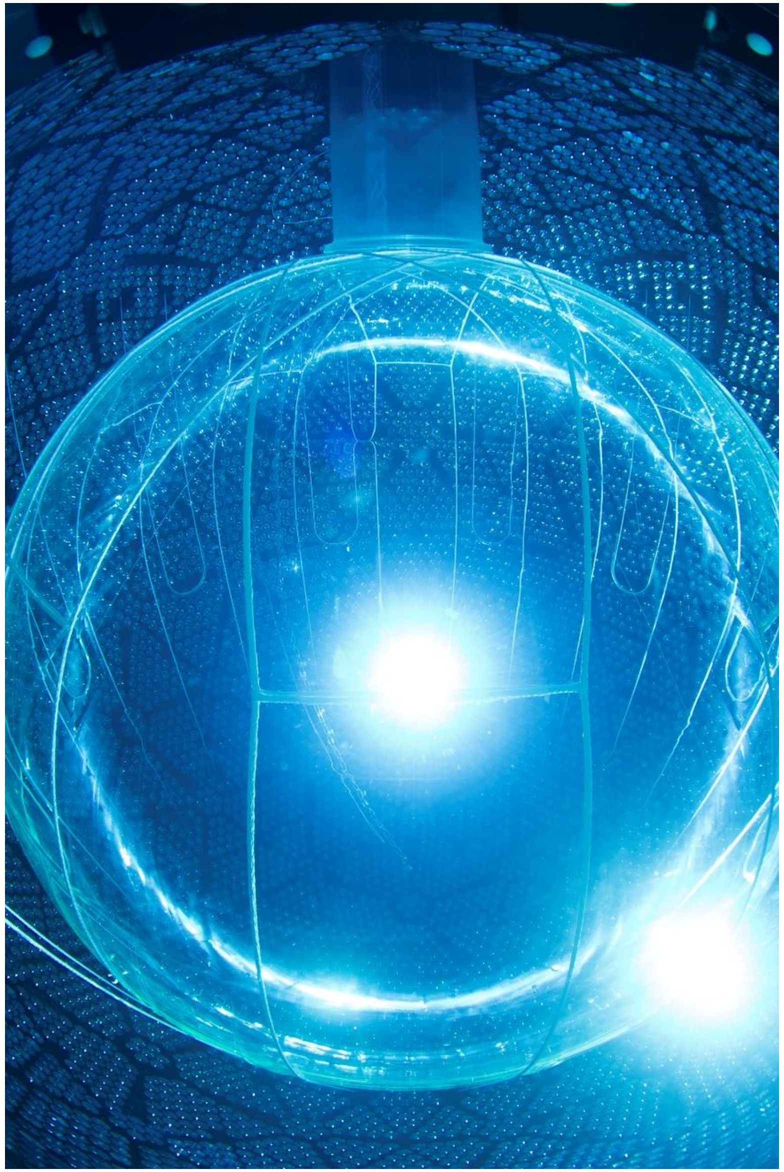
Hold-down ropes system

Run plan



The data taking period will be divided into three main phases:

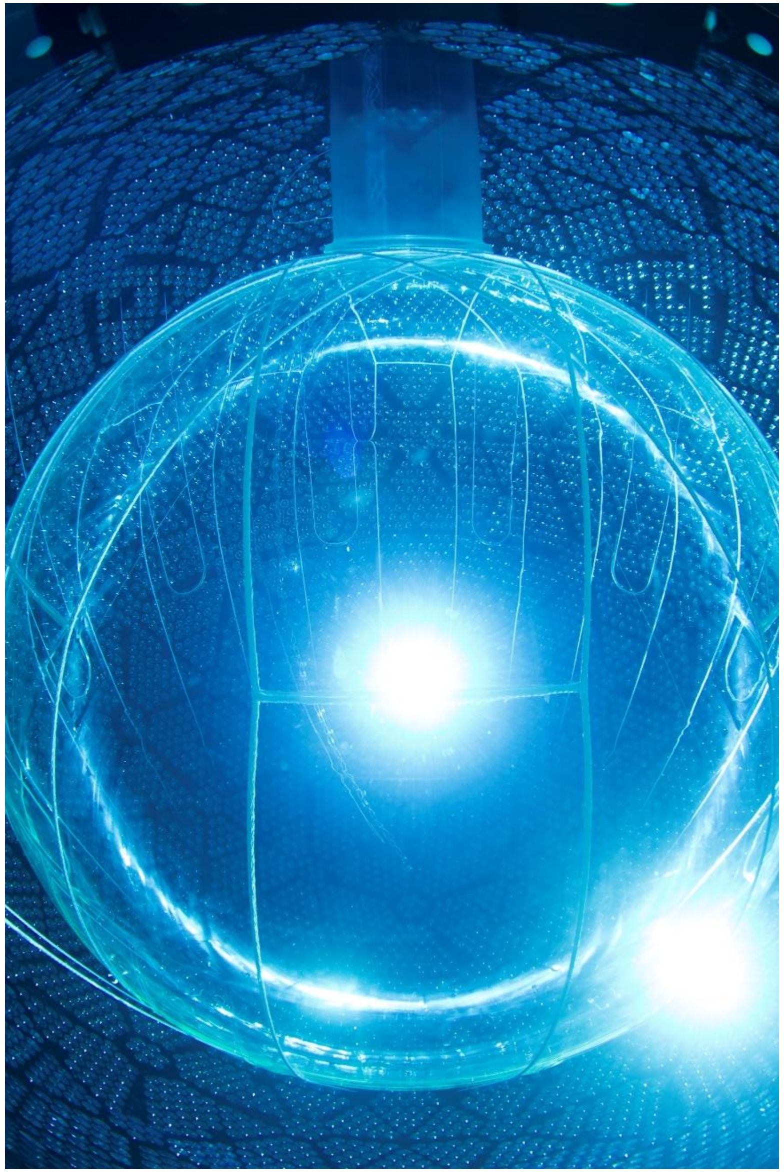
Run plan



The data taking period will be divided into three main phases:

- Water phase: The detector is filled with 905 tonnes of ultra-pure water.

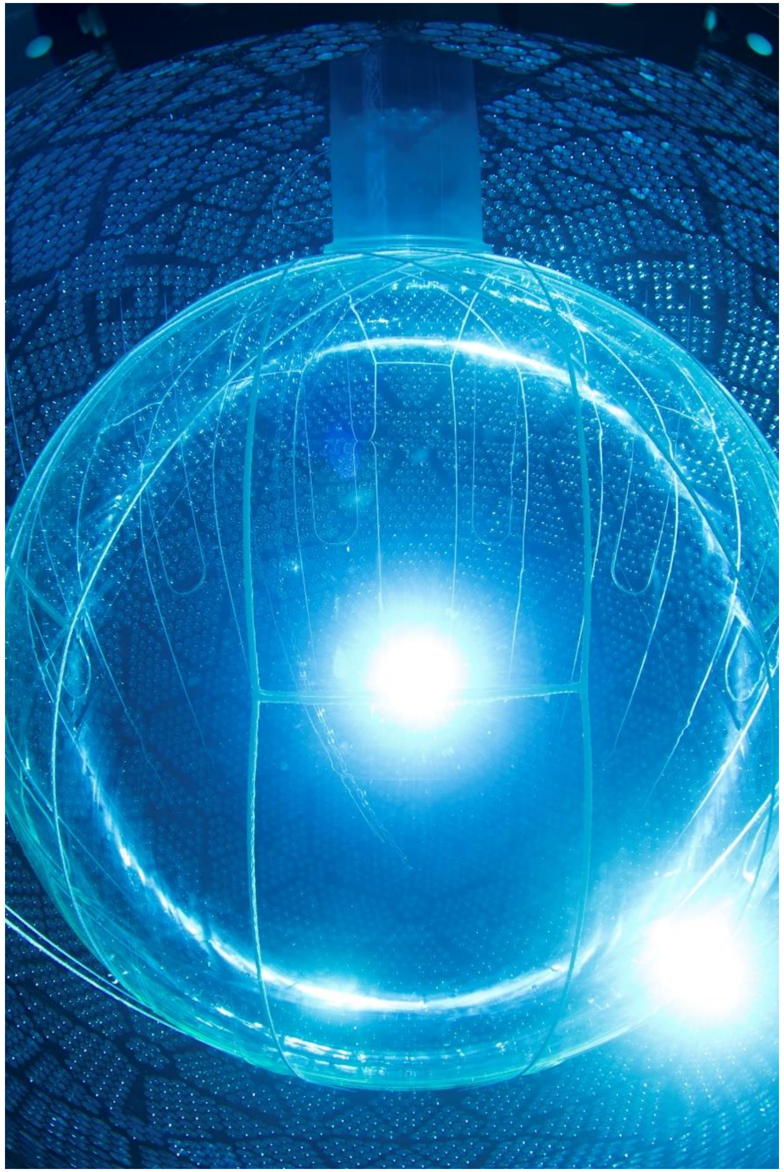
Run plan



The data taking period will be divided into three main phases:

- Water phase: The detector is filled with 905 tonnes of ultra-pure water.
- Pure scintillator phase: 780 tonnes of LAB (linear alkylbenzene)-PPO (2,5 diphenyloxazole) will be stored in the detector.

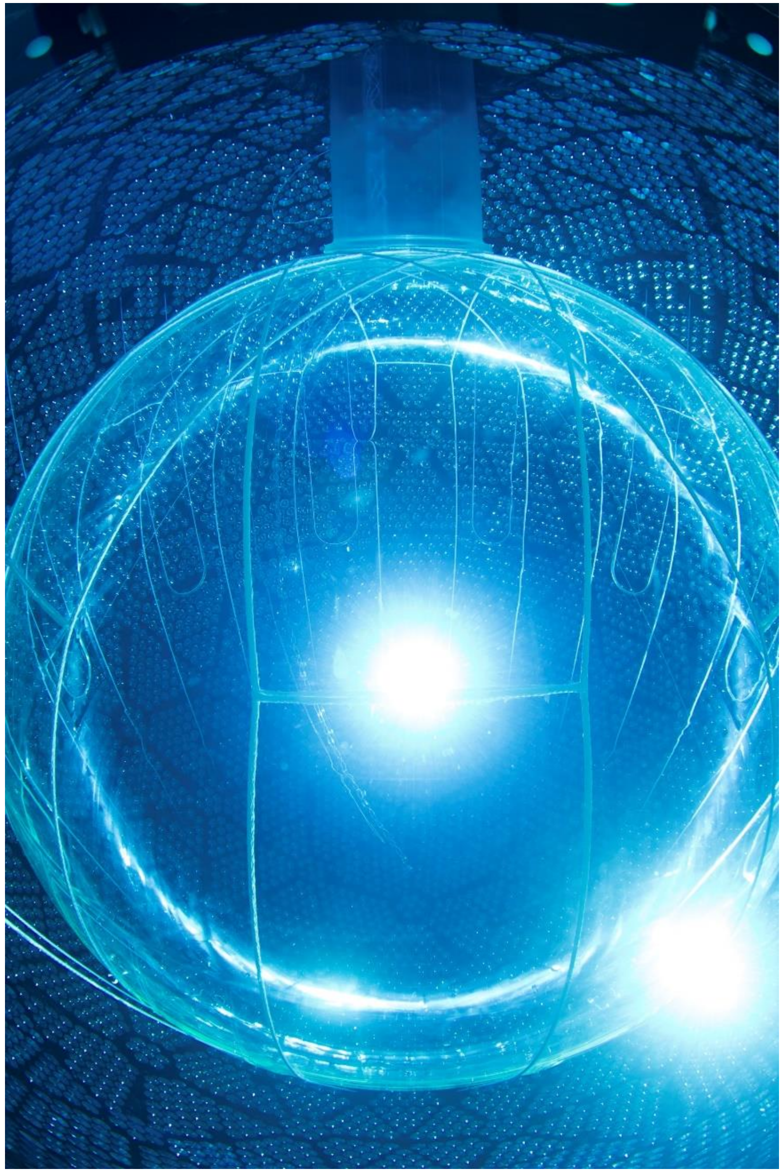
Run plan



The data taking period will be divided into three main phases:

- Water phase: The detector is filled with 905 tonnes of ultra-pure water.
- Pure scintillator phase: 780 tonnes of LAB (linear alkylbenzene)-PPO (2,5 diphenyloxazole) will be stored in the detector.
- Te-loading phase: About 2.3 tonnes of natural tellurium will be added to the scintillator for the search of neutrinoless double-beta decay.

Run plan



The data taking period will be divided into three main phases:

- Water phase: The detector is filled with 905 tonnes of ultra-pure water.
- Pure scintillator phase: 780 tonnes of LAB (linear alkylbenzene)-PPO (2,5 diphenyloxazole) will be stored in the detector.
- Te-loading phase: About 2.3 tonnes of natural tellurium will be added to the scintillator for the search of neutrinoless double-beta decay.

The SNO+ detector is currently filled with ultra pure water since March 2017

Backgrounds in the SNO+ experiment

Backgrounds can be classified by their source into two groups:

Backgrounds in the SNO+ experiment

Backgrounds can be classified by their source into two groups:

- Radioactive sources: mainly γ's from ^{238}U, ^{232}Th and ^{40}K chains.

Backgrounds in the SNO+ experiment

Backgrounds can be classified by their source into two groups:

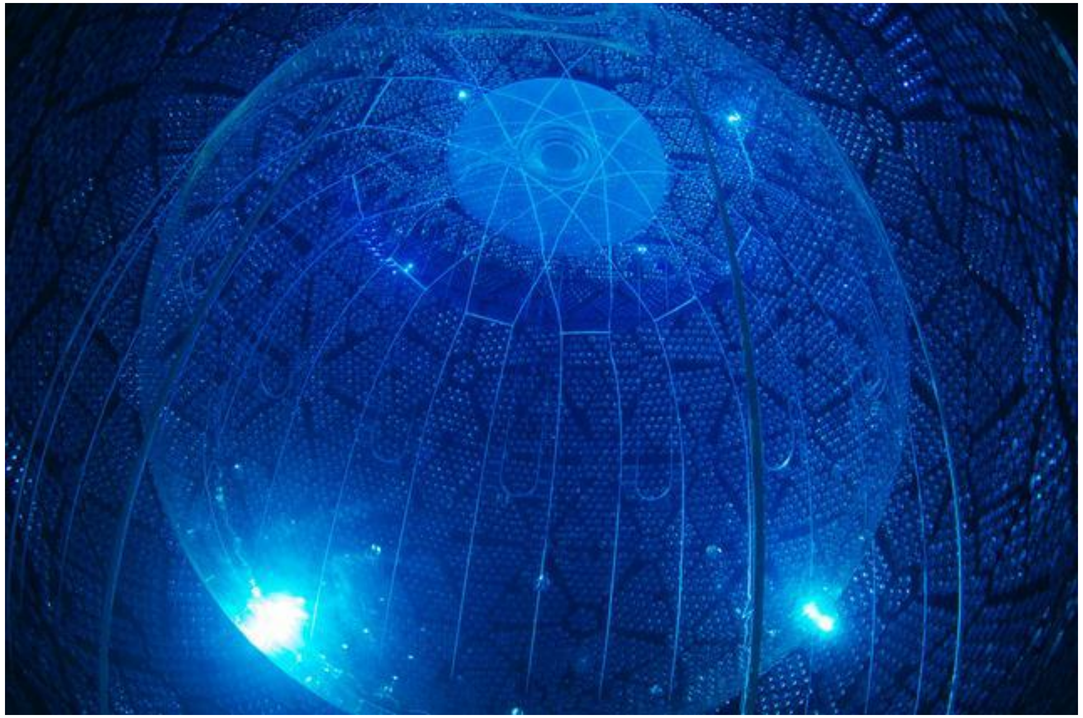
- Radioactive sources: mainly γ's from ^{238}U, ^{232}Th and ^{40}K chains.
- Cosmogenically induced backgrounds: mainly high energy muons and γ's

Backgrounds in the SNO+ experiment

Backgrounds can be classified by their source into two groups:

- Radioactive sources: mainly γ's from ^{238}U, ^{232}Th and ^{40}K chains.
- Cosmogenically induced backgrounds: mainly high energy muons and γ's

The deep underground, high purity of materials used, and water shield for the radioactivity are some of the background preventive measures in SNO+.



Neutron Backgrounds in the SNO+ experiment

Neutron backgrounds are signals in a detector induced by **neutrons**, which are produced by:

Neutron Backgrounds in the SNO+ experiment

Neutron backgrounds are signals in a detector induced by **neutrons**, which are produced by:

- Naturally occurring radioisotopes in the materials that compose the detector

Neutron Backgrounds in the SNO+ experiment

Neutron backgrounds are signals in a detector induced by **neutrons**, which are produced by:

- Naturally occurring radioisotopes in the materials that compose the detector
- High energy muons that arrive from the atmosphere from all directions.

Neutron Backgrounds in the SNO+ experiment

Neutron backgrounds are signals in a detector induced by **neutrons**, which are produced by:

- Naturally occurring radioisotopes in the materials that compose the detector
- High energy muons that arrive from the atmosphere from all directions.

The following processes are the main sources of neutrons:

- ❑ Spontaneous fission (SF). Radioactive decay of ^{238}U, ^{232}Th and ^{235}U.
- ❑ Delayed neutrons (DN). Products as a result of fission can decay by β^- emission to a highly excited state which can decay by emitting a neutron.
- ❑ (α, n) reactions. The interaction of α radiation from ^{238}U, ^{232}Th and ^{235}U chains with some lighter elements of the materials of the detector can produce neutrons with energies up to 13 MeV.

Neutron Backgrounds in the SNO+ experiment

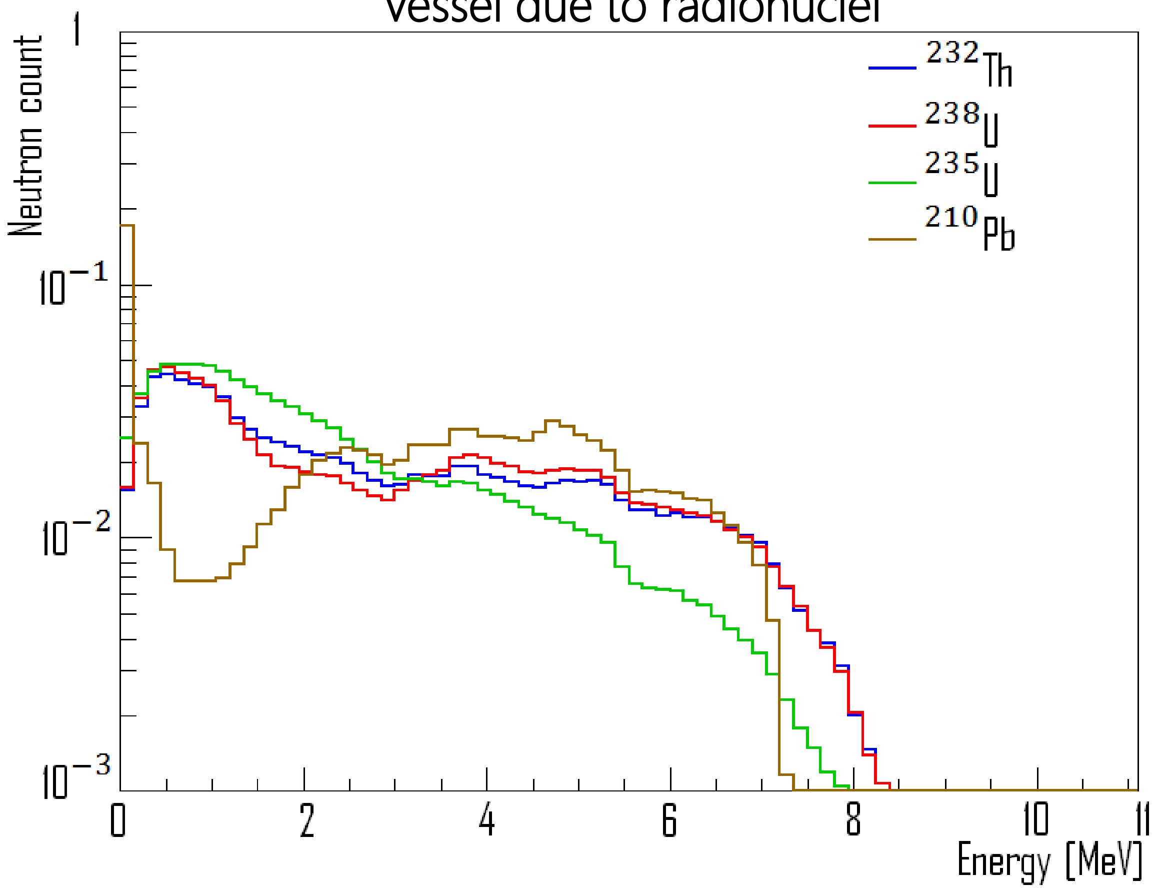
Neutron backgrounds are signals in a detector induced by **neutrons**, which are produced by:

- Naturally occurring radioisotopes in the materials that compose the detector
- High energy muons that arrive from the atmosphere from all directions.

The following processes are the main sources of neutrons:

- Spontaneous fission (SF). Radioactive decay of ^{238}U, ^{232}Th and ^{235}U.
- Delayed neutrons (DN). Products as a result of fission can decay by β^- emission to a highly excited state which can decay by emitting a neutron.
- (α, n) reactions. The interaction of α radiation from ^{238}U, ^{232}Th and ^{235}U chains with some lighter elements of the materials of the detector can produce neutrons with energies up to 13 MeV.

Energy spectrum of neutrons produced in the Acrylic Vessel due to radionuclei



Neutron Backgrounds in the SNO+ experiment

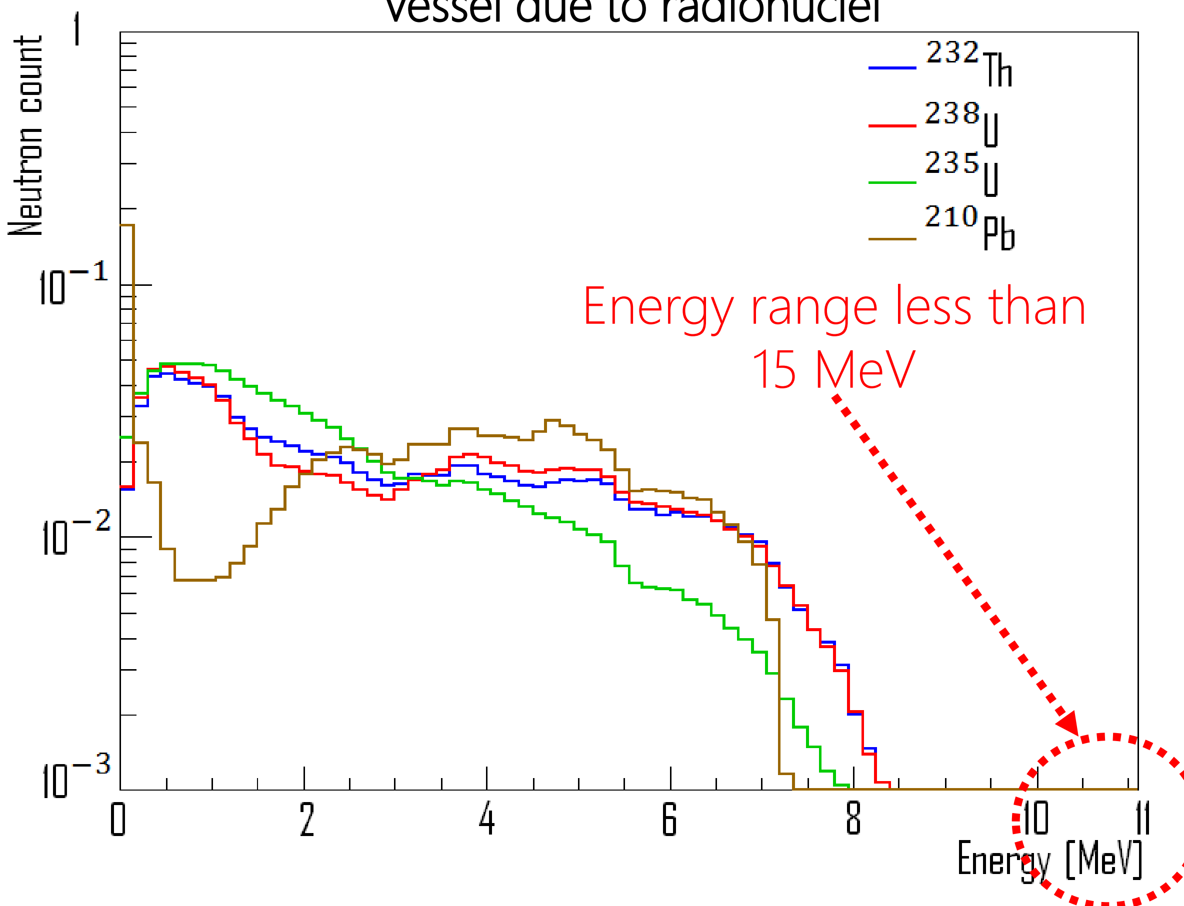
Neutron backgrounds are signals in a detector induced by **neutrons**, which are produced by:

- Naturally occurring radioisotopes in the materials that compose the detector
- High energy muons that arrive from the atmosphere from all directions.

The following processes are the main sources of neutrons:

- Spontaneous fission (SF). Radioactive decay of ^{238}U, ^{232}Th and ^{235}U.
- Delayed neutrons (DN). Products as a result of fission can decay by β^- emission to a highly excited state which can decay by emitting a neutron.
- (α, n) reactions. The interaction of α radiation from ^{238}U, ^{232}Th and ^{235}U chains with some lighter elements of the materials of the detector can produce neutrons with energies up to 13 MeV.

Energy spectrum of neutrons produced in the Acrylic Vessel due to radionuclei



Neutron Backgrounds in the SNO+ experiment

- (μ, n) reactions. An emission of high energy neutrons with energies up to 3.5 GeV is generated from the interaction of muons with nuclei of water (from the water shield) and external rock.

Neutron Backgrounds in the SNO+ experiment

- (μ, n) reactions. An emission of high energy neutrons with energies up to 3.5 GeV is generated from the interaction of muons with nuclei of water (from the water shield) and external rock.

It is well known from the SNO experiment that the cosmic muon event rate is sufficiently low, namely, **67 muons per day all over the cavity**

Neutron Backgrounds in the SNO+ experiment

- (μ, n) reactions. An emission of high energy neutrons with energies up to 3.5 GeV is generated from the interaction of muons with nuclei of water (from the water shield) and external rock.

It is well known from the SNO experiment that the cosmic muon event rate is sufficiently low, namely, 67 muons per day all over the cavity

Mei D. y Hime A. (2006). Muon-induced background study for underground laboratories. Phys. Rev., D73:053004

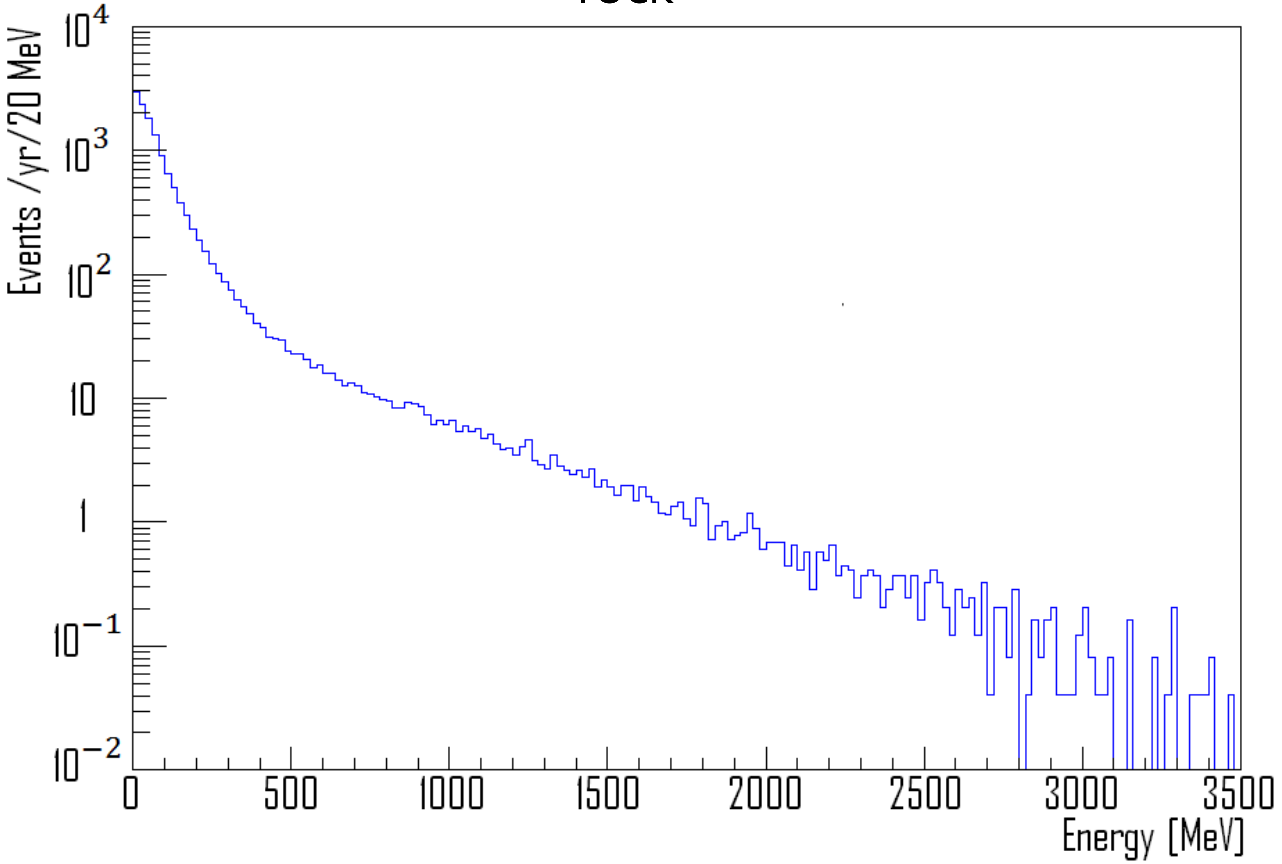
Neutron Backgrounds in the SNO+ experiment

- (μ, n) reactions. An emission of high energy neutrons with energies up to 3.5 GeV is generated from the interaction of muons with nuclei of water (from the water shield) and external rock.

It is well known from the SNO experiment that the cosmic muon event rate is sufficiently low, namely, **67 muons per day all over the cavity**

Mei D. y Hime A. (2006). Muon-induced background study for underground laboratories. Phys. Rev., D73:053004

Energy spectrum of neutrons induced by muons in the rock



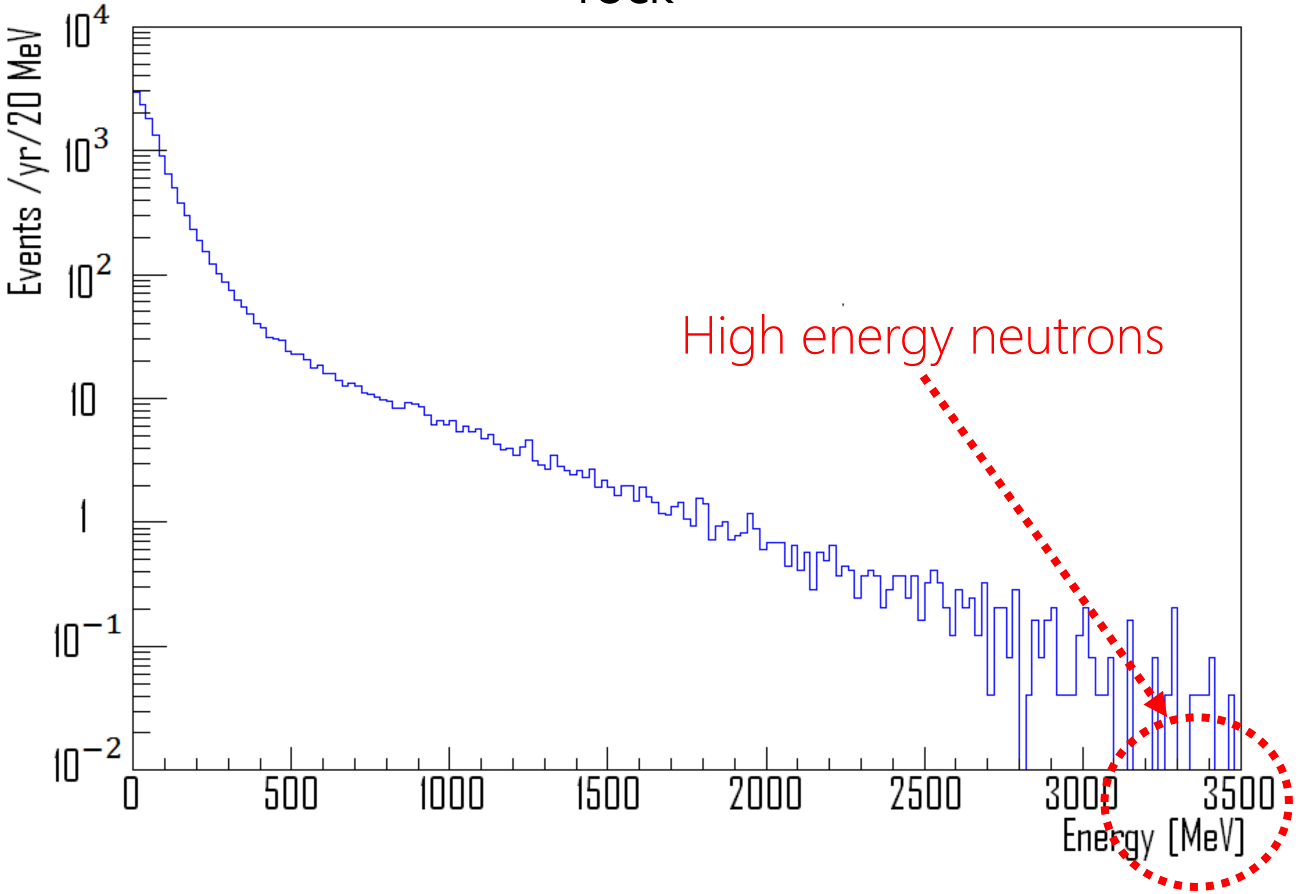
Neutron Backgrounds in the SNO+ experiment

- (μ, n) reactions. An emission of high energy neutrons with energies up to 3.5 GeV is generated from the interaction of muons with nuclei of water (from the water shield) and external rock.

It is well known from the SNO experiment that the cosmic muon event rate is sufficiently low, namely, **67 muons per day all over the cavity**

Mei D. y Hime A. (2006). Muon-induced background study for underground laboratories. Phys. Rev., D73:053004

Energy spectrum of neutrons induced by muons in the rock



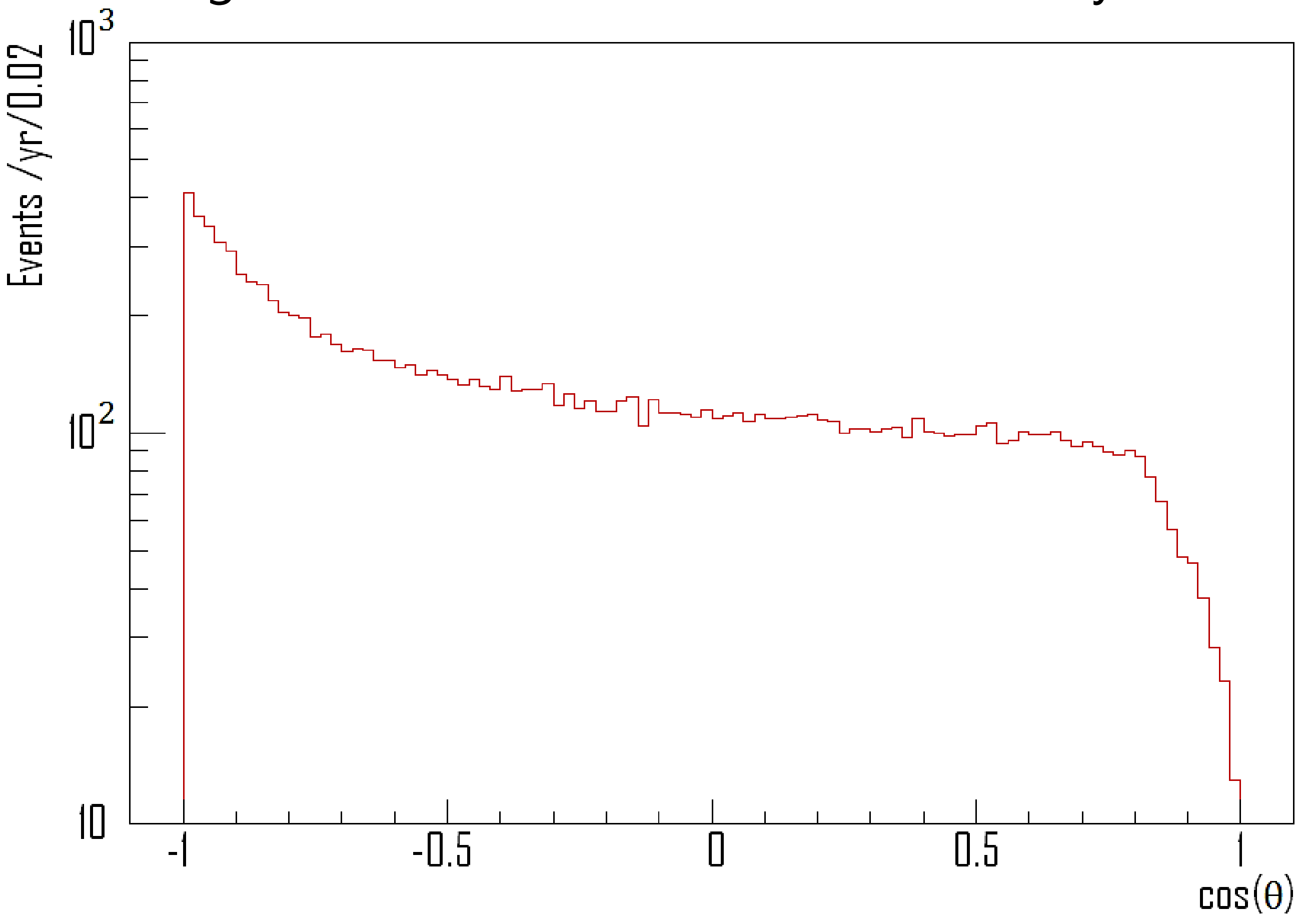
Neutron Backgrounds in the SNO+ experiment

- (μ, n) reactions. An emission of high energy neutrons with energies up to 3.5 GeV is generated from the interaction of muons with nuclei of water (from the water shield) and external rock.

It is well known from the SNO experiment that the cosmic muon event rate is sufficiently low, namely, **67 muons per day all over the cavity**

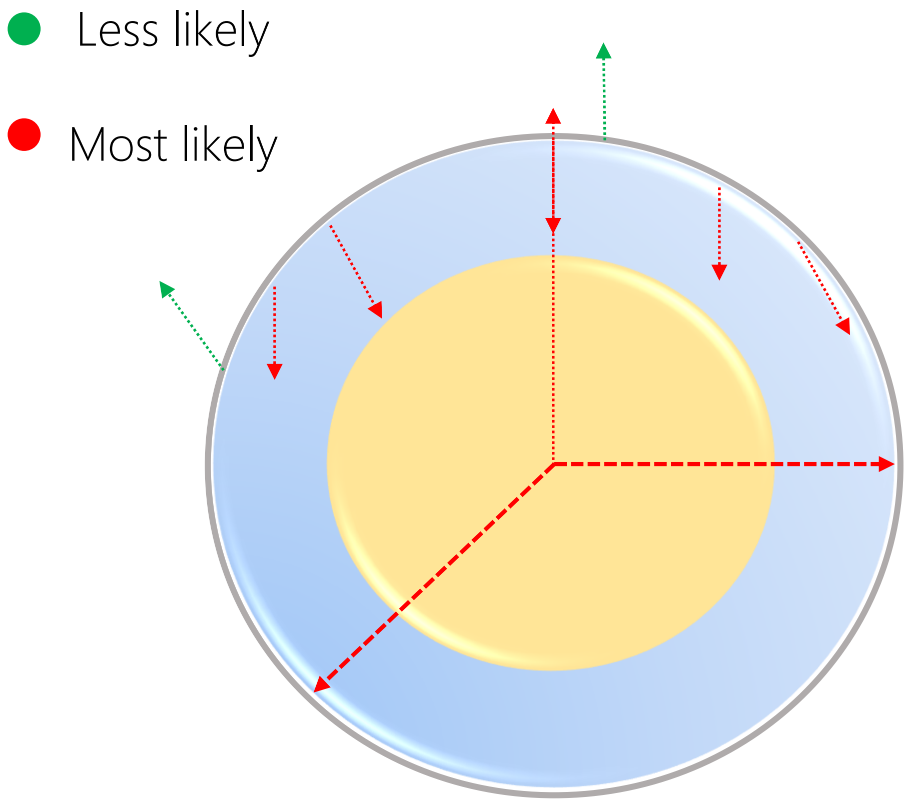
Mei D. y Hime A. (2006). Muon-induced background study for underground laboratories. Phys. Rev., D73:053004

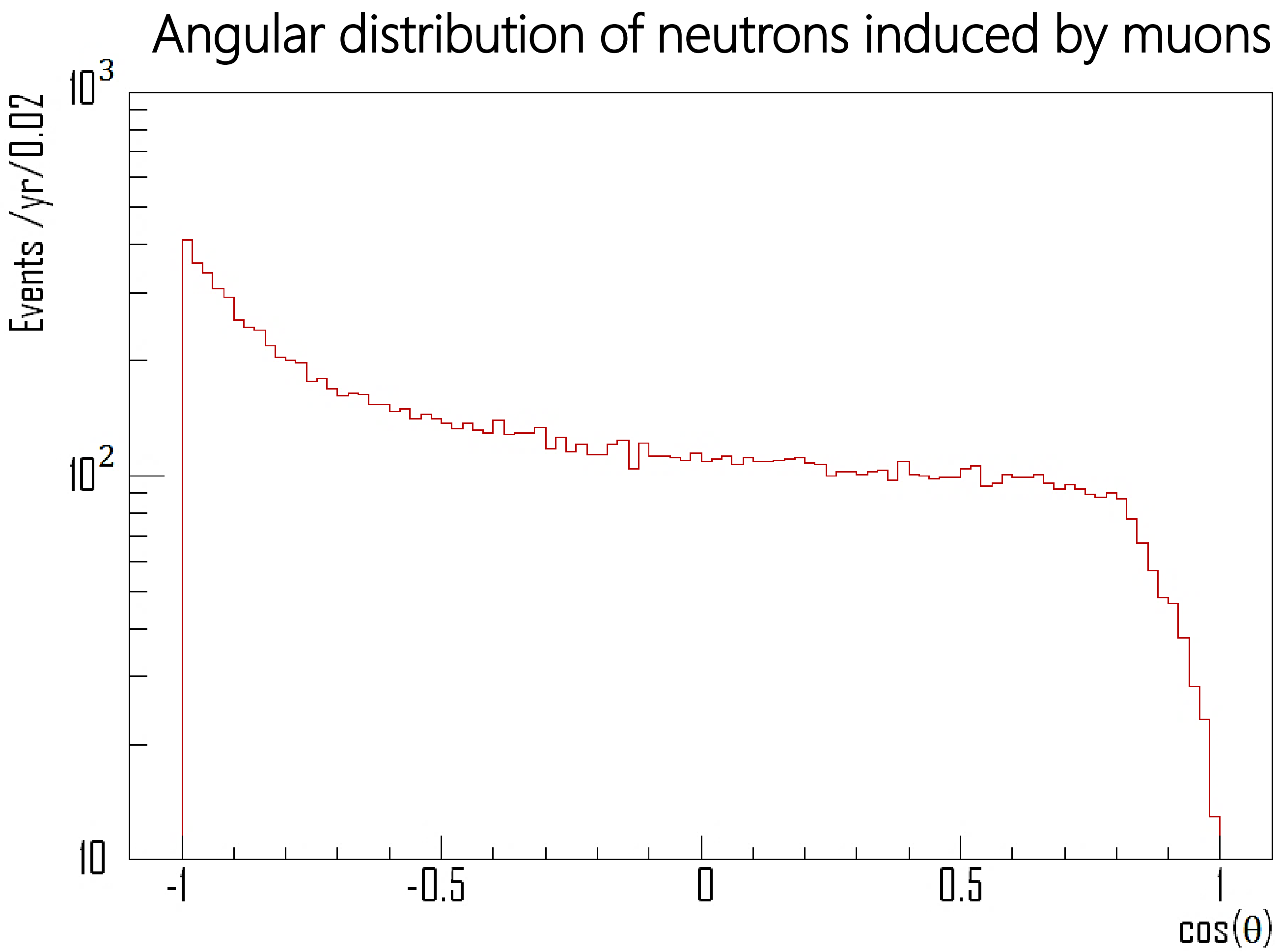
Angular distribution of neutrons induced by muons



Neutron Backgrounds in the SNO+ experiment

- (μ, n) reactions. An emission of high energy neutrons with energies up to 3.5 GeV is generated from the interaction of muons with nuclei of water (from the water shield) and external rock.

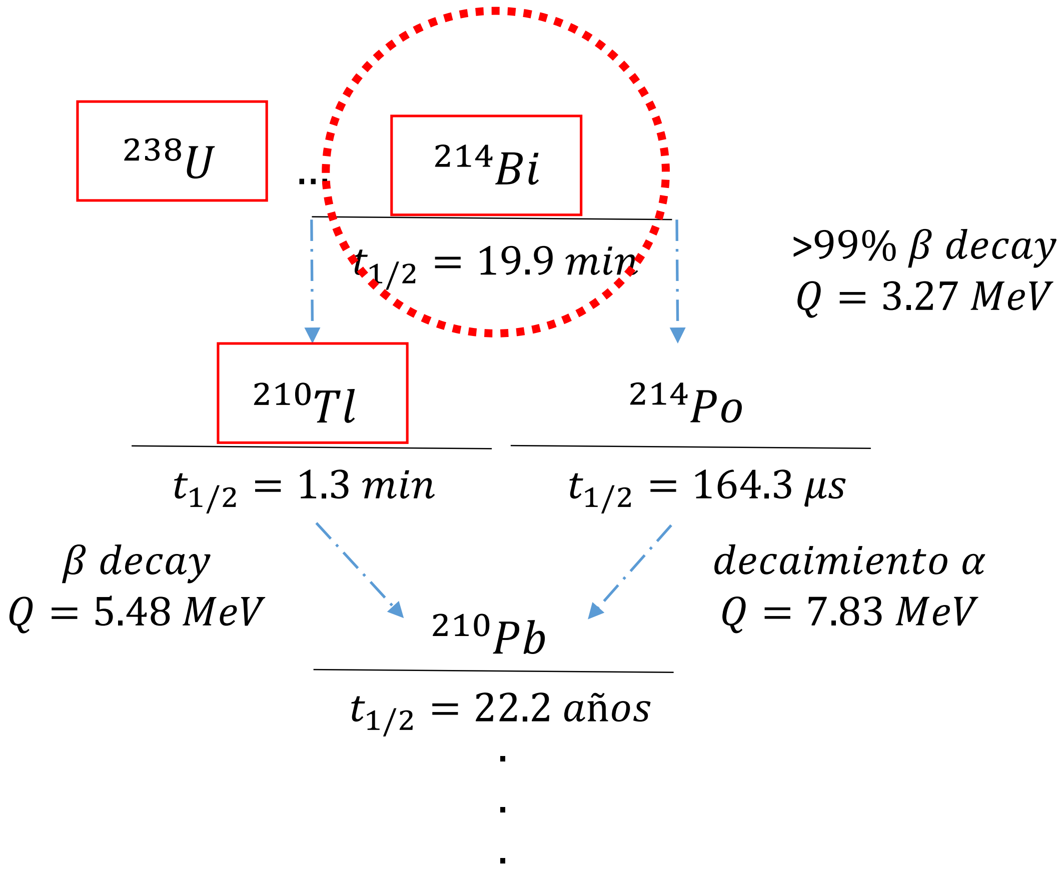




Neutron Backgrounds in SNO+ Experiment

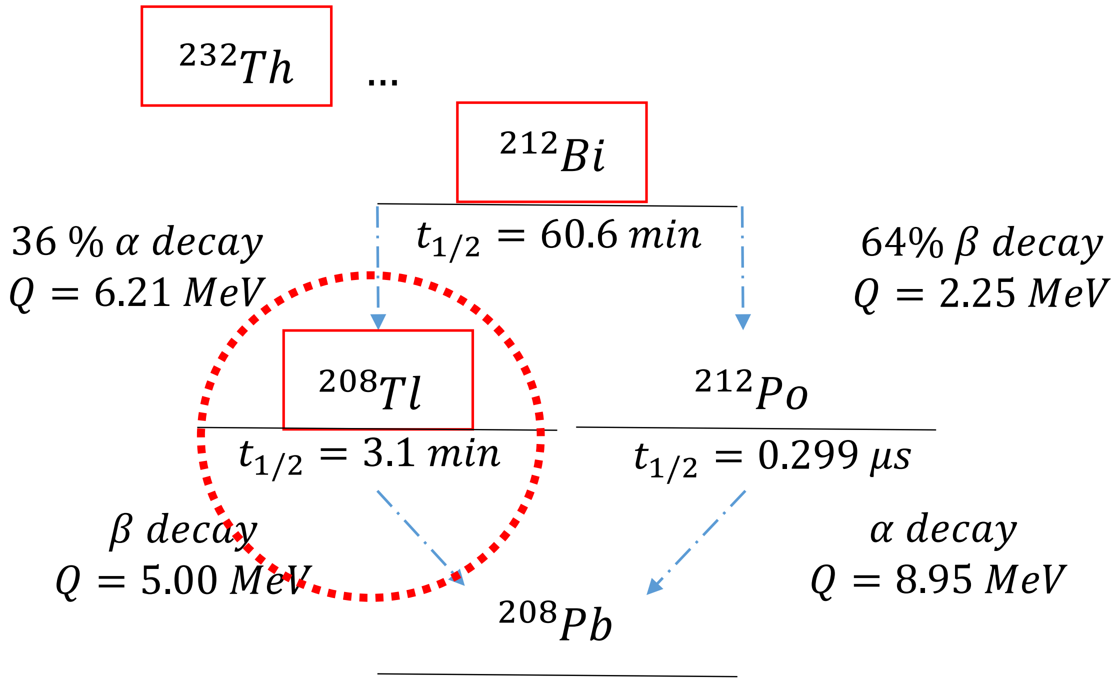
- (γ, n) reactions. Photons from decay processes in the ^{238}U, ^{232}Th radioactive chains and spallation can interact mainly with deuterium nuclei inside the detector and produce photoneutrons.

¡Photons with E > 2.2 MeV !



Neutron Backgrounds in SNO+ Experiment

- (γ, n) reactions. Photons from decay processes in the ^{238}U, ^{232}Th radioactive chains and spallation can interact mainly with deuterium nuclei inside the detector and produce photoneutrons.



¡Photons with $E = 2.614$ MeV !

Monte Carlo simulations of neutron backgrounds

A Monte Carlo simulation of neutrons from the components of the detector requires the following **input parameters**:

Monte Carlo simulations of neutron backgrounds

A Monte Carlo simulation of neutrons from the components of the detector requires the following **input parameters**:

Neutron yield and energy spectrum from:

- ❑ Spontaneous fission (SF)
- ❑ Delayed neutrons (DN)
- ❑ (α, n) reactions

Monte Carlo simulations of neutron backgrounds

A Monte Carlo simulation of neutrons from the components of the detector requires the following **input parameters**:

Neutron yield and energy spectrum from:

- Spontaneous fission (SF)
- Delayed neutrons (DN)
- (α, n) reactions

- (μ, n) reactions

Known neutron flux and energy spectrum from muon interactions with rock.

Monte Carlo simulations of neutron backgrounds

A Monte Carlo simulation of neutrons from the components of the detector requires the following **input parameters**:

Neutron yield and energy spectrum from:

- ❑ Spontaneous fission (SF)
- ❑ Delayed neutrons (DN)
- ❑ (α, n) reactions

❑ (μ, n) reactions

Known neutron flux and energy spectrum from muon interactions with rock.

❑ (γ, n) reactions

Known γ flux, energy spectrum and (γ, n) cross sections for different isotopes that compose the detector.

Monte Carlo simulations of neutron backgrounds

A Monte Carlo simulation of neutrons from the components of the detector requires the following **input parameters**:

Neutron yield and energy spectrum from:

- ❑ Spontaneous fission (SF)
- ❑ Delayed neutrons (DN)
- ❑ (α, n) reactions

❑ (μ, n) reactions

Known neutron flux and energy spectrum from muon interactions with rock.

❑ (γ, n) reactions

Known γ flux, energy spectrum and (γ, n) cross sections for different isotopes that compose the detector.

On the other hand, **RAT (Reactor Analysis Tool)** is the Monte Carlo tool of the SNO+ Collaboration, it reproduces the geometry of the detector and the interaction of particles with the detection media (using libraries from **GEANT4**).

Data analysis from the simulations

A specific region of energy (region of interest, ROI) is relevant for each data phase, in addition a fiducial cut was implemented in order to optimize the events of interest over the background signals.

Data analysis from the simulations

A specific region of energy (region of interest, **ROI**) is relevant for each data phase, in addition a fiducial cut was implemented in order to optimize the events of interest over the background signals.

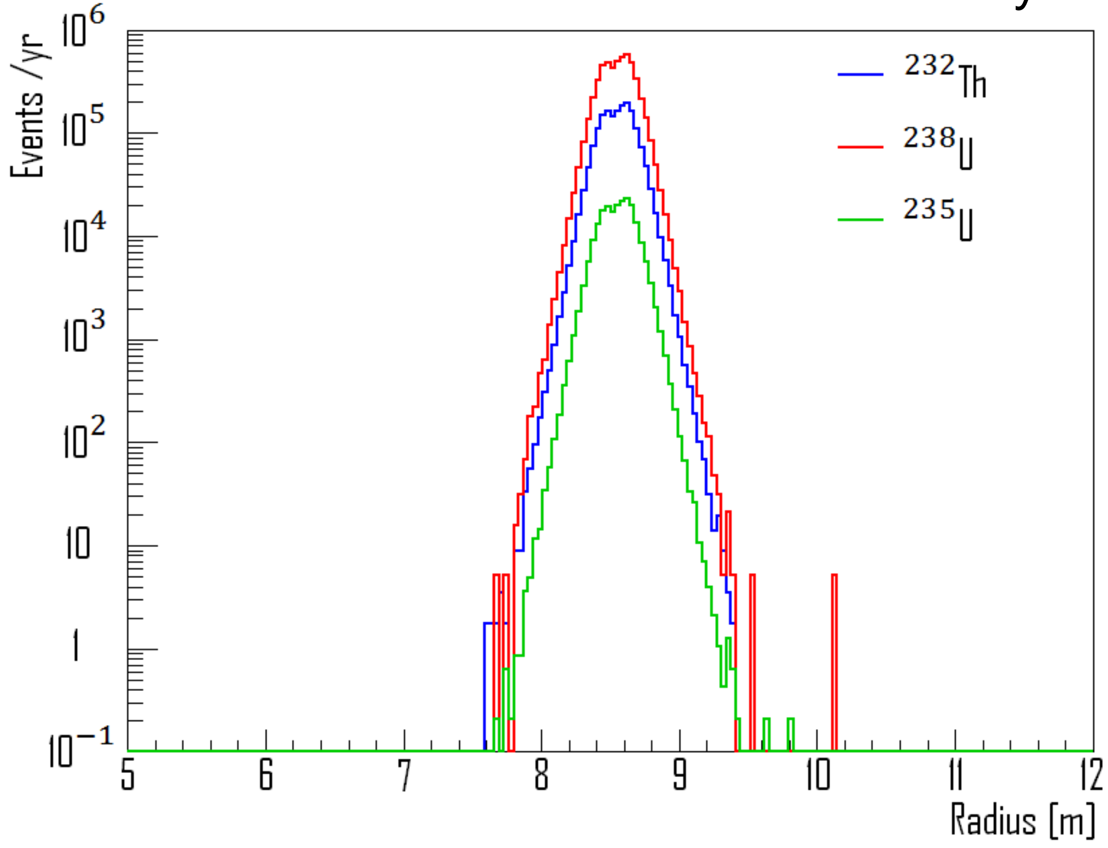
The results of the neutron simulations inside the detector are histograms of **the reconstruted energy of the neutron-induced events (photons)** and their **radial distribution relative to the AV (acrylic vessel) center.**

Data analysis from the simulations

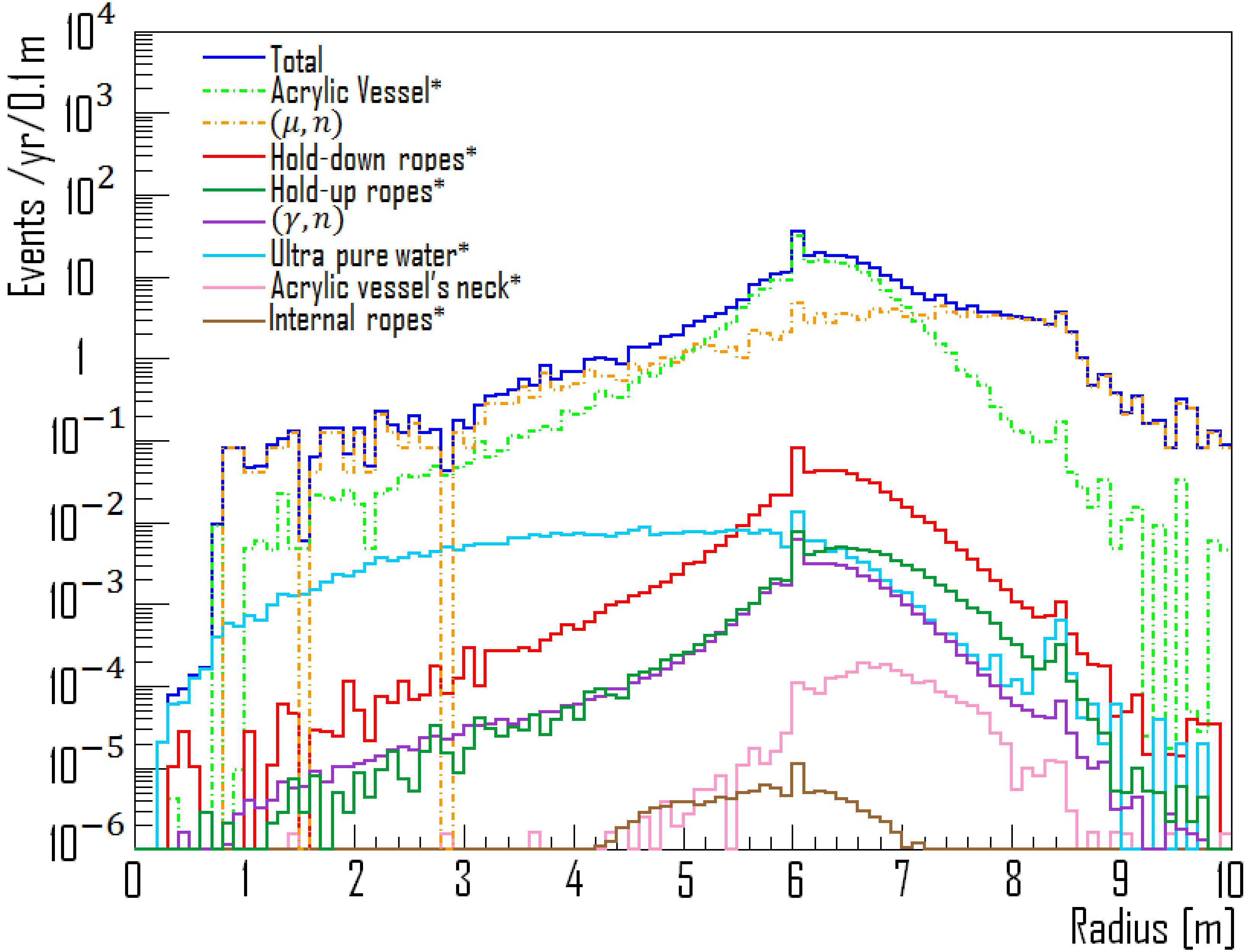
A specific region of energy (region of interest, **ROI**) is relevant for each data phase, in addition a fiducial cut was implemented in order to optimize the events of interest over the background signals.

The results of the neutron simulations inside the detector are histograms of **the reconstruted energy of the neutron-induced events (photons)** and their **radial distribution relative to the AV (acrylic vessel) center.**

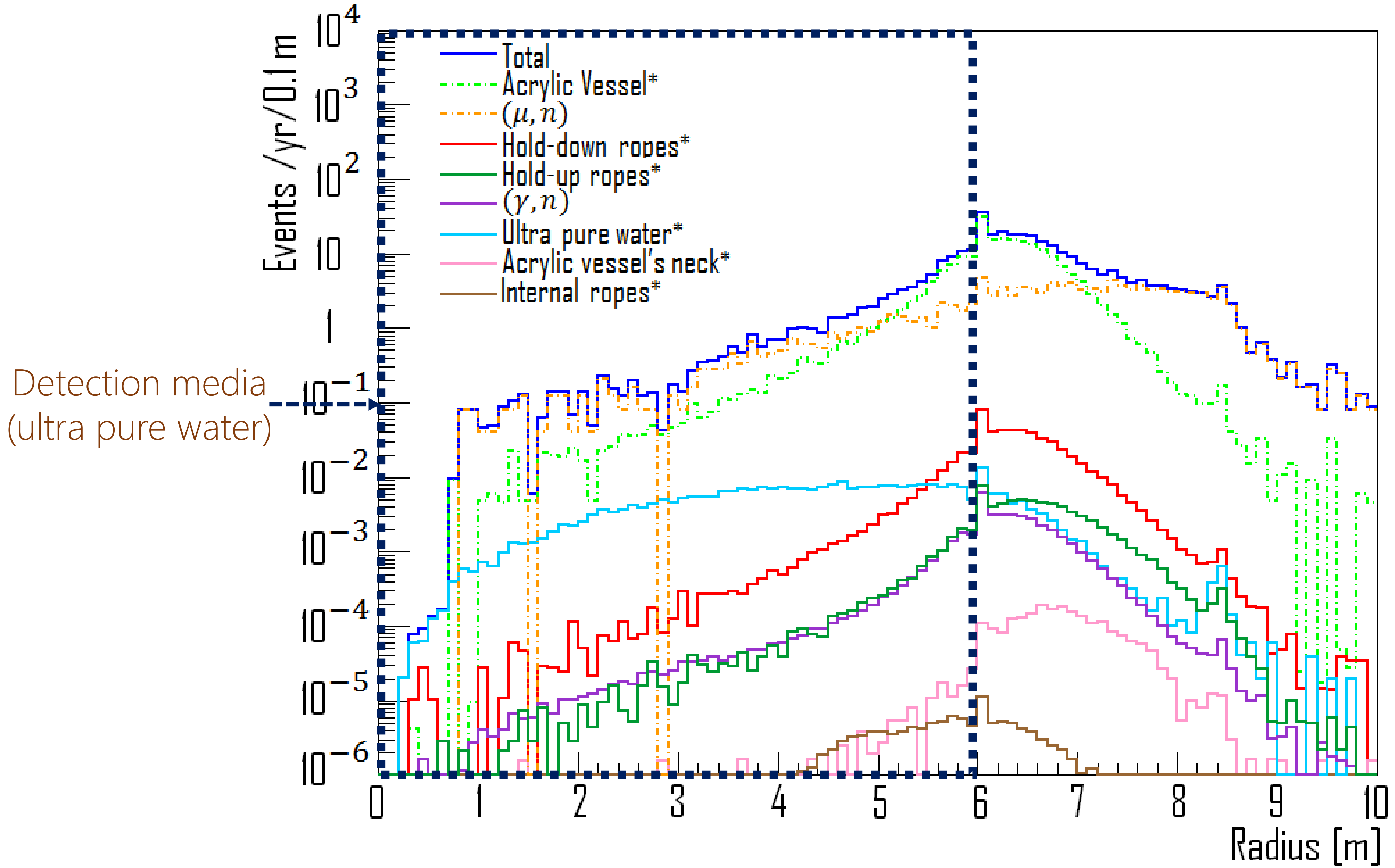
Radial distribution of neutrons from the PMT system



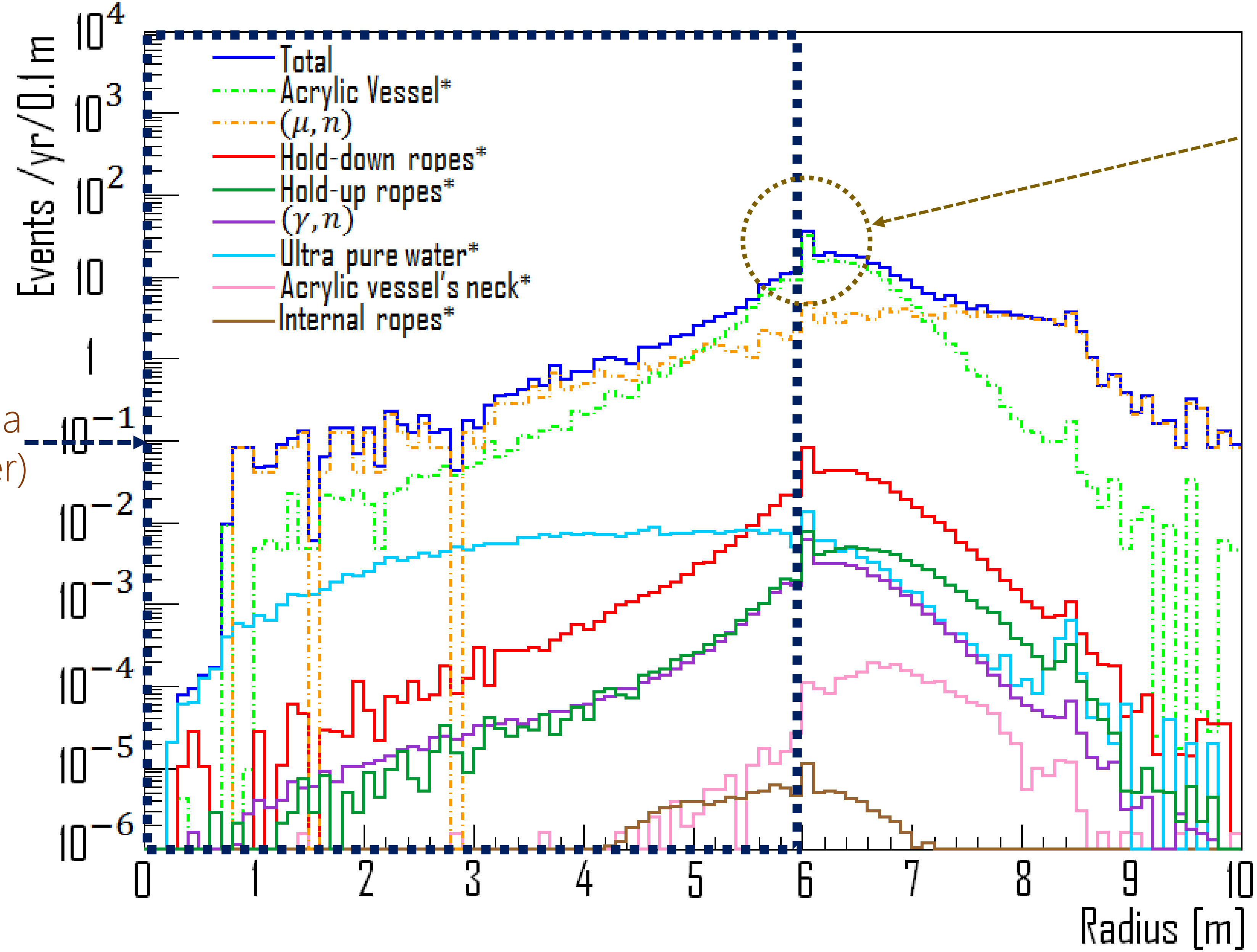
Radial distribution of neutron-induced events during the water phase



Radial distribution of neutron-induced events during the water phase



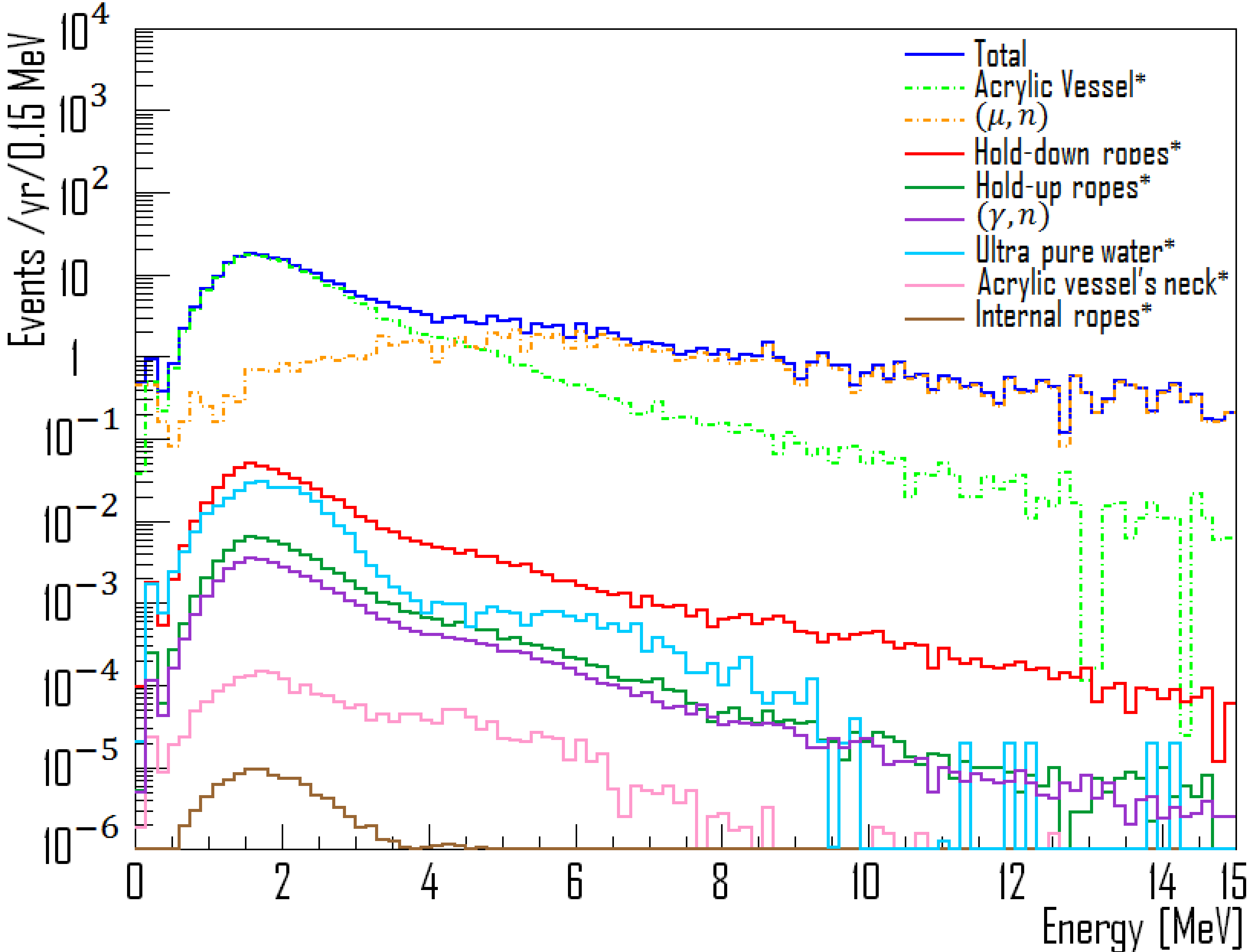
Radial distribution of neutron-induced events during the water phase



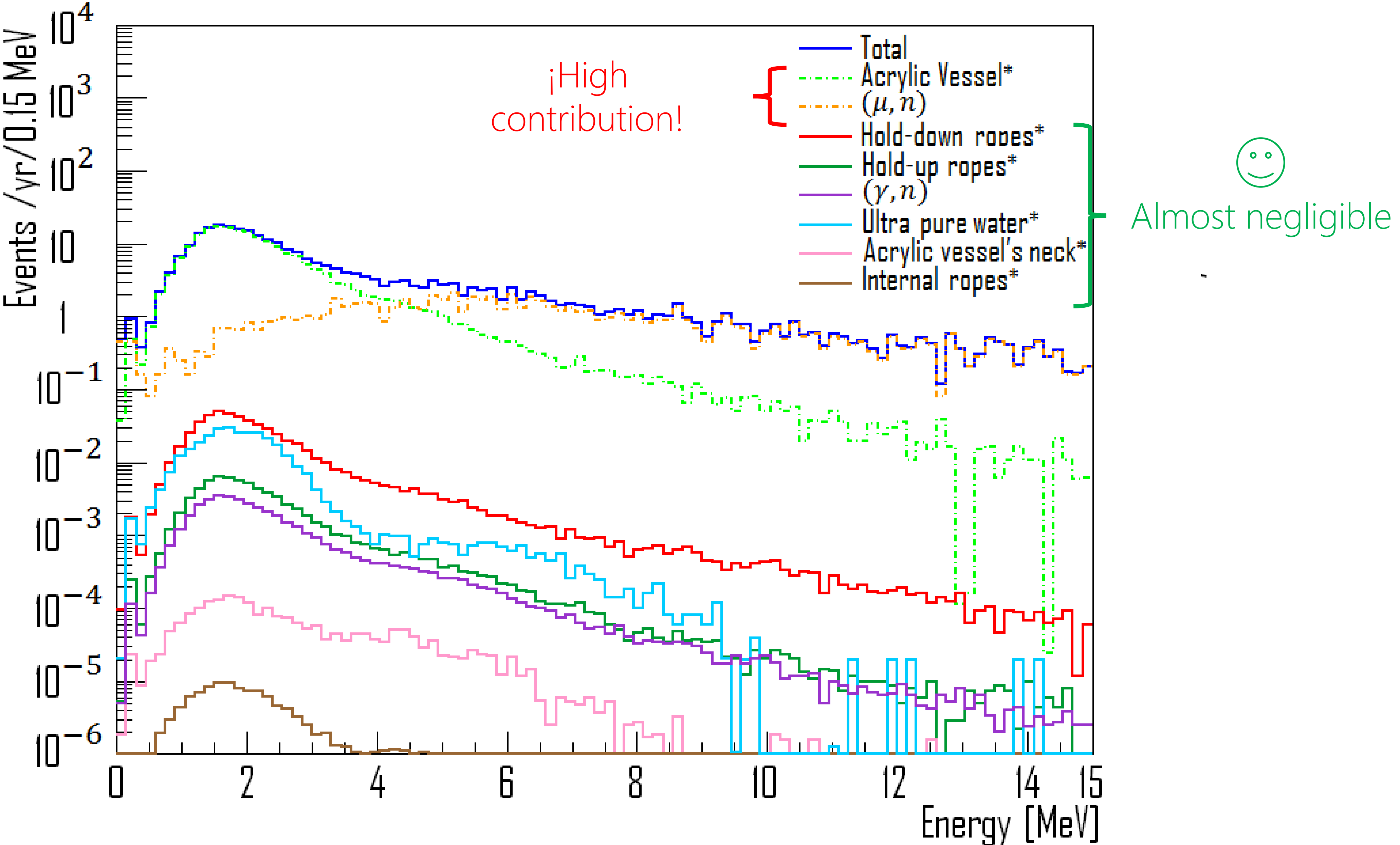
Detection media (ultra pure water)

Most of the events at the boundary between the AV and the water shield

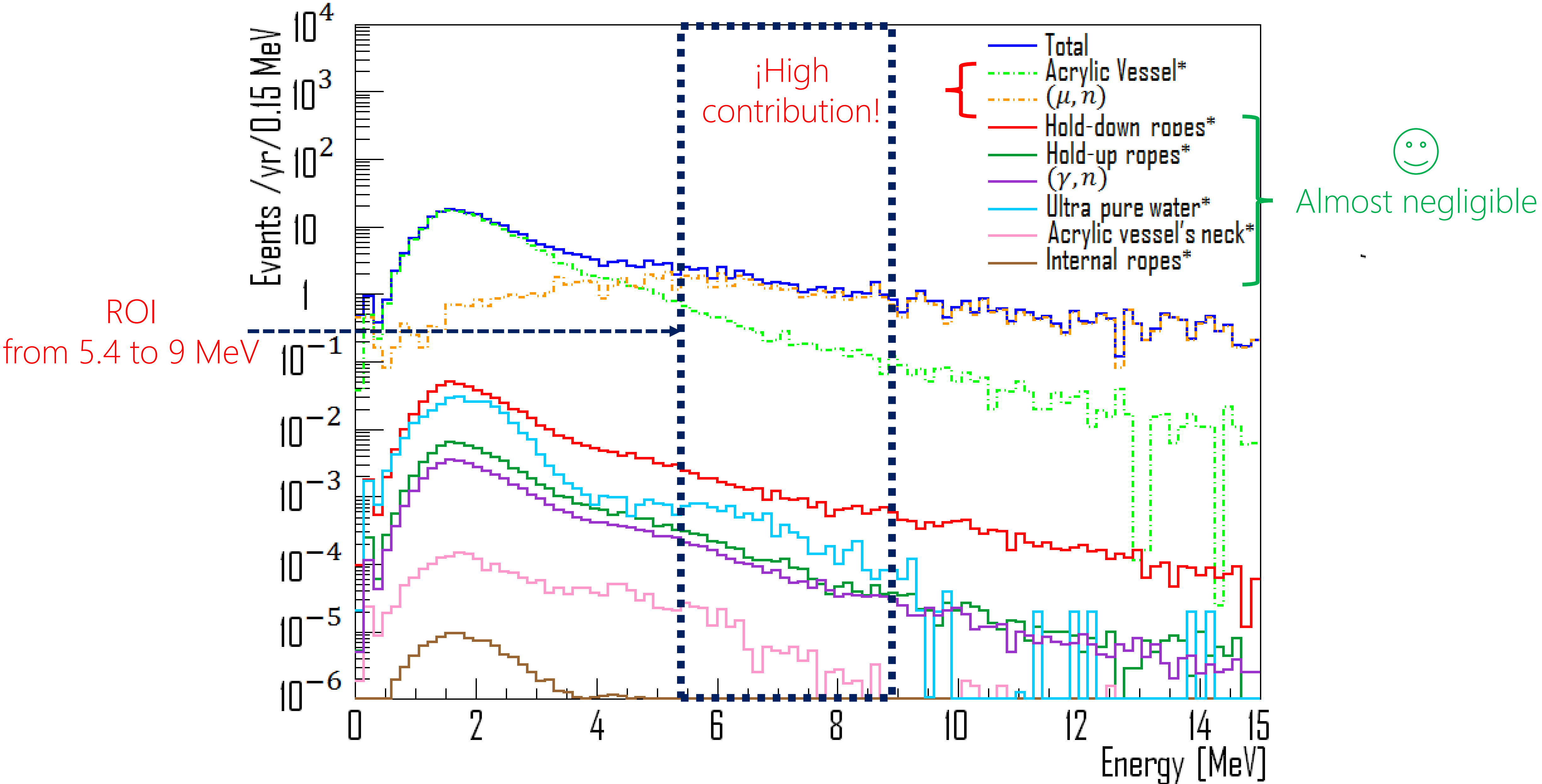
Energy spectrum during the water phase



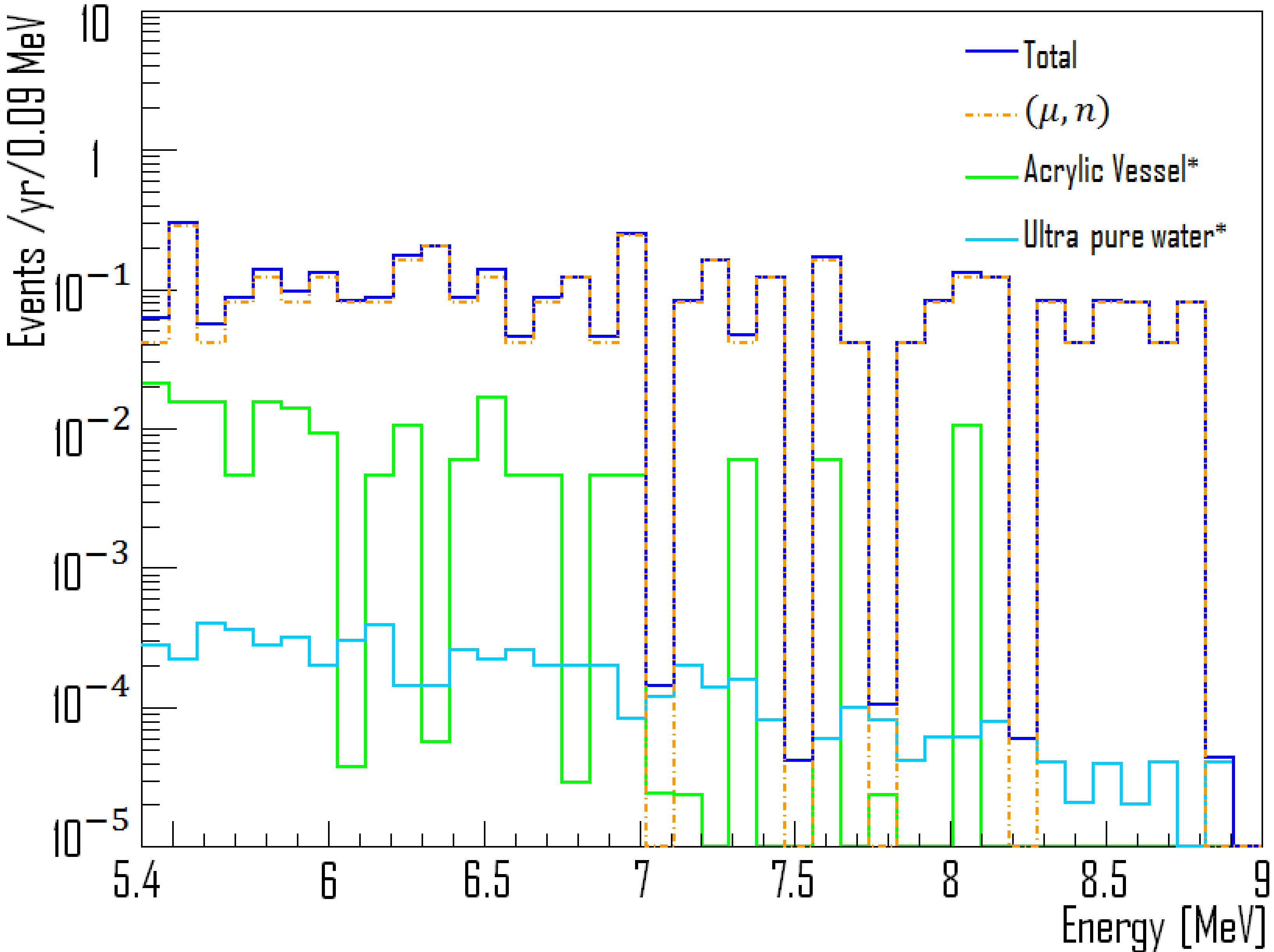
Energy spectrum during the water phase



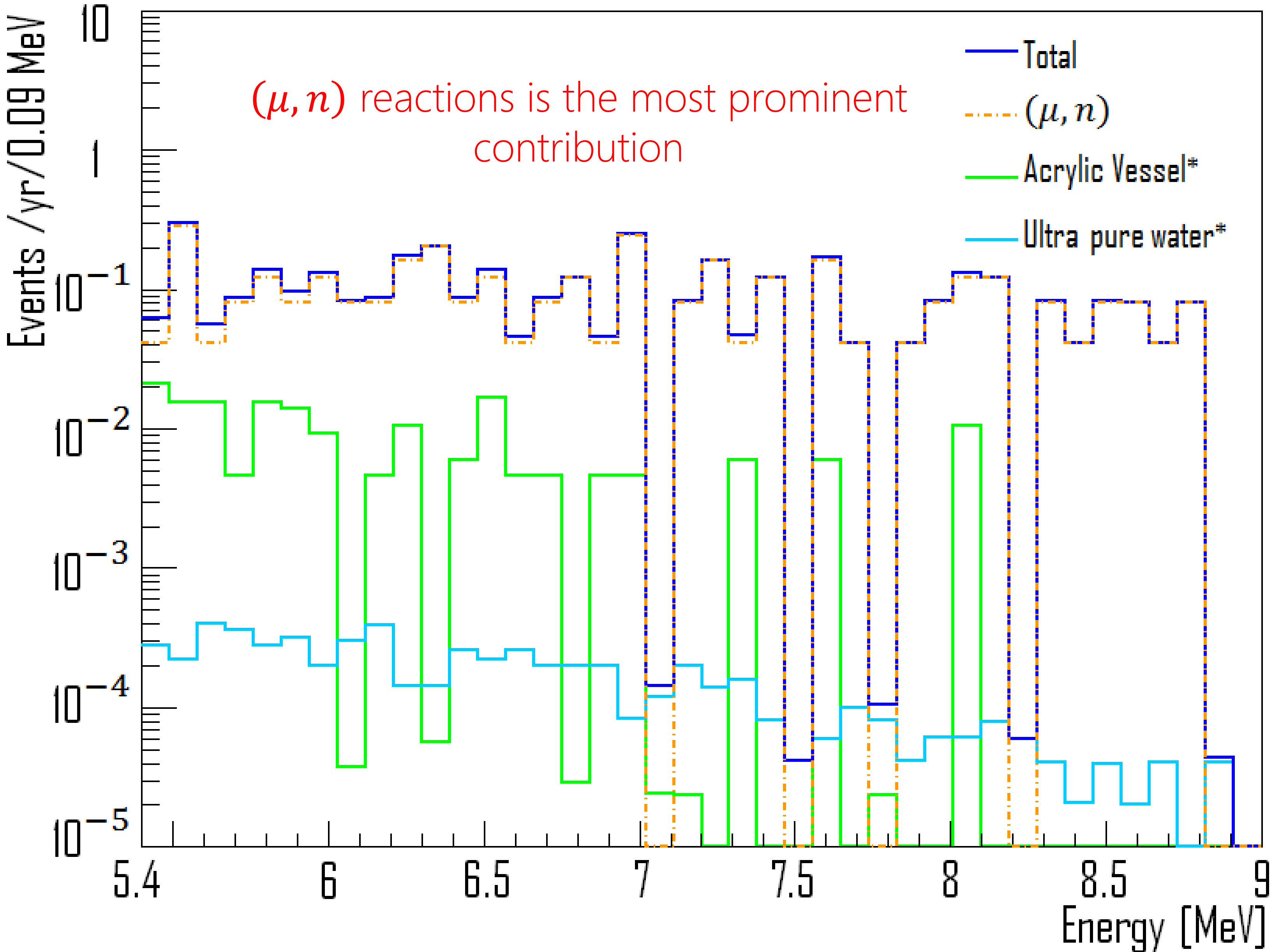
Energy spectrum during the water phase



Energy spectrum during the water phase (ROI)

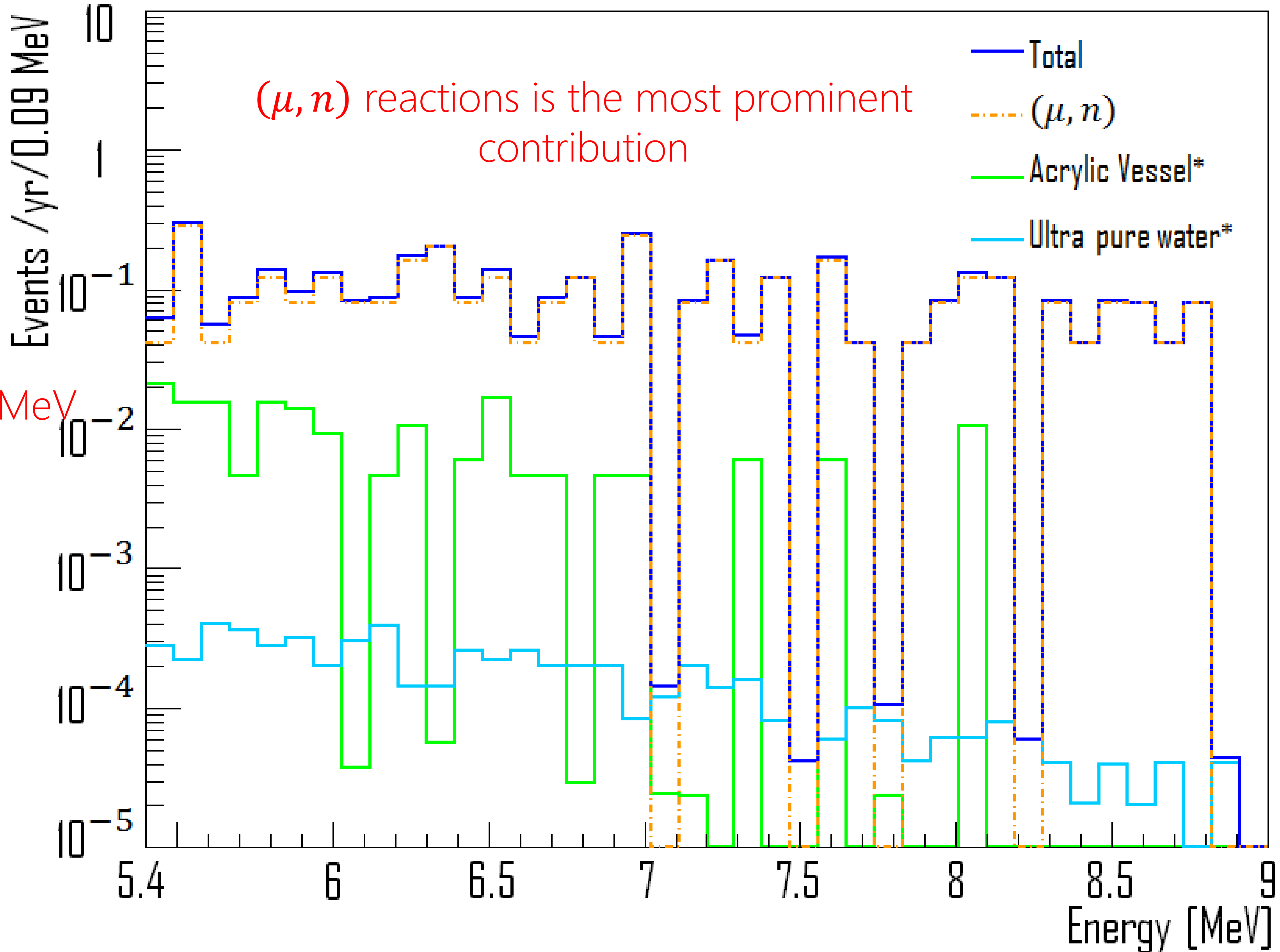


Energy spectrum during the water phase (ROI)



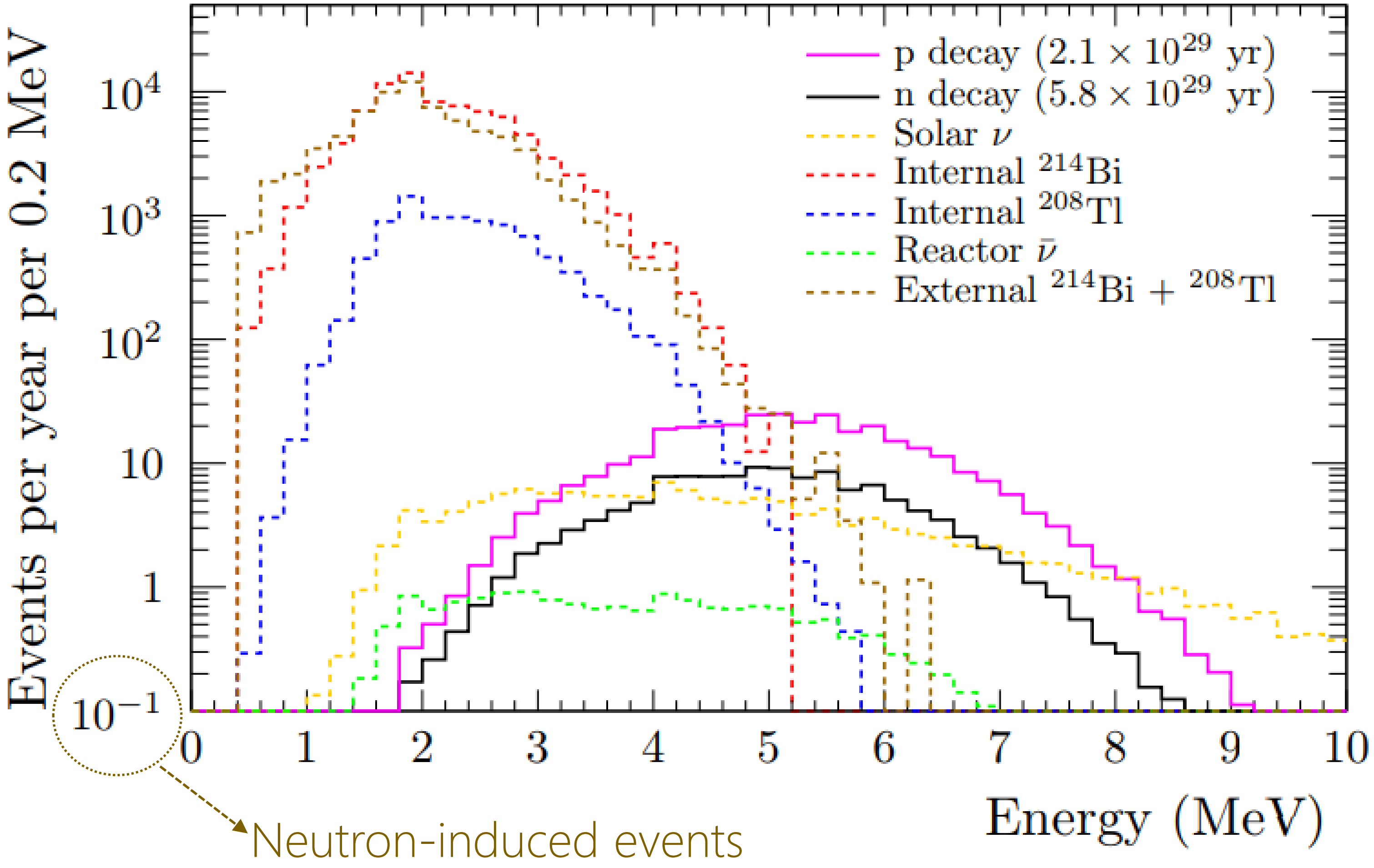
Energy spectrum during the water phase (ROI)

ROI from 5.4 MeV to 9 MeV

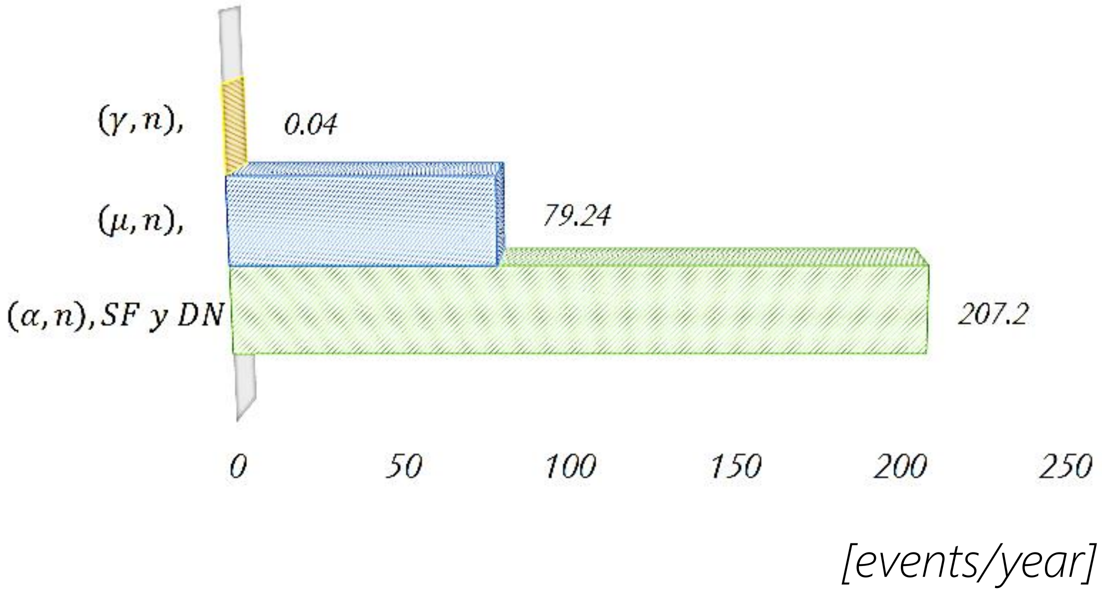


Fiducial cut <5.5m

Expected energy spectrum for the water phase backgrounds.

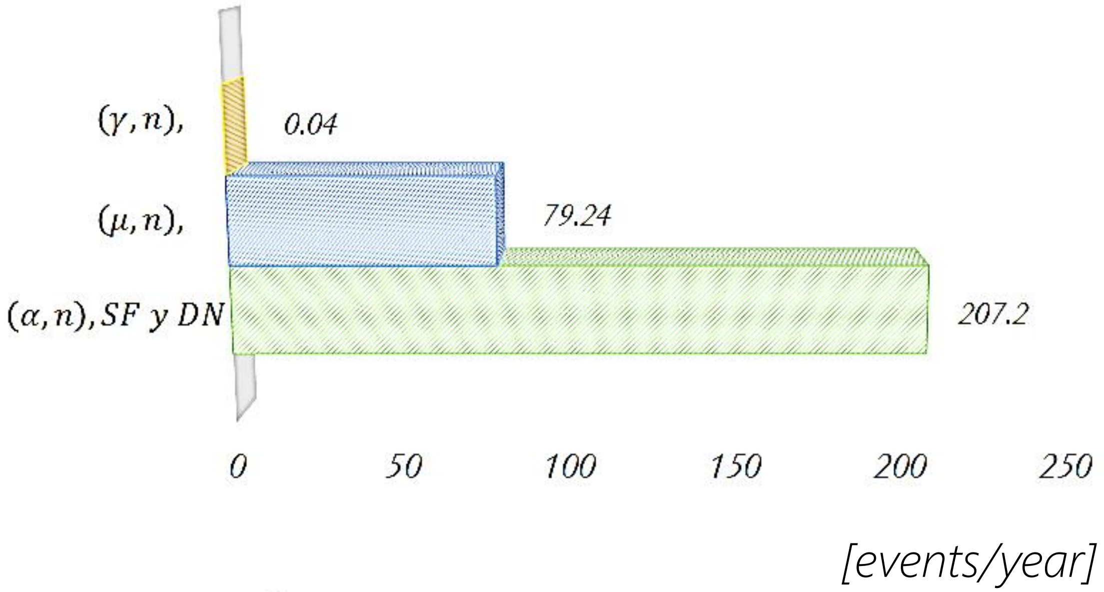


Results of the neutron rate and neutron-induced event rate during the water phase

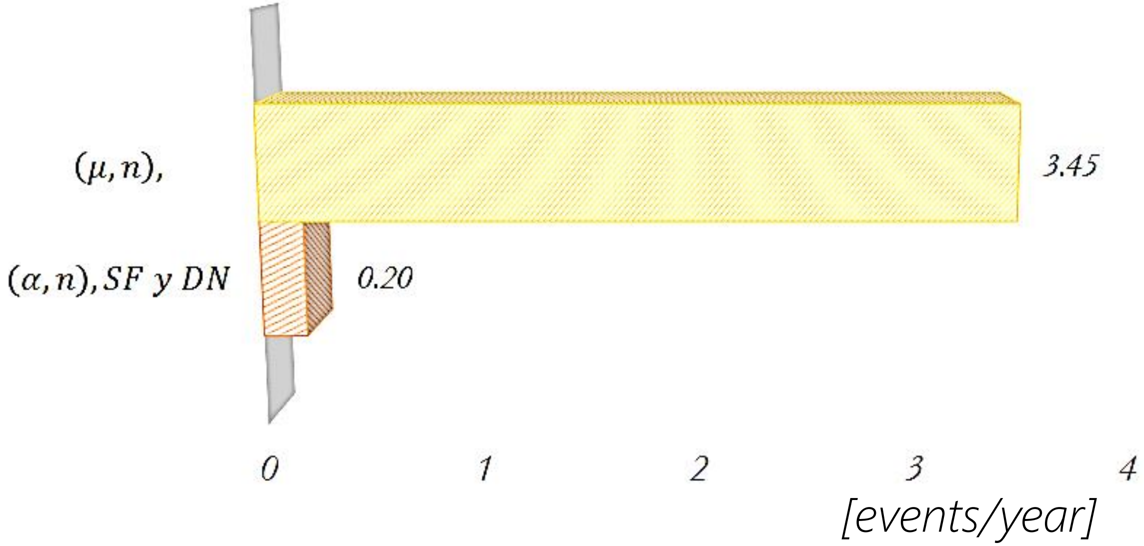


Source	Neutron rate [neutrons/year]	Neutron-induced events [events/year]
$(\alpha,n), SF\ y\ DN$	6794.72 ± 2944.62	207.20 ± 89.71
(μ,n)	12946.89 ± 1318.23	79.24 ± 8.07
(γ,n) (upper limit)	1.52	0.04

Results of the neutron rate and neutron-induced event rate during the water phase

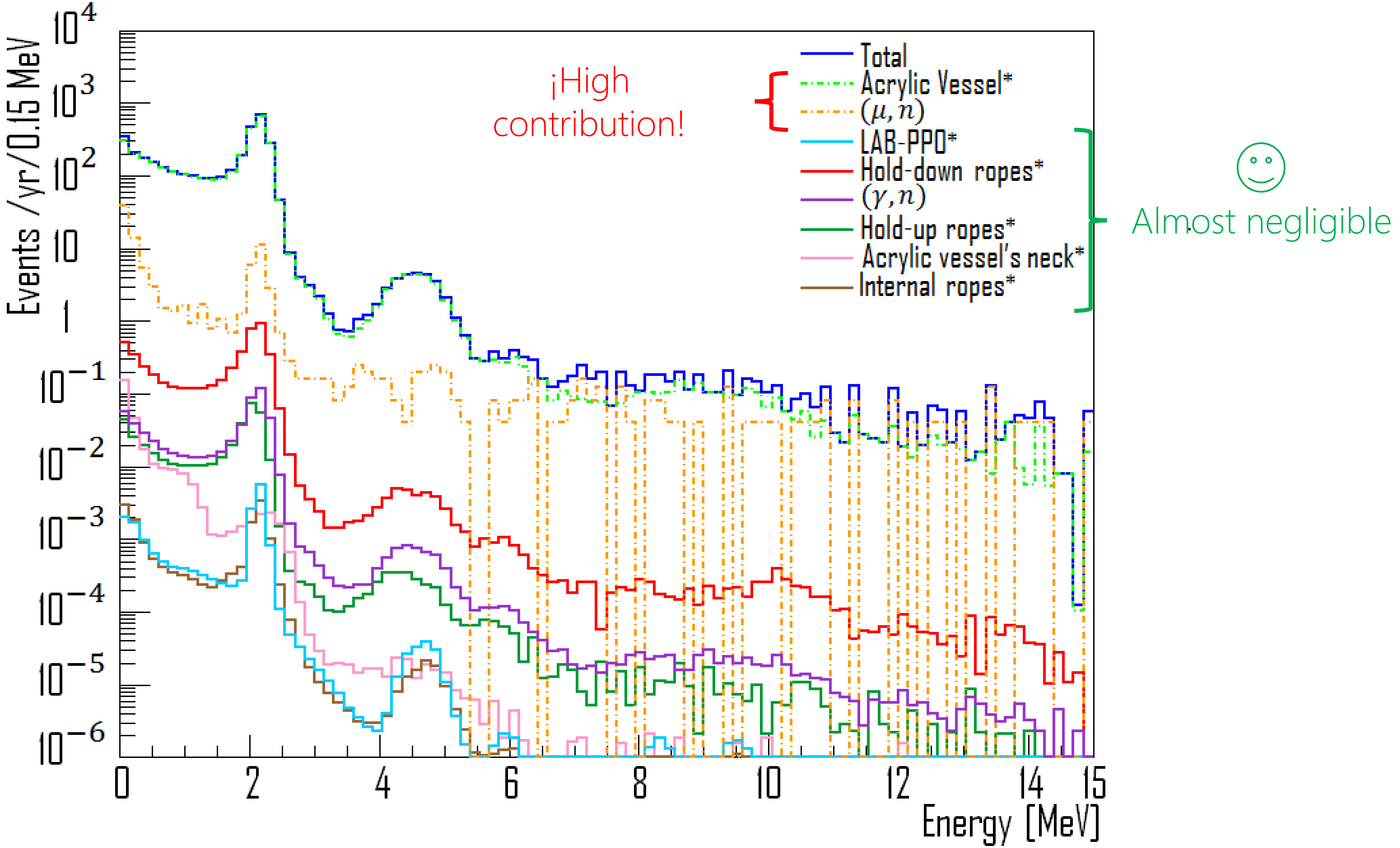


Source	Neutron rate [neutrons/year]	Neutron-induced events [events/year]
$(\alpha,n), SF\ y\ DN$	6794.72 ± 2944.62	207.20 ± 89.71
(μ,n)	12946.89 ± 1318.23	79.24 ± 8.07
(γ,n) (upper limit)	1.52	0.04

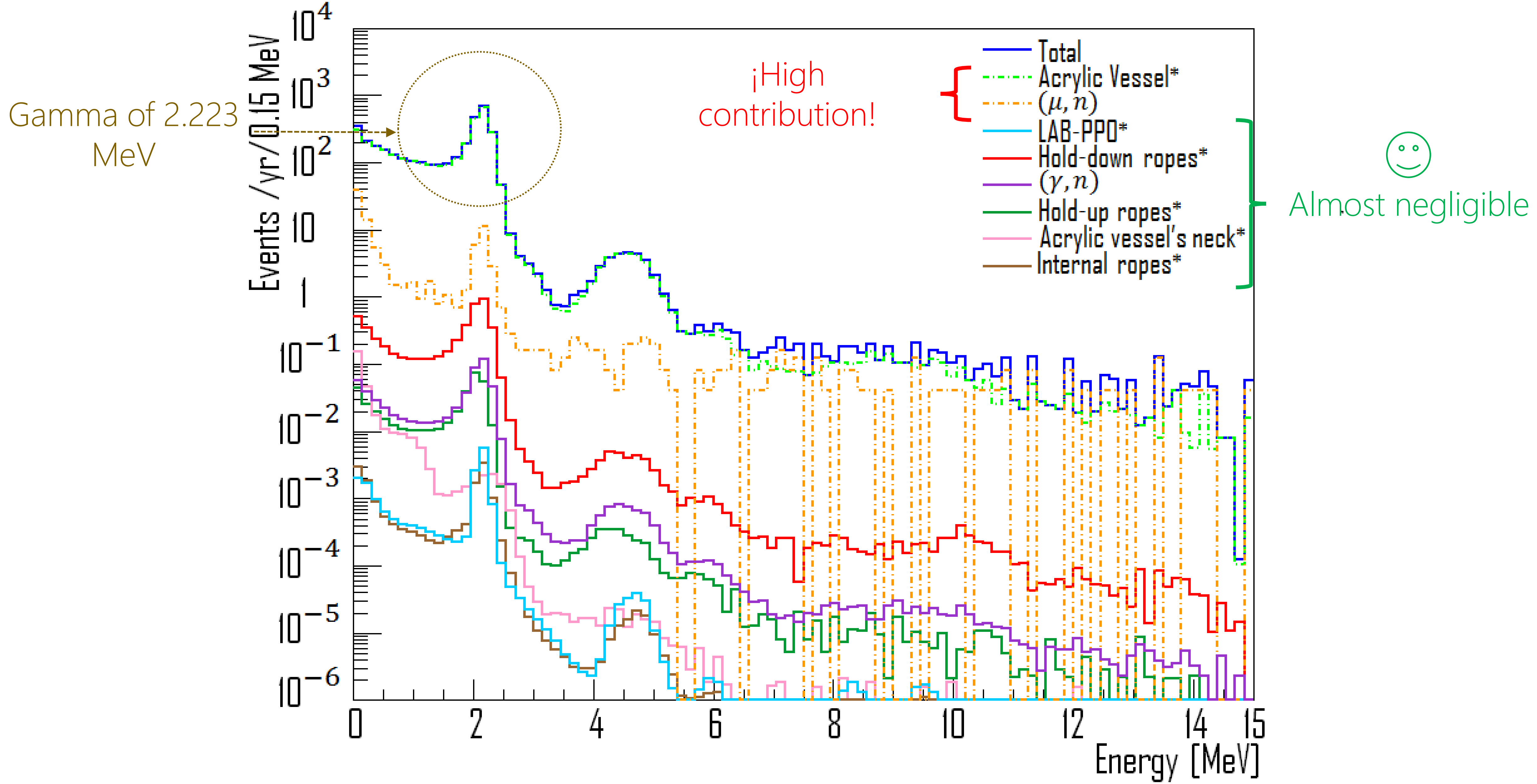


Source	Events (ROI) [events/year]
$(\alpha,n), SF\ y\ DN$	0.20 ± 0.09
(μ,n)	3.45 ± 0.35

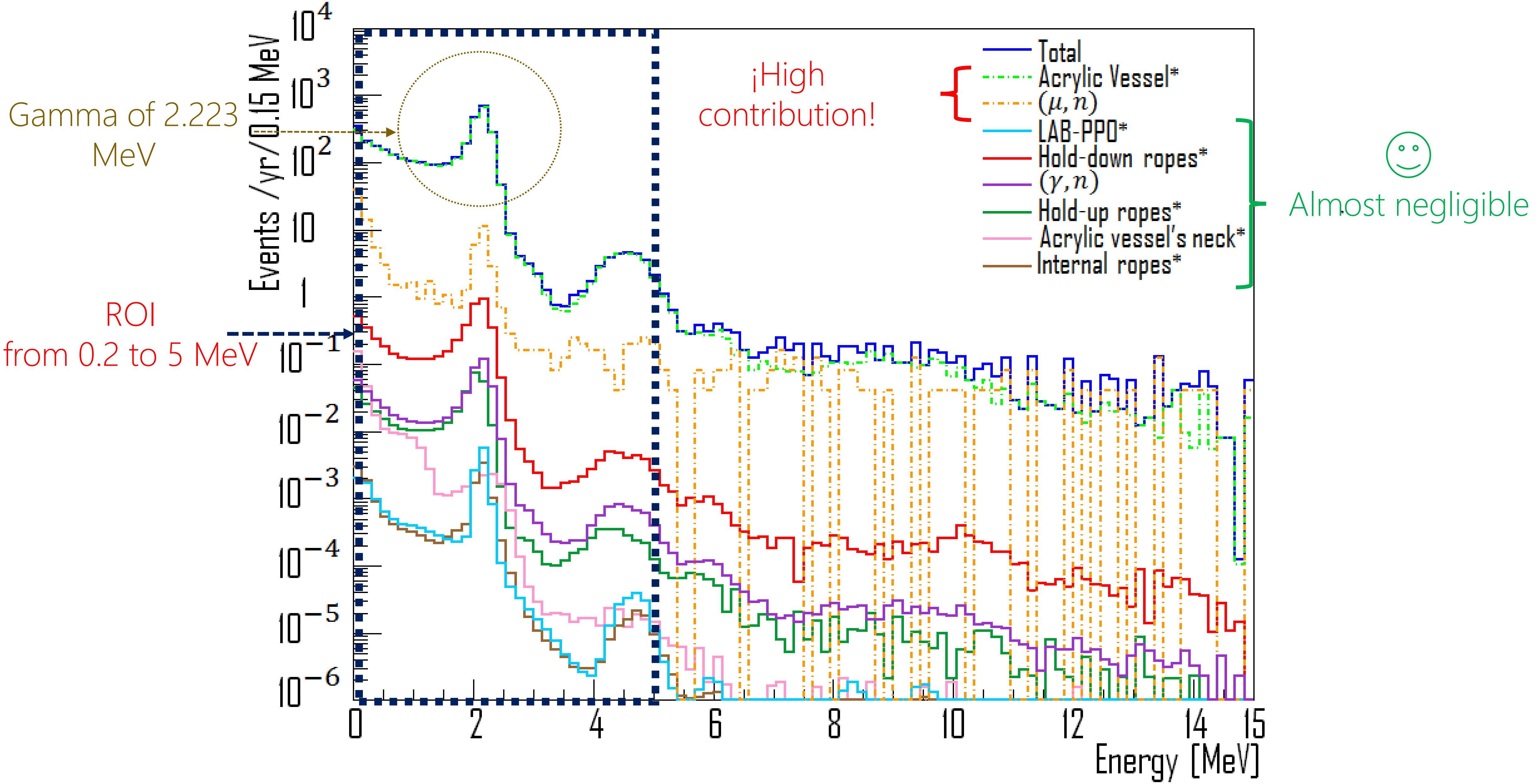
Energy spectrum during the liquid scintillator phase



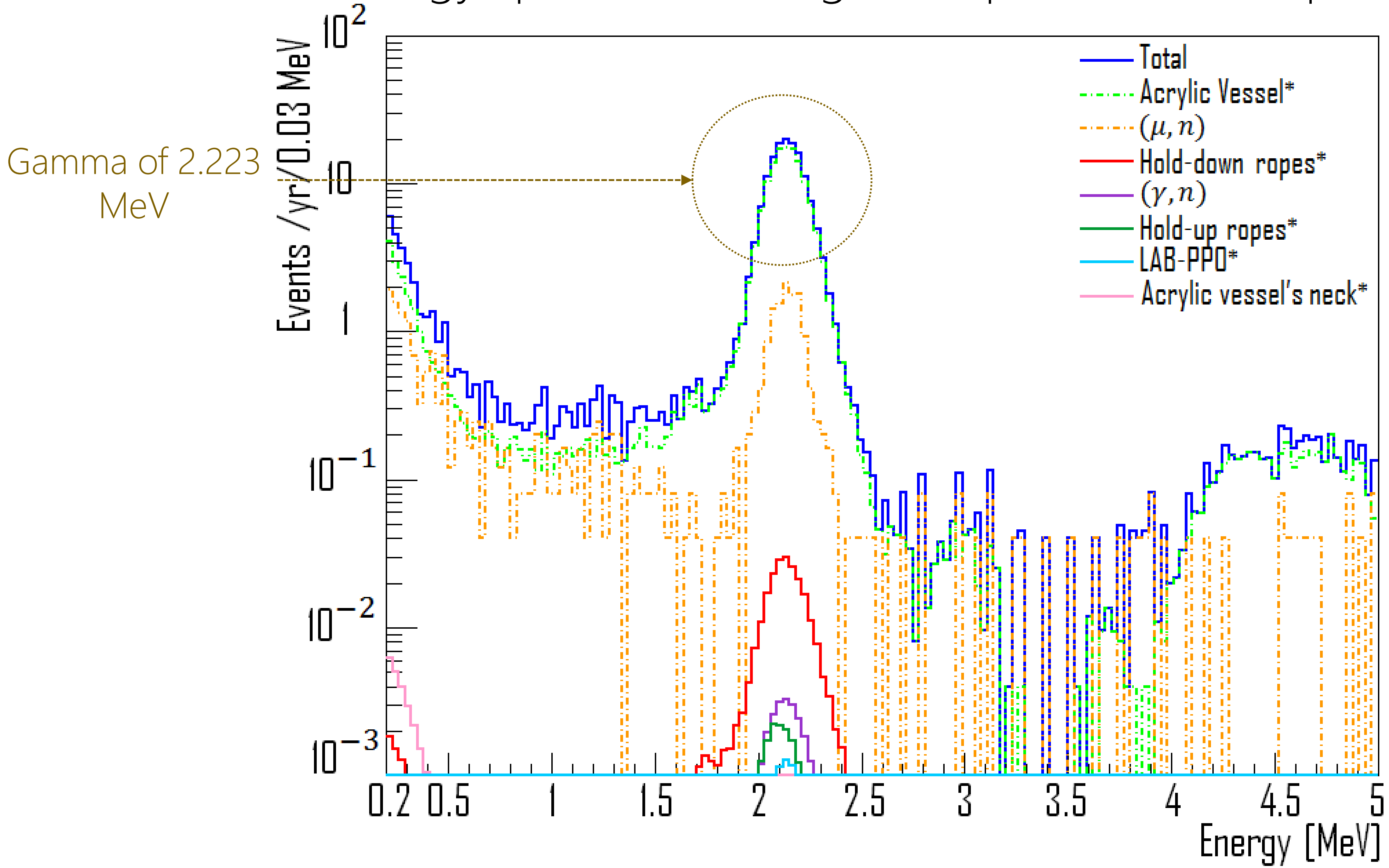
Energy spectrum during the liquid scintillator phase



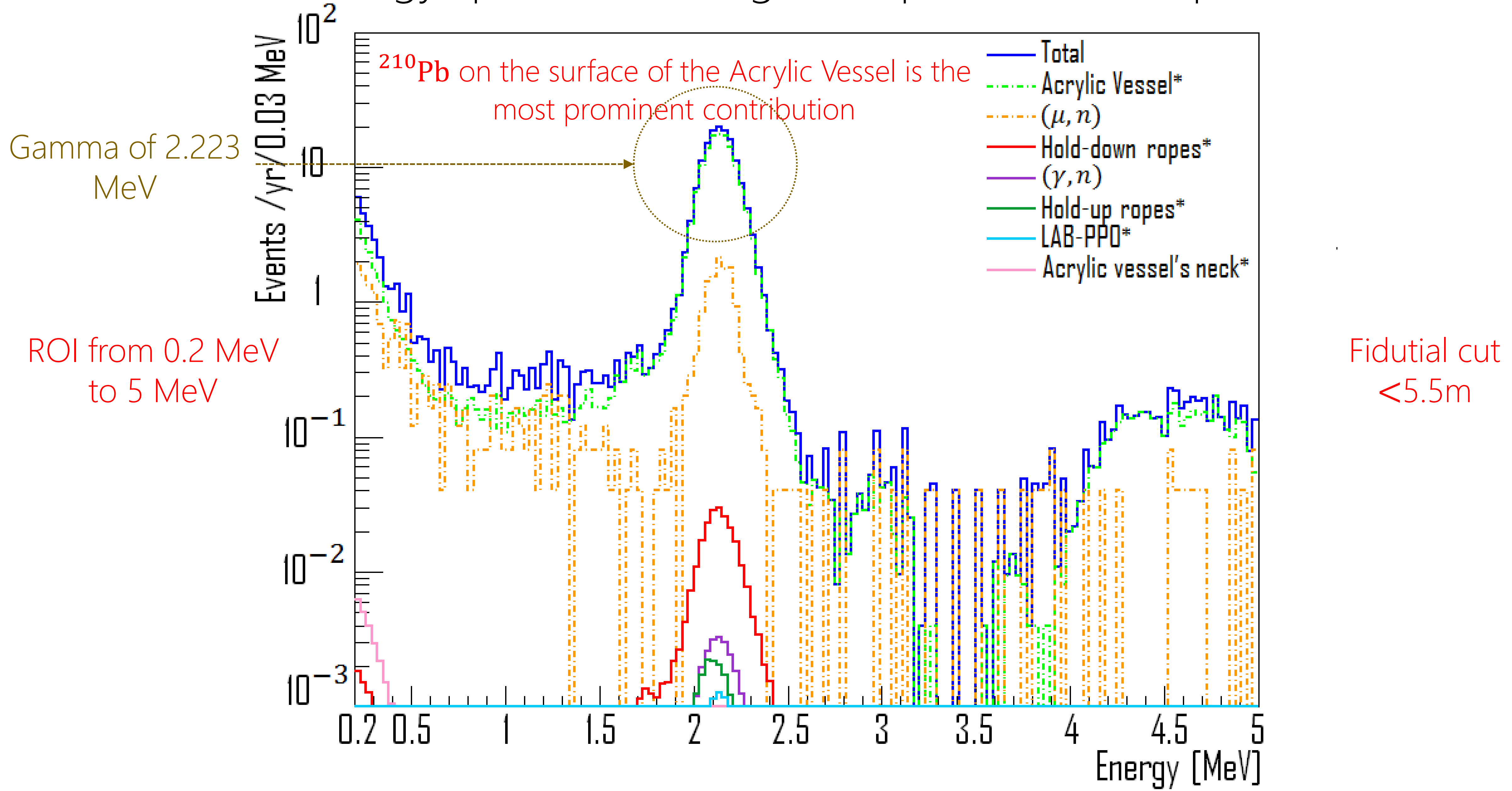
Energy spectrum during the liquid scintillator phase



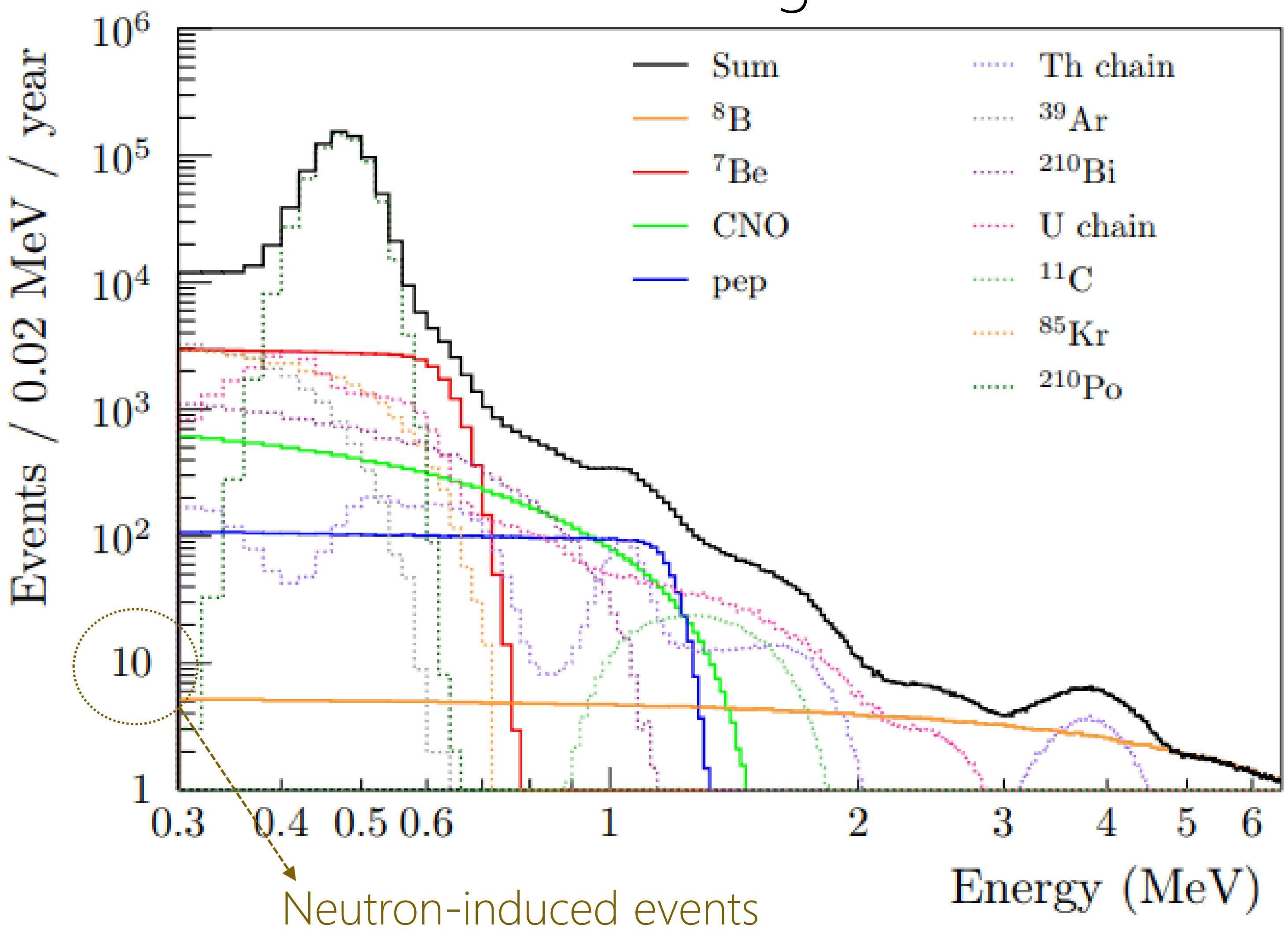
Energy spectrum during the liquid scintillator phase



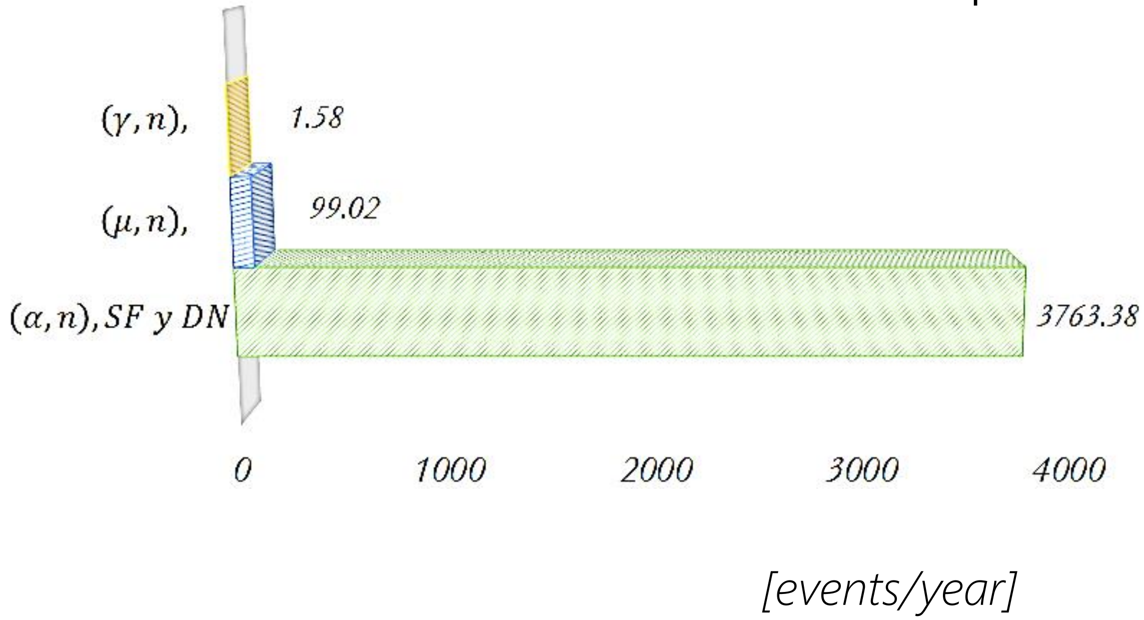
Energy spectrum during the liquid scintillator phase



Expected solar neutrino fluxes as detected by SNO+ and the corresponding main backgrounds

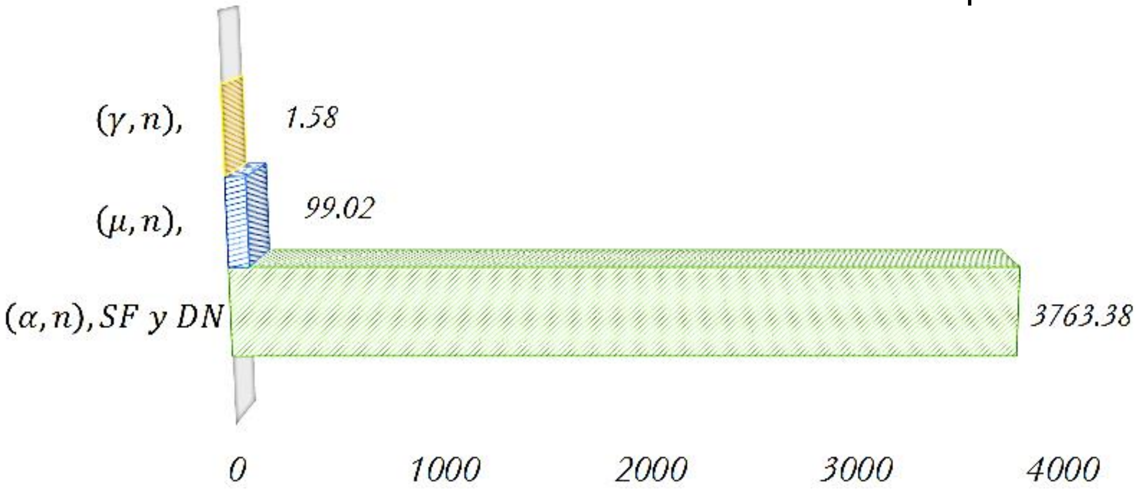


Results of the neutron rate and neutron-induced event rate during the Liquid scintillator phase

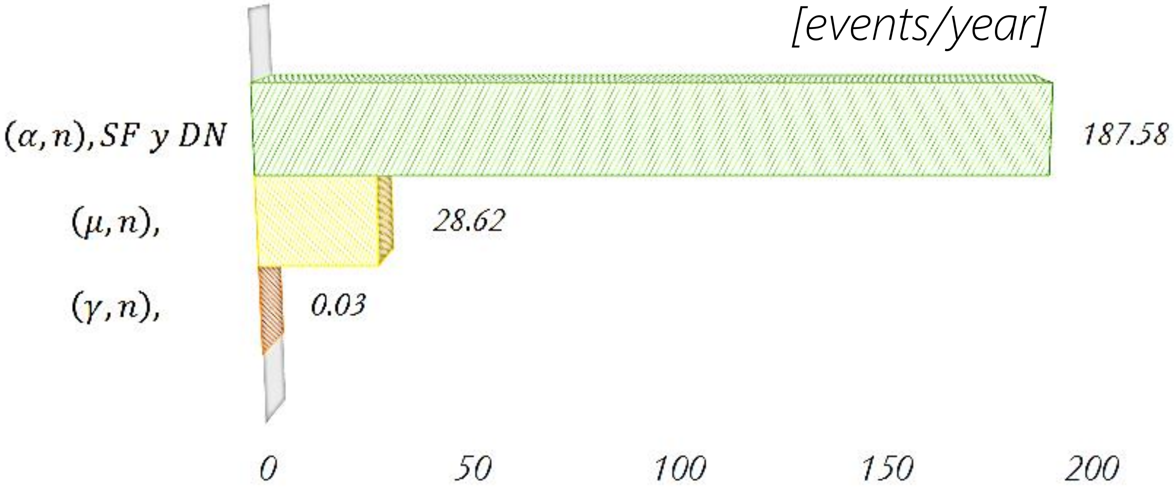


Source	Neutron rate [neutrons/year]	Neutron-induced events [events/year]
$(\alpha,n), SF\ y\ DN$	6003.42 ± 2599.51	3763.38 ± 1624.52
(μ,n)	12946.89 ± 1318.23	99.02 ± 10.08
(γ,n) (upper limit)	1.75	1.58

Results of the neutron rate and neutron-induced event rate during the Liquid scintillator phase

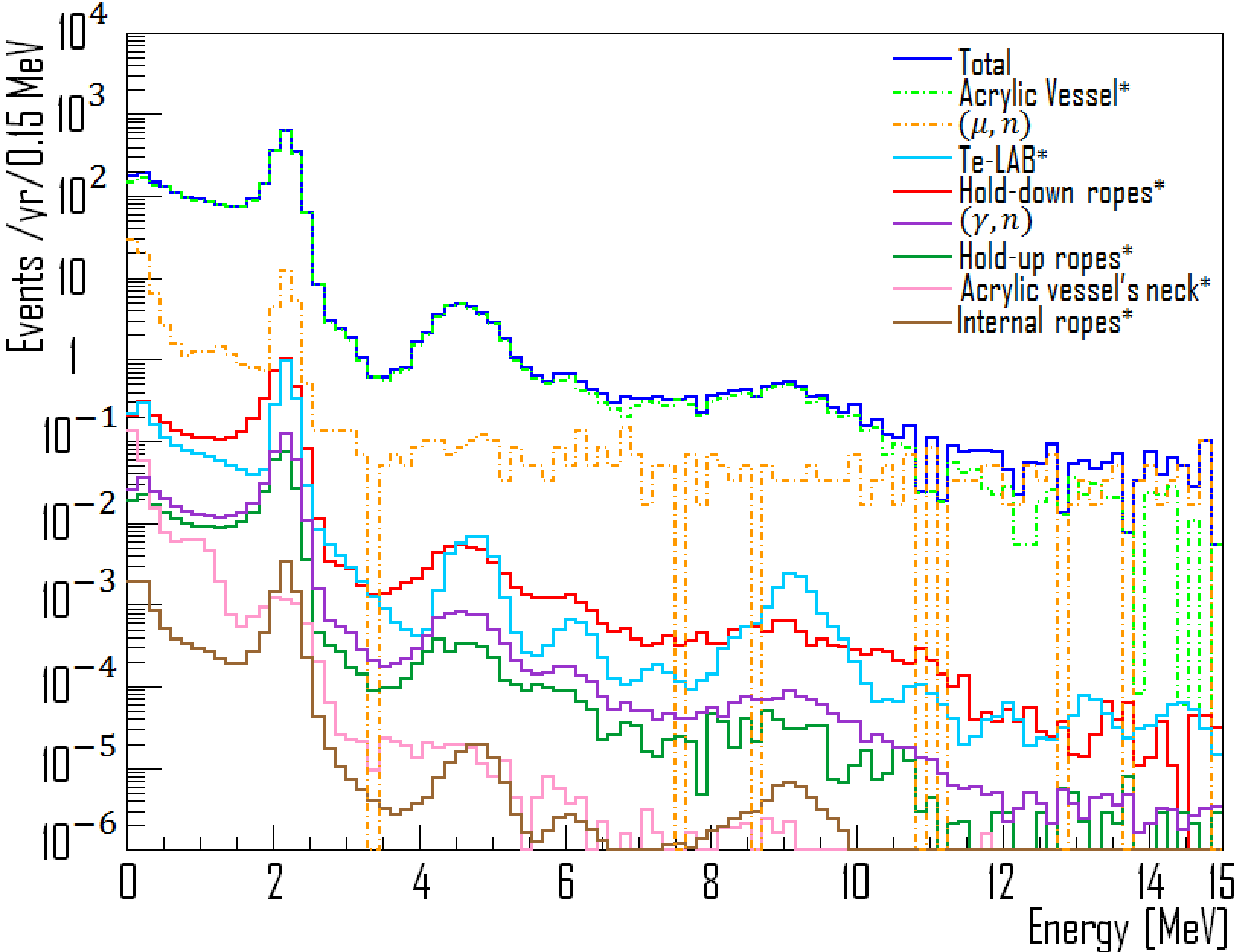


Source	Neutron rate [neutrons/year]	Neutron-induced events [events/year]
$(\alpha, n), SF\ y\ DN$	6003.42 ± 2599.51	3763.38 ± 1624.52
(μ, n)	12946.89 ± 1318.23	99.02 ± 10.08
(γ, n) (upper limit)	1.75	1.58

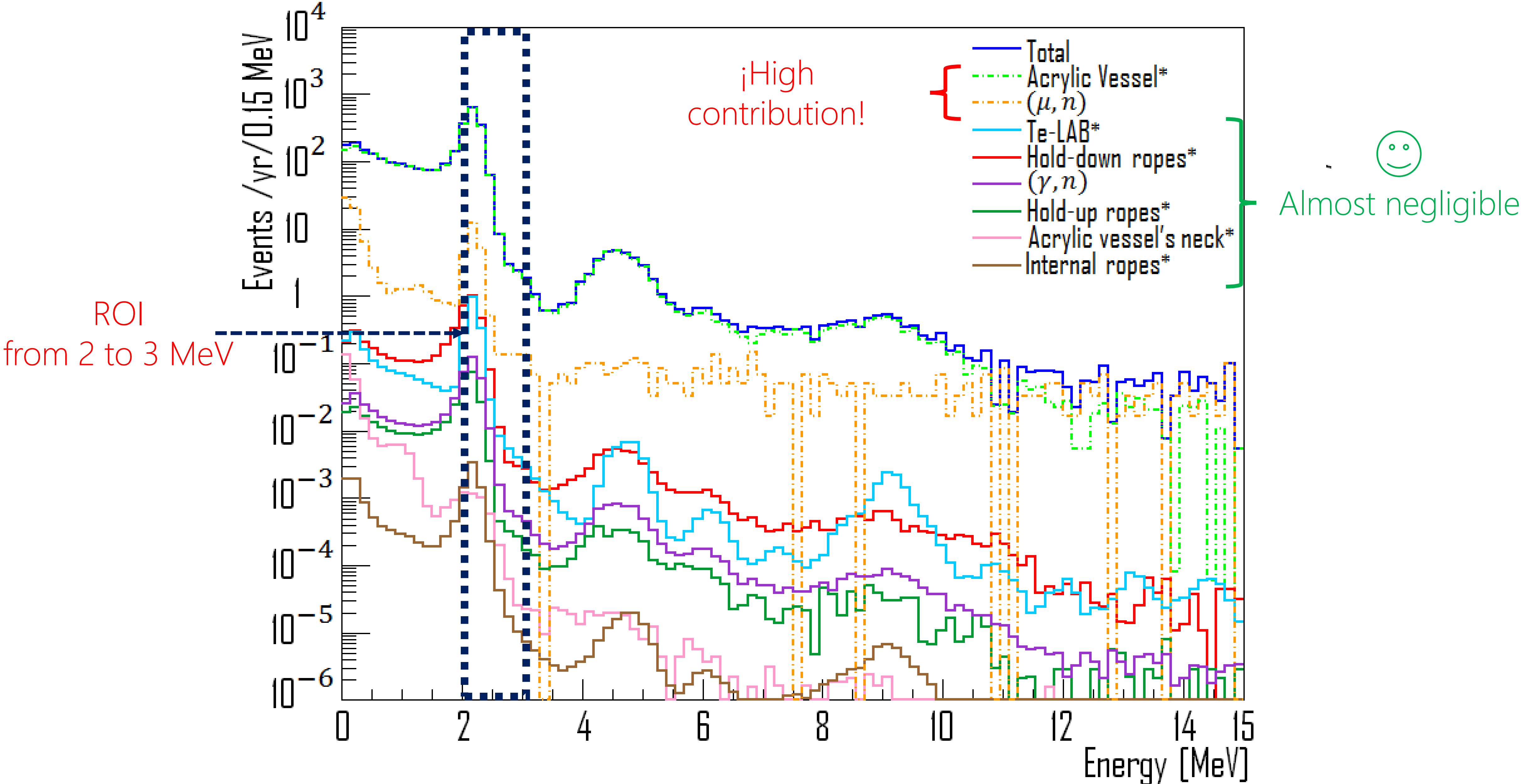


Source	Events (ROI) [events/year]
$(\alpha, n), SF\ y\ DN$	187.58 ± 78.63
(μ, n)	28.62 ± 2.91
(γ, n) (upper limit)	0.03

Energy spectrum during the Te-loaded phase

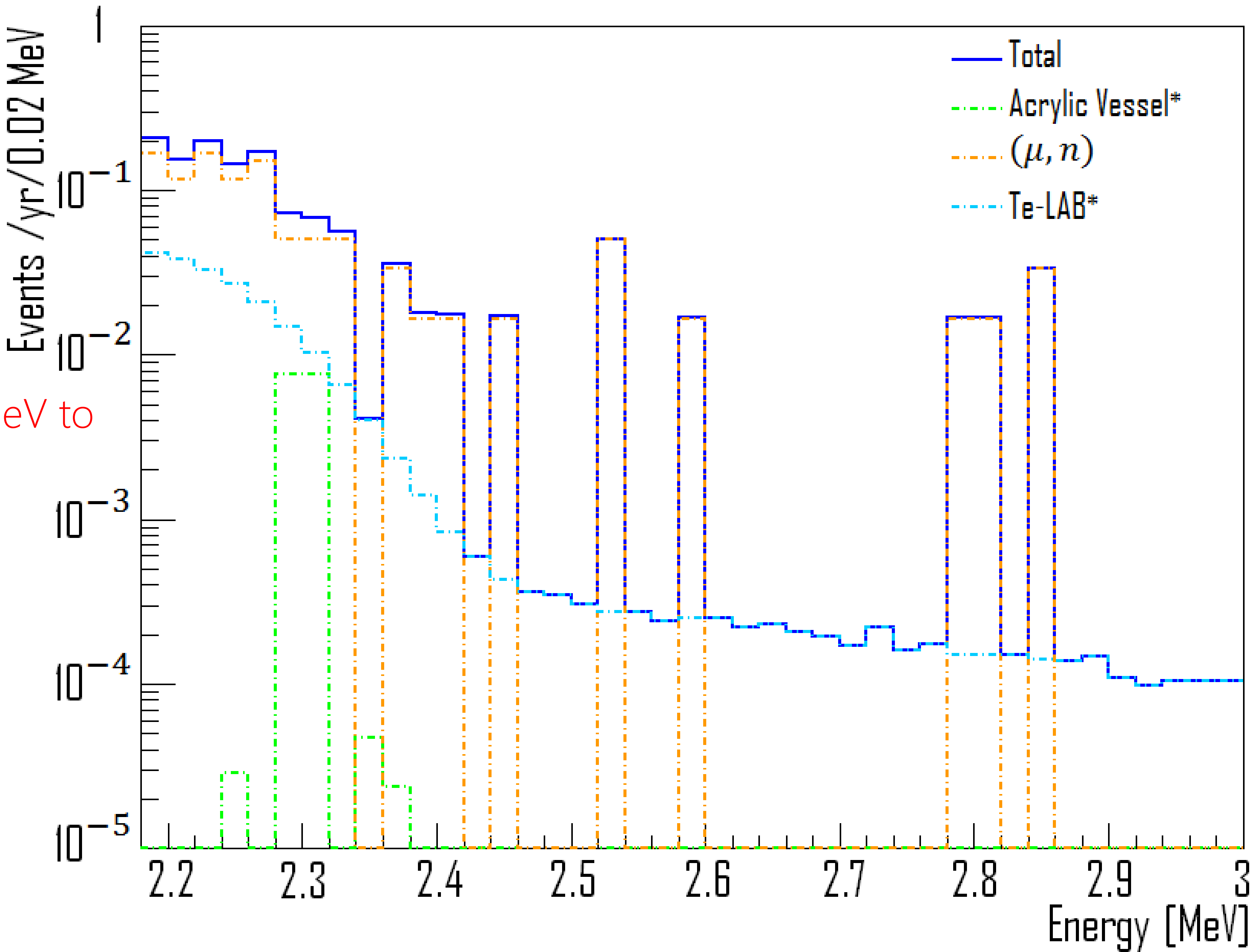


Energy spectrum during the Te-loaded phase



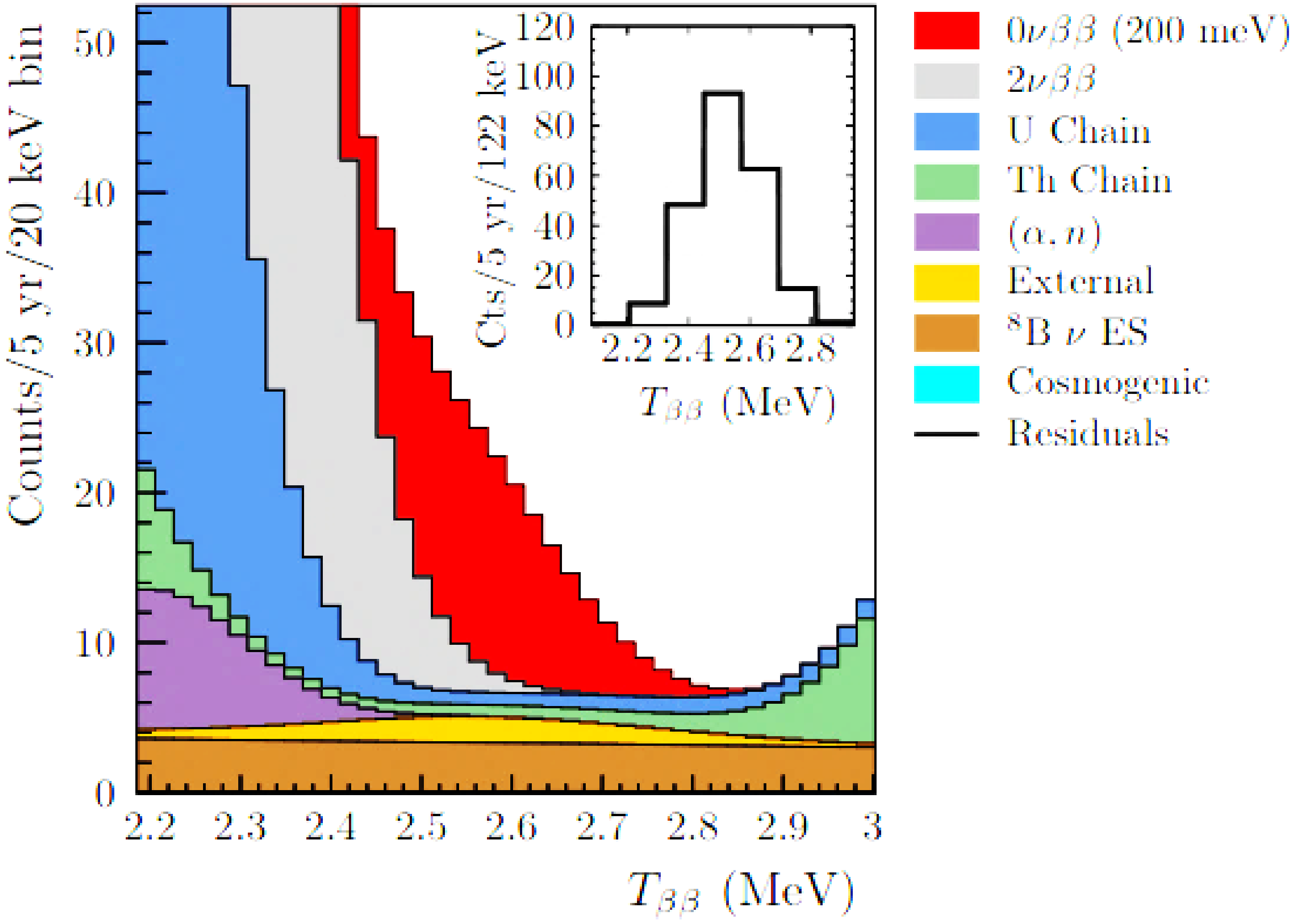
Energy spectrum during the Te-loaded phase

ROI from 2 MeV to 3 MeV

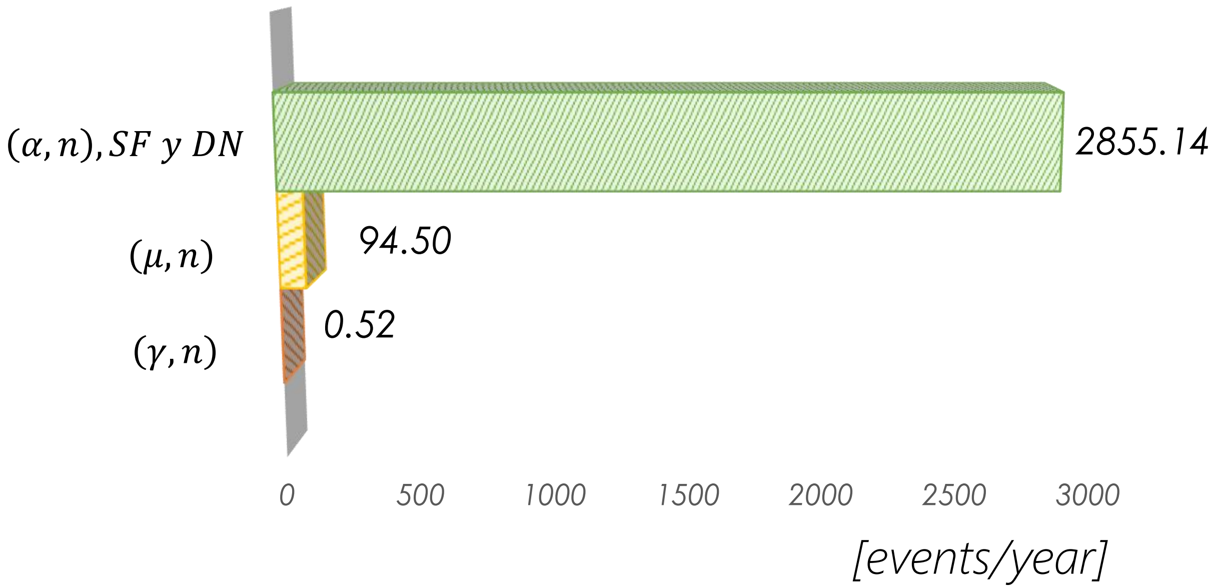


Fidutial cut <3.5m

Effective kinetic energy of neutrinoless double-beta decay

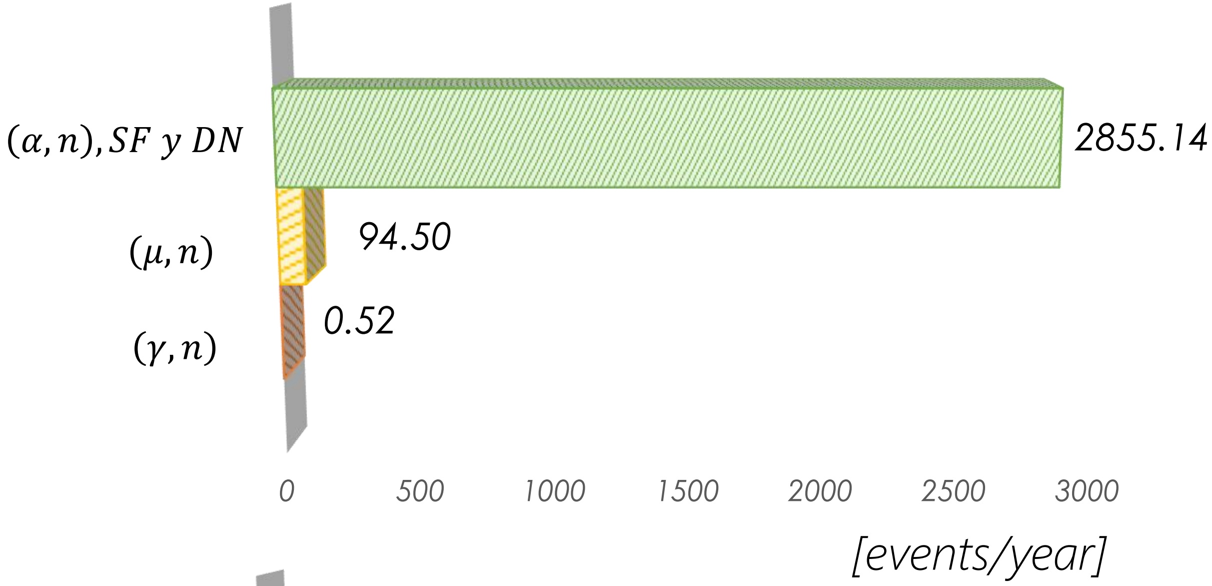


Results of the neutron rate and neutron-induced event rate during the Te-loaded phase

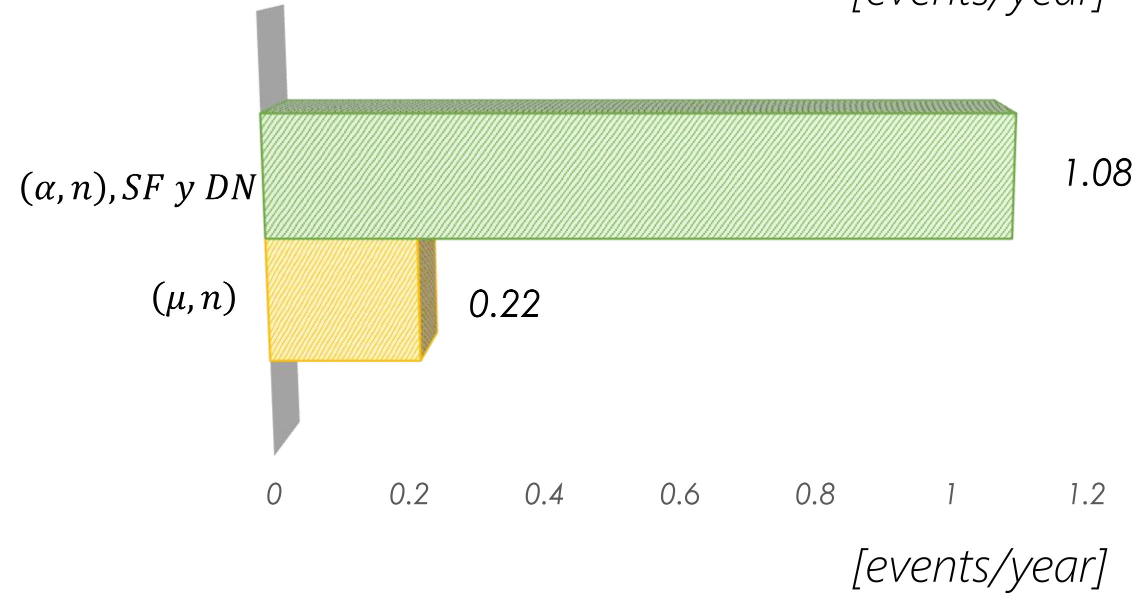


Source	Neutron rate [neutrons/year]	Neutron-induced events [events/year]
$(\alpha,n), SF\ y\ DN$	5574.68 ± 2415.88	2855.14 ± 1234.39
(μ,n)	12946.89 ± 1318.23	94.50 ± 9.62
(γ,n) (upper limit)	1.70	0.52

Results of the neutron rate and neutron-induced event rate during the Te-loaded phase



Source	Neutron rate [neutrons/year]	Neutron-induced events [events/year]
$(\alpha,n), SF\ y\ DN$	5574.68 ± 2415.88	2855.14 ± 1234.39
(μ,n)	12946.89 ± 1318.23	94.50 ± 9.62
(γ,n) (upper limit)	1.70	0.52

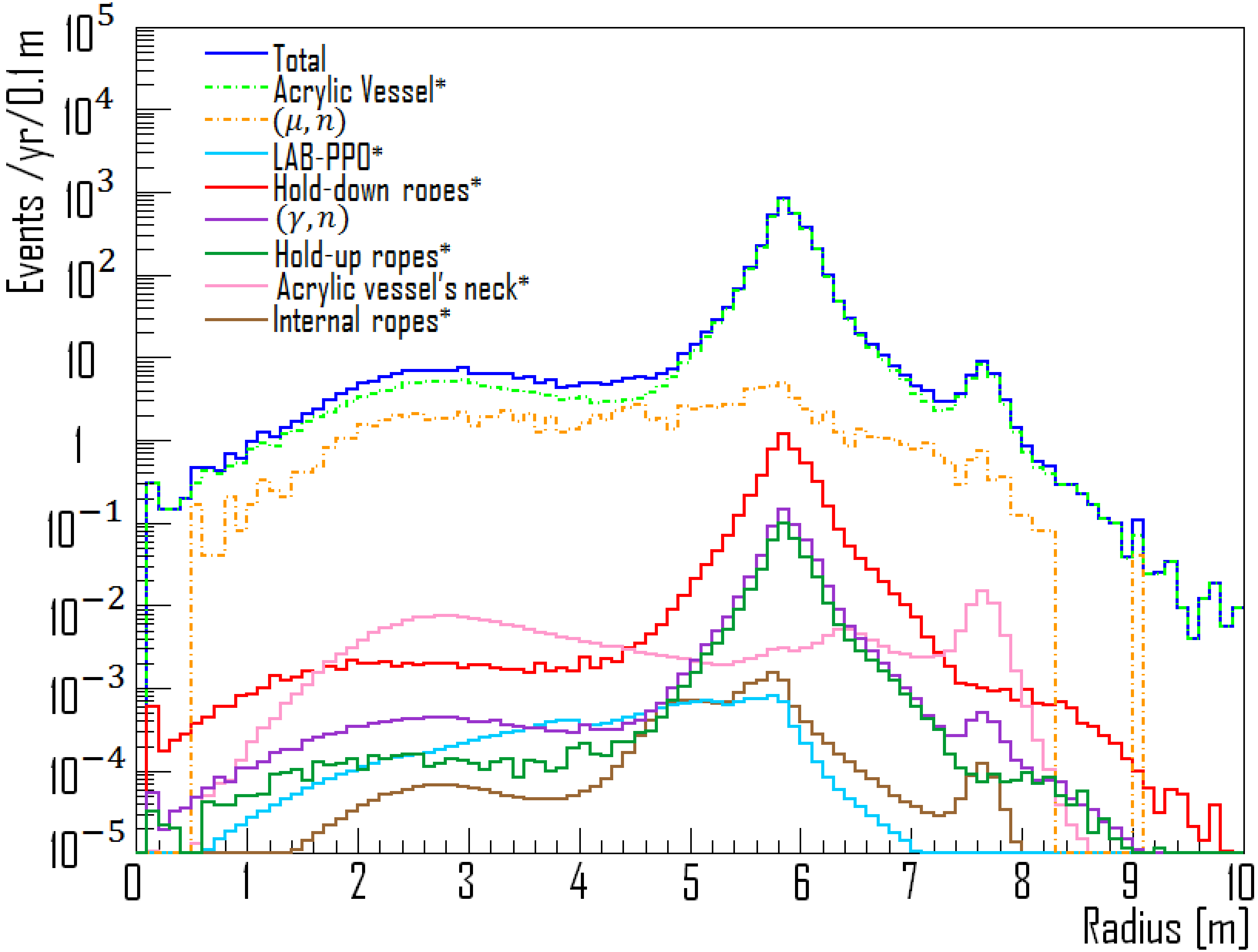


Source	Events (ROI) [events/year]
$(\alpha,n), SF\ y\ DN$	0.22 ± 0.06
(μ,n)	1.08 ± 0.11

Final remarks

- This study has completed a previous analysis and incorporated a completed simulation using the detector geometry.
- An estimation of neutron backgrounds was performed during the main data taking phases of the SNO+ Experiment.
- There is a publication about the prospects of this experiment: Andringa, S., et al. (2016). Current Status and Future Prospects of the SNO+ Experiment. Advances in High Energy Physics, 2016:21.
- The SNO+ detector is currently filled with ultra pure water since March 2017.
- The SNO+ detector will be filled with liquid scintillator soon.

Radial distribution of neutron-induced events during the LS phase



Radial distribution of neutron-induced events during the Te-loaded phase