Distillation and Separation of some Rare Isotopes and their Applications

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OUTLINE

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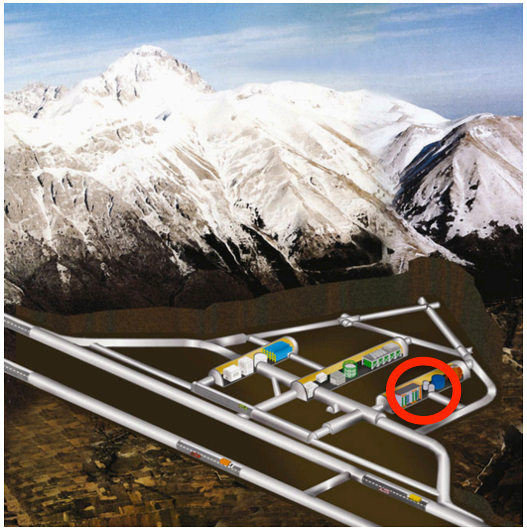
4. Application fields of ^{3}He isotope
5. ^{3}He separation with the SOPHIE Project

The Darkside Experiment



- Searches for **dark matter** (WIMPs) using a direct detection method in the underground laboratories in Gran Sasso (LNGS – Hall C)

- Is the new research program worldwide using liquid argon, as all the research groups have joined the DS-20k experiment (while still completing their current research programs):

Darkside
DEAP
ArDM
MiniCLEAN

} DS-20k → multi-100 ton scale experiment

The Darkside Experiment

To this new collaboration will take part:

- 68 Research Institutes and Universities
- 350+ Researchers, Engineers and Technicians
- 12 Countries: Brazil, Canada, China, France, Greece, Italy, UK, Poland, Romania, Spain, Switzerland, USA.

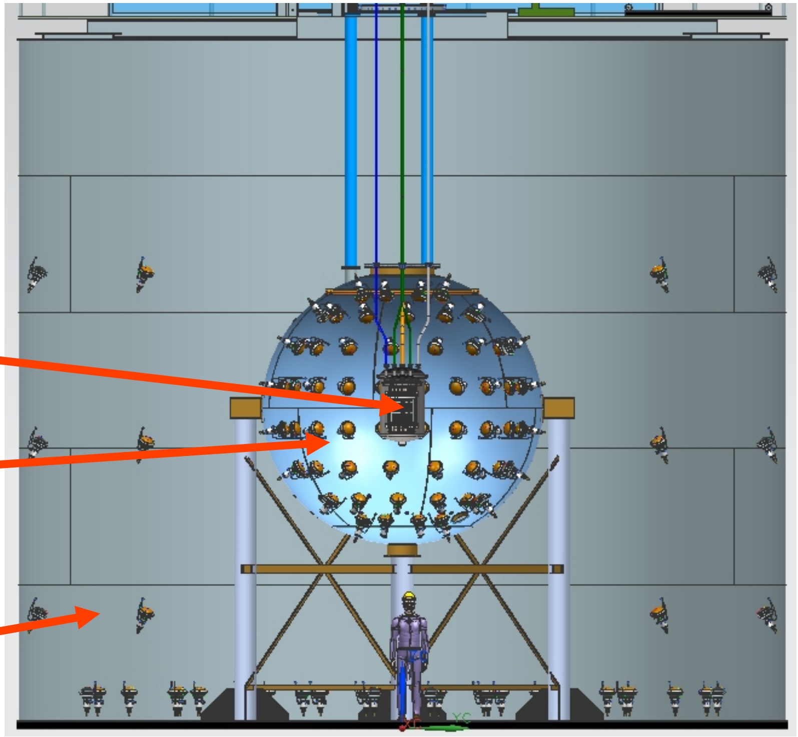
The Darkside Experiment

- Employs a double phase **Liquid Argon** Time Projection Chamber (**TPC**) capable of 3D event localization
- Provides a very powerful background suppression through the Pulse Shape Discrimination (**PSD**) and the Scintillation (S1) and Ionization (S2) channels: **S2/S1** parameter
- Operates with active Muon and Neutron Vetoes
- Aims to run in background free mode (<0.1 event in total exposure): **a necessary condition for a discovery program.**

Liquid Argon TPC as DM target

Liquid scintillator Neutron Veto

Water Cherenkov Muon Veto



The Darkside Experiment

Appealing **Argon properties** as dark matter target:

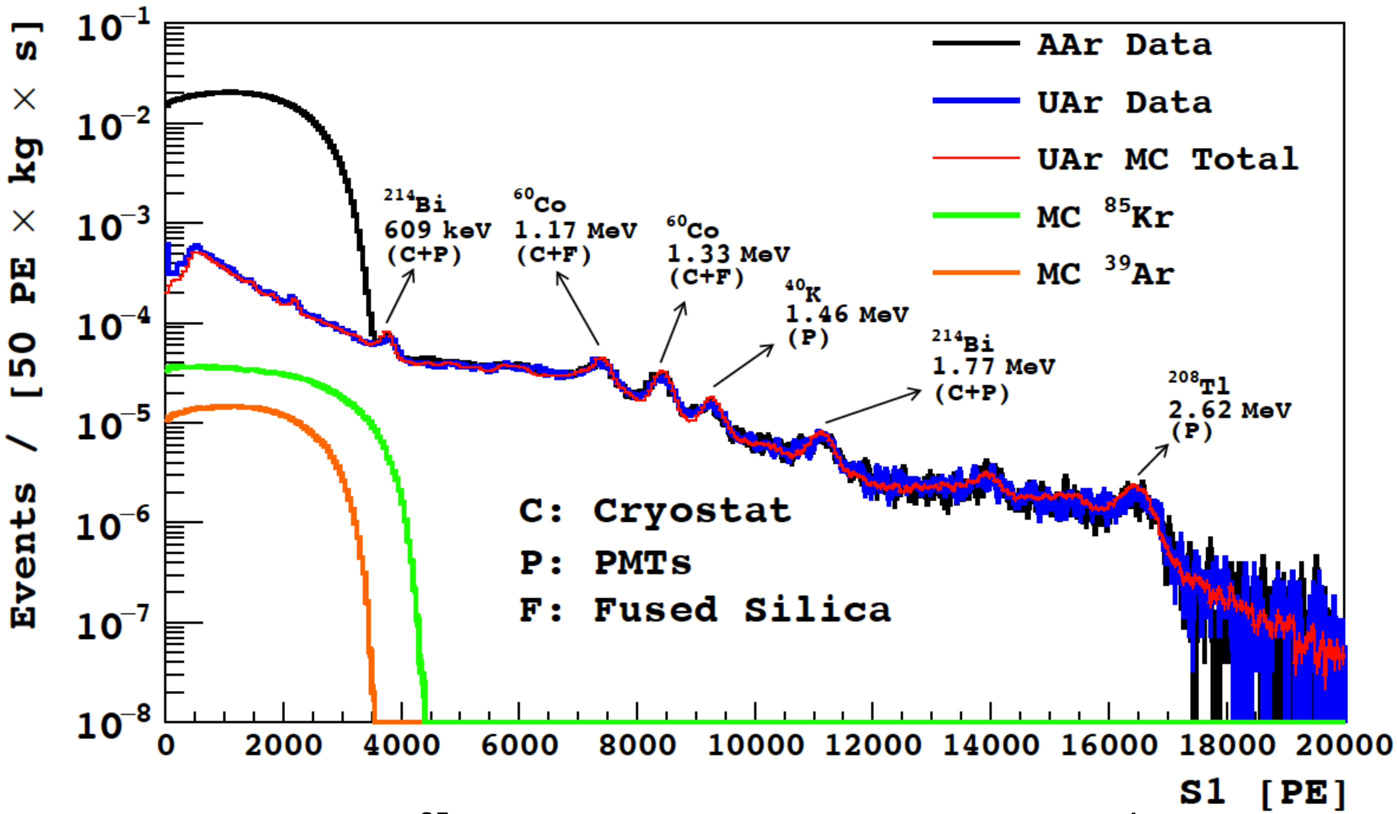
- Liquefies at 87 K, simply using LN_2 or cryogen free techniques
- Purification: contaminants/impurities may be easily trapped (e.g. Rn)
- May be scaled to larger masses
- Sufficiently high A (WIMP-nucleon cross section goes as A^2 for spin-independent interaction)
- Scintillates with high scintillation yield (40k photons/MeV) and is transparent to the emitted light.
- High ionization signal (electroluminescence in Ar gas)
- **Excellent background discrimination power**

One only drawback: cosmogenic production of the unstable isotope ^{39}Ar in the atmospheric Ar (AAr) via the **^{40}Ar(n, 2n)^{39}Ar** reaction.
^{39}Ar is present in traces (1 part in 10^{15}) and β-decays (Q=565 keV, $T_{1/2}$=269 y) -> a=1 Bq/kg.

Solution: Underground Argon (UAr) from deep underground wells (Cortez, CO).
Depletion factor of ^{39}Ar measured by DS-50 is $(1.4\pm0.2)\times10^3$ with respect to AAr.

The Darkside Experiment

UAr depleted in ^{39}Ar of a factor 1400 with respect to AAr

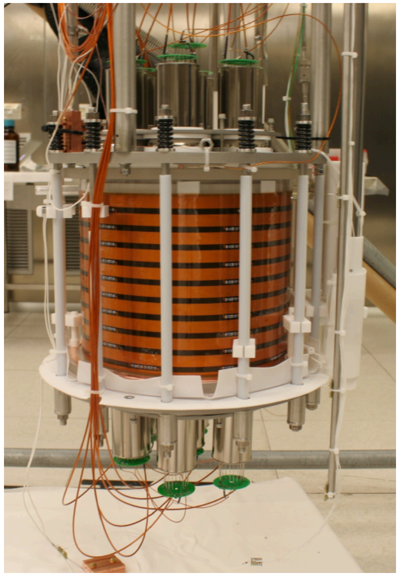


Fitted ^{85}Kr activity in UAr: 2.05 ± 0.13 mBq/kg

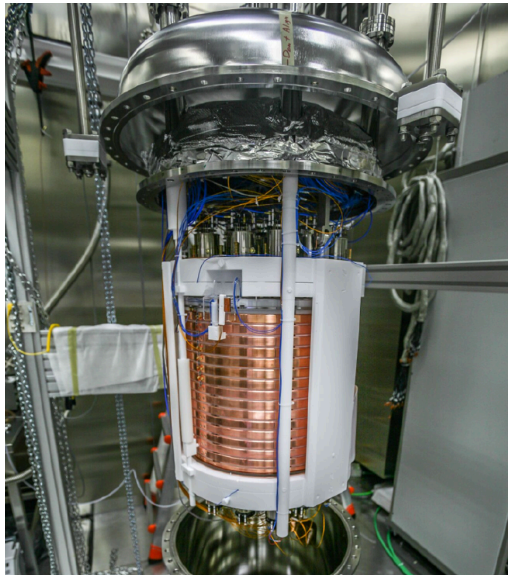
Fitted ^{39}Ar activity in UAr: 0.73 ± 0.11 mBq/kg

^{39}Ar activity in AAr: 1000 mBq/kg

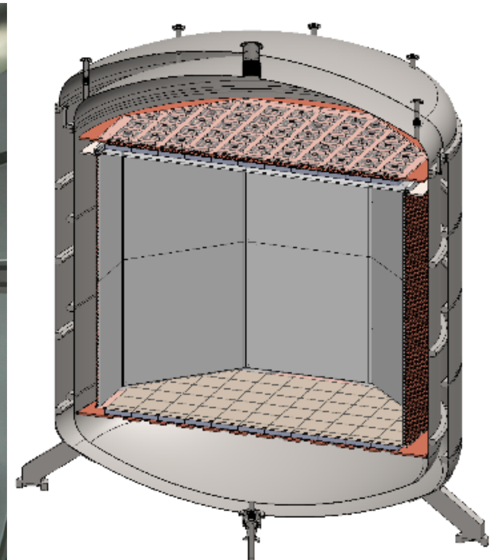
The Darkside Experiment



DS-10 (2011-13)



DS-50 (2013 - presently running)

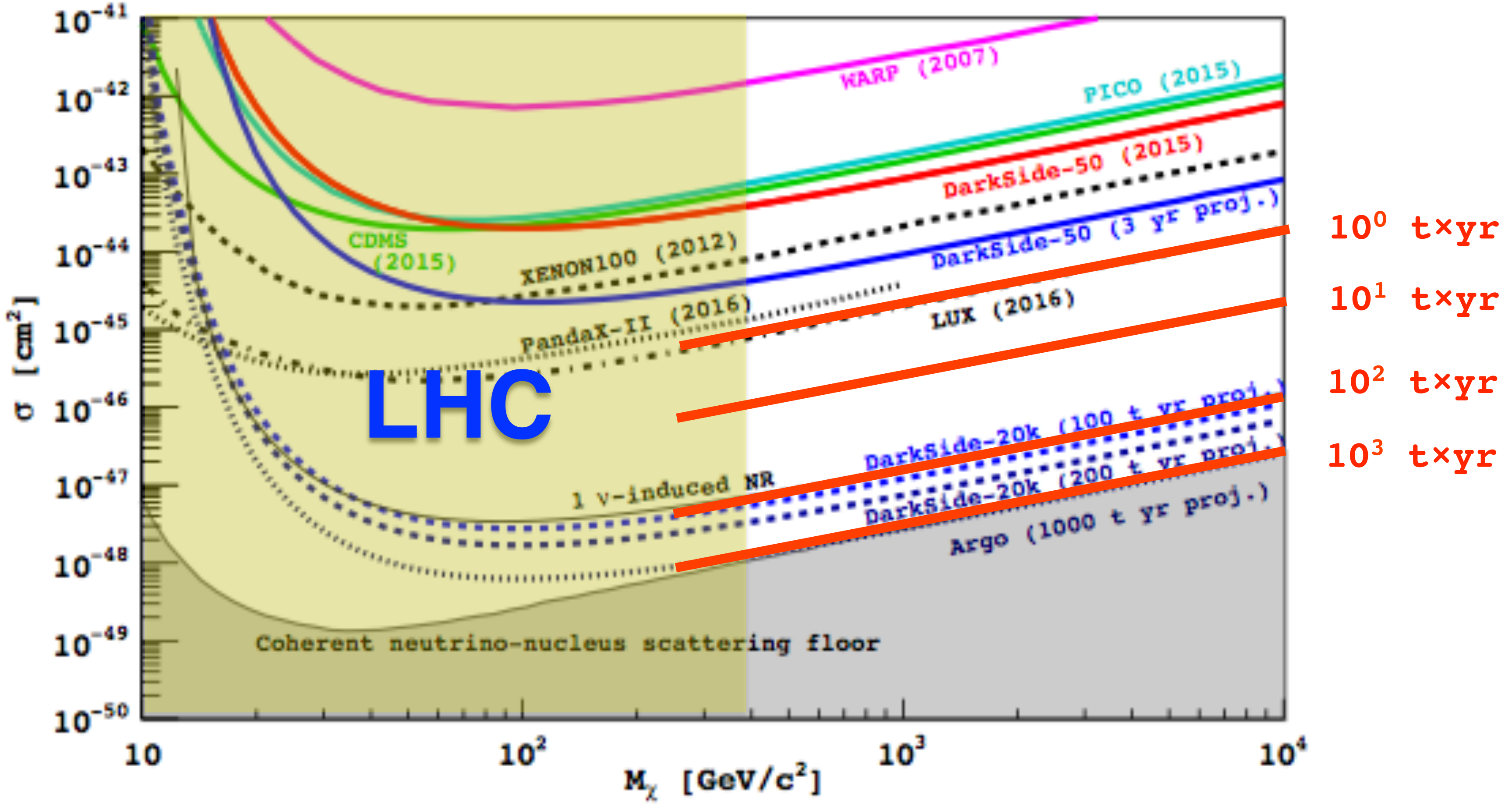


DS-20k (Data taking starts in 2021)

ARGO
200 t
(THE FUTURE)

Darkside 50 is currently running with UAr in bkgd free mode.
Next steps:
DS-20k: 20 t (FV) of liquid UAr and **SiPM instead of PMTs (for bkgd reduction)**
ARGO: 200 t (FV) of liquid UAr -> **is in this case the depletion factor 1400 still sufficient to run in background free mode?**

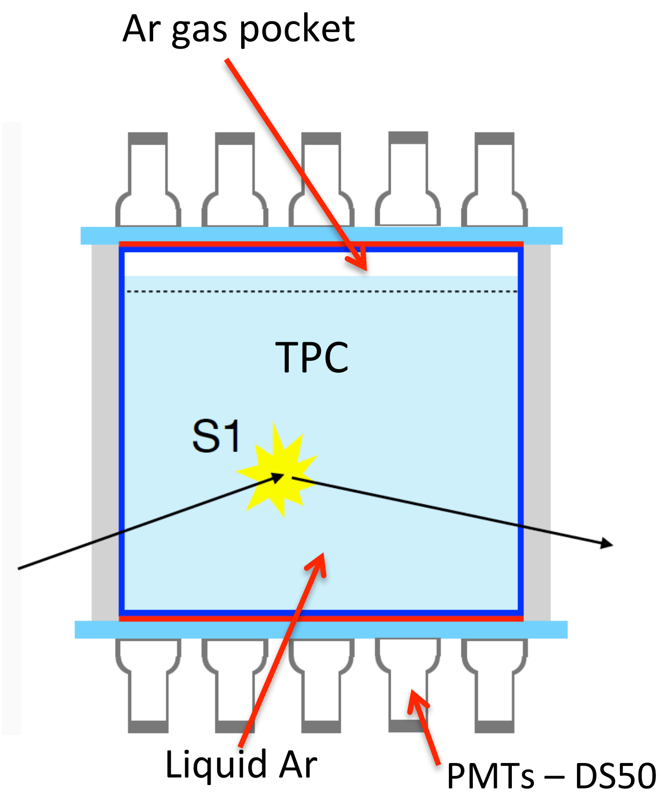
The Darkside Experiment

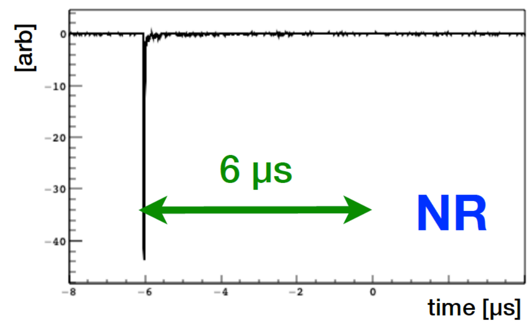


Motivation for the Aria project

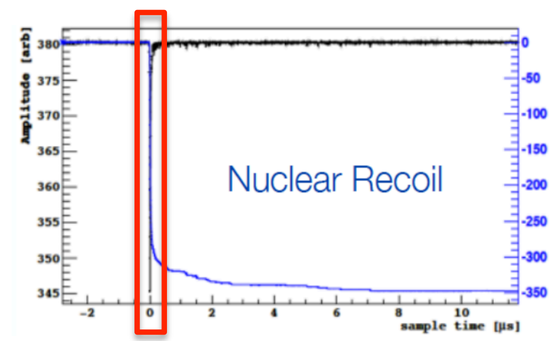
Background Rejection/1:

S1 (scintillation signal) - Pulse Shape Discrimination (**PSD**) using the $\mathbf{f_{90}}$ parameter (fraction of light in the first 90 ns).



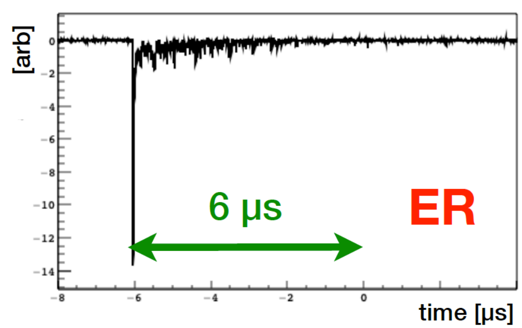


Scintillation signal **S1** for **NR**

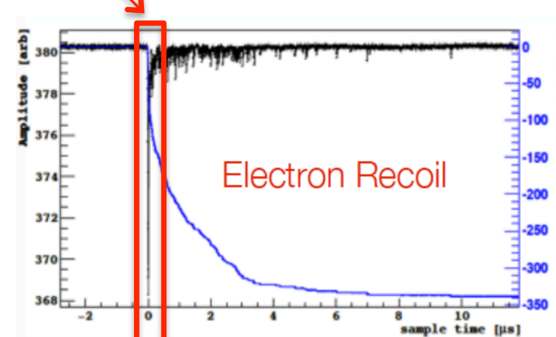


S1 integral for **NR**

90 ns windows



Scintillation signal **S1** for **ER**

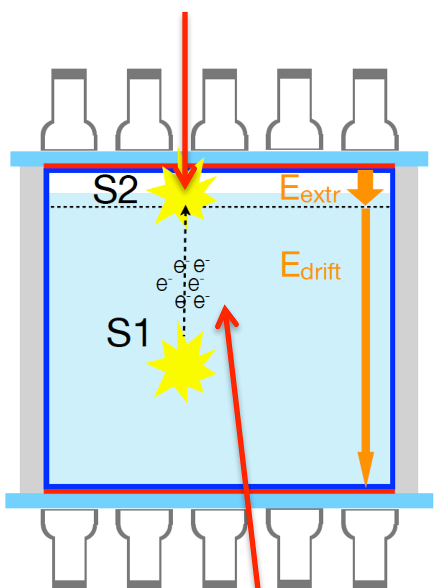


S1 integral for **ER**

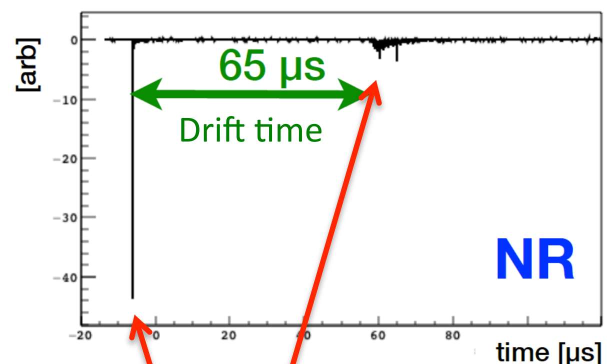
Motivation for the Aria project

Background Rejection/2:
S2/S1 – Ionization/Scintillation signal ratio.

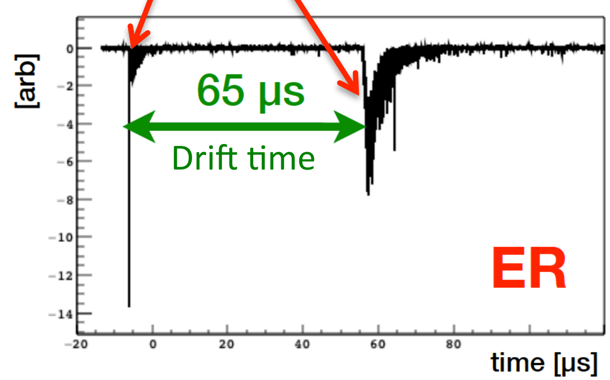
Light collection produced by accelerated (E_{extr}=3 kV/cm) electrons in the Ar gas pocket

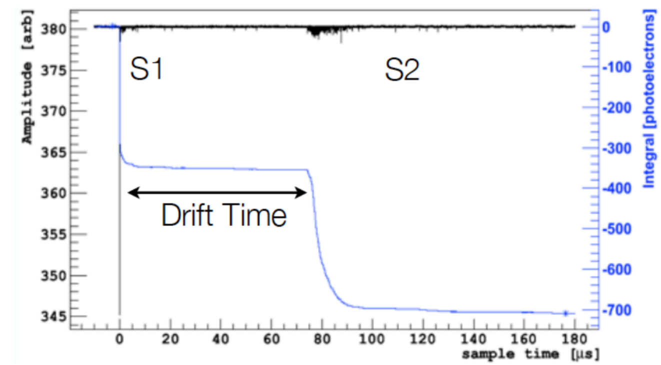


Electrons drift up (E_{drift}=200 V/cm)



S1 and **S2** for **NR** and **ER**





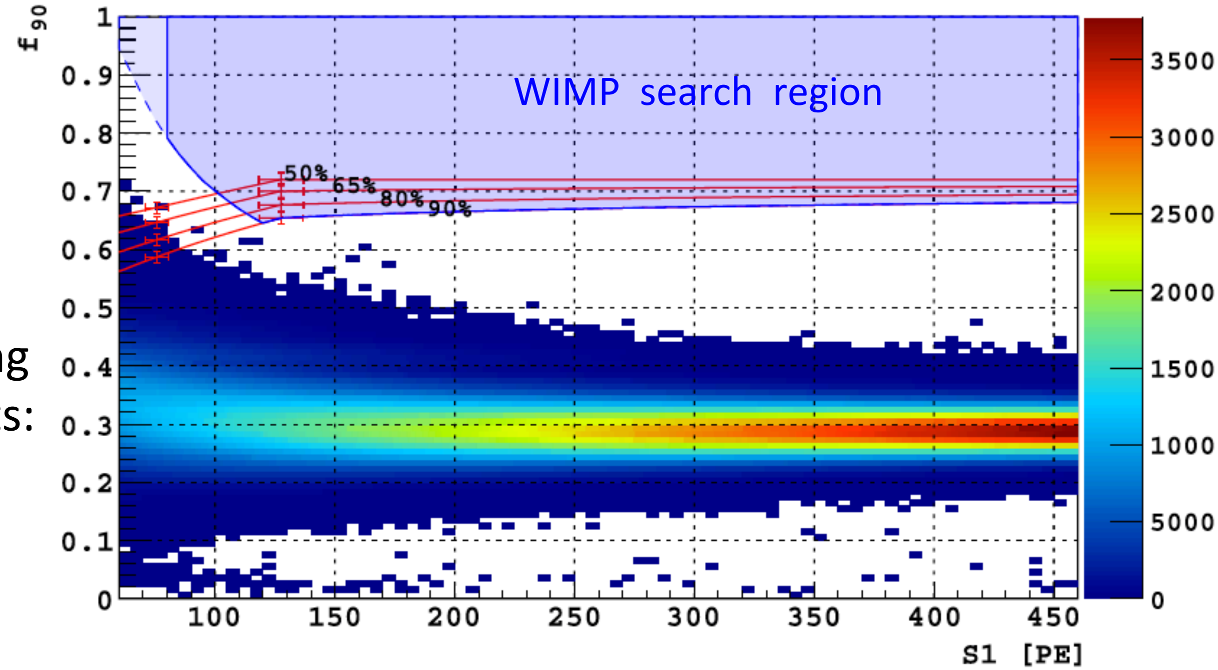
S1 and S2 integral

The ionization signal **S2** allows to determine the **3D position** of the event: **X** and **Y** from PMTs light collection and **Z** from the electrons drift time.

Motivation for the Aria project

Atmospheric Argon: 1422±67 kg day exposure - Phys. Lett B 743 (2015) 456

f_{90} vs S1 plot after applying all quality and physics cuts: **1.6 ×10^7 events remain (mainly ^{39}Ar)**

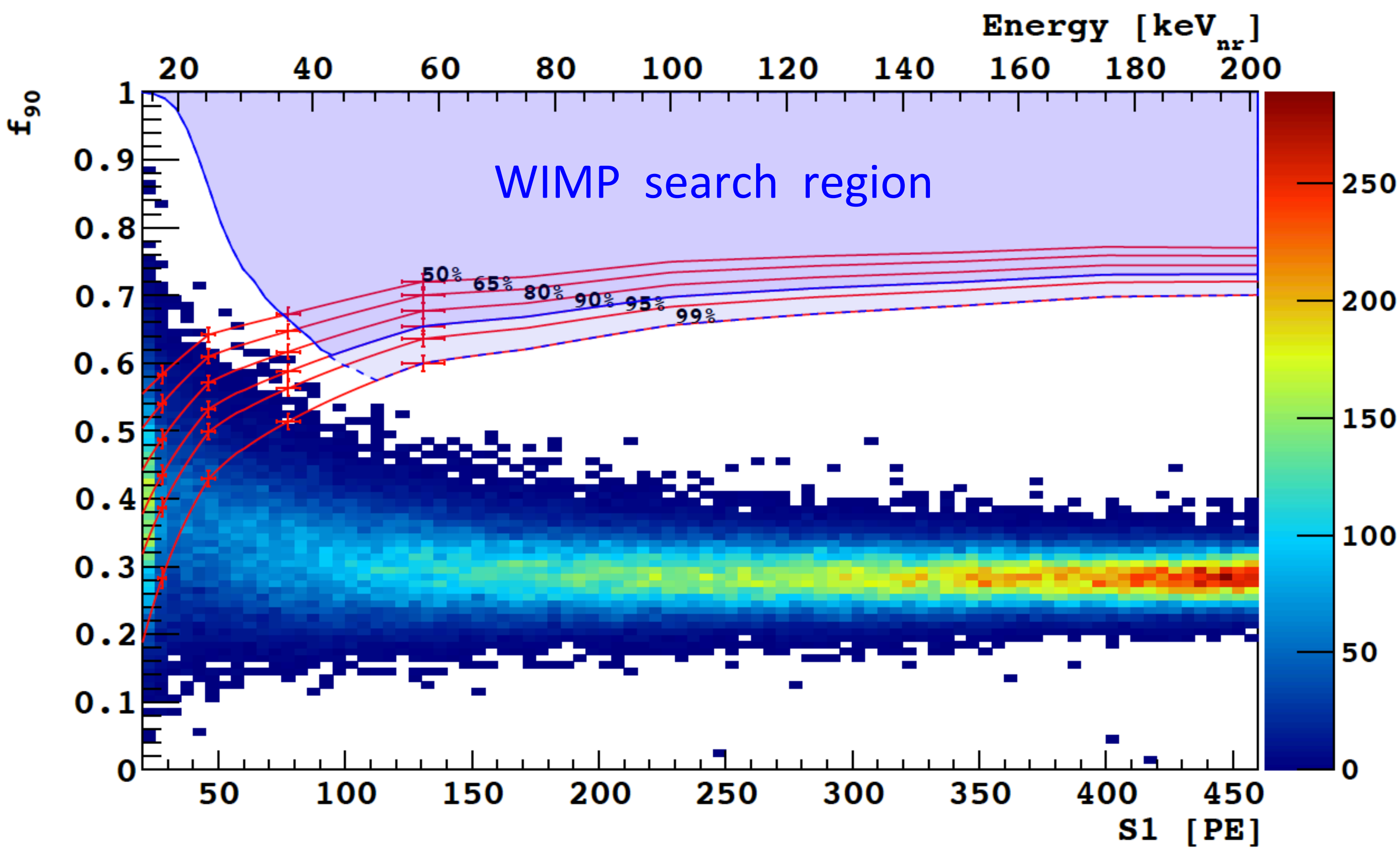


No events in the WIMP Search Region at 90% C.L. -> β/γ rejection power is greater than 1/1.6×10^7 -> DS-20k may run in bkgd free mode for 5.5 t×yr.

Monte Carlo study -> DS-20k may run bkgd free for the 100 t×yr exposure.
ARGO (1000 t×yr) would not be able to run in bkgd free mode.
-> NEED TO FURTHER DEPLETE ARGON OF ^{39}Ar -> **ARIA PROJECT.**

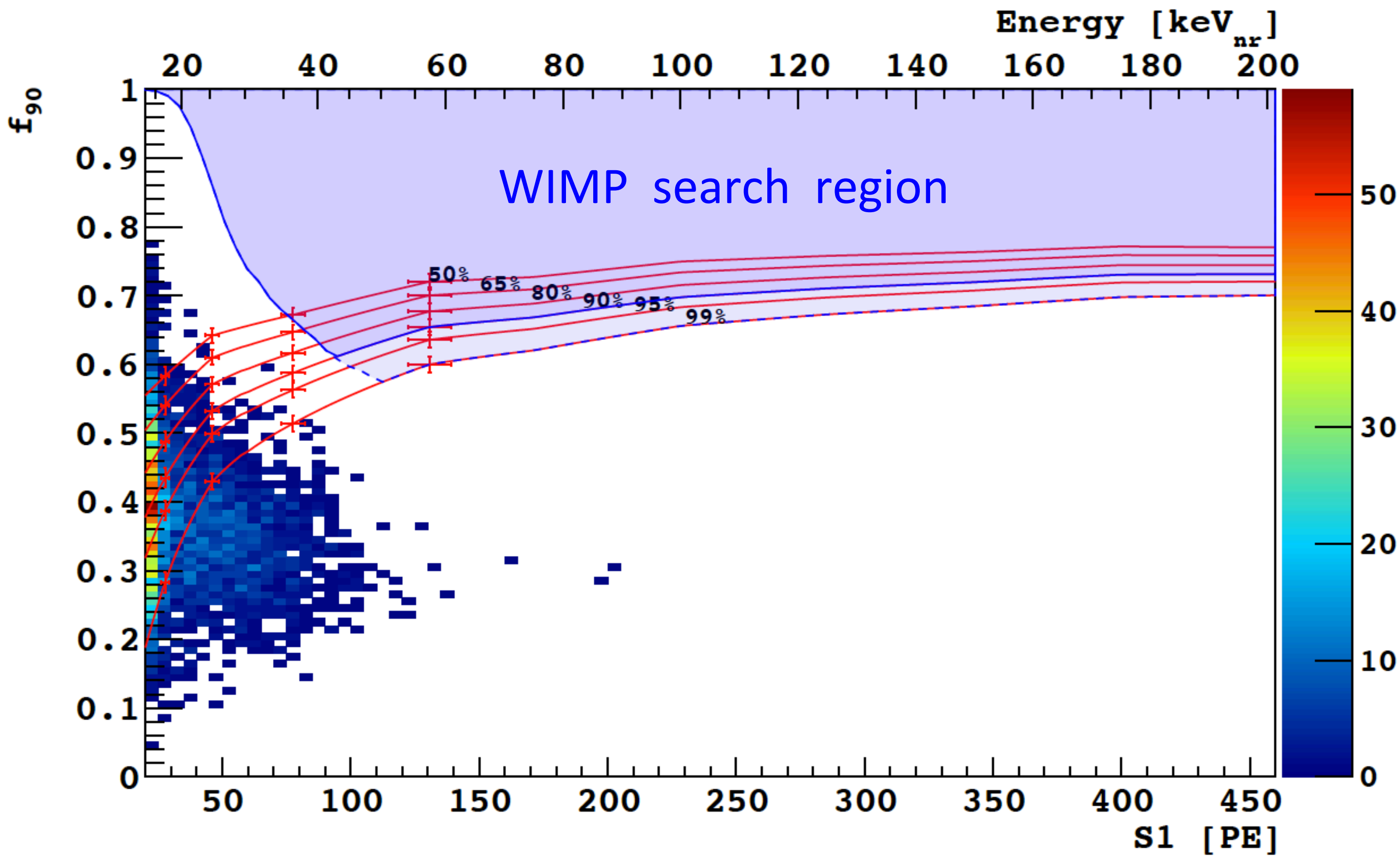
Motivation for the Aria project

Underground Argon: 2616 ± 43 kg×d exposure.
Acceptance in WIMP Search Region grows from 90% to 99%



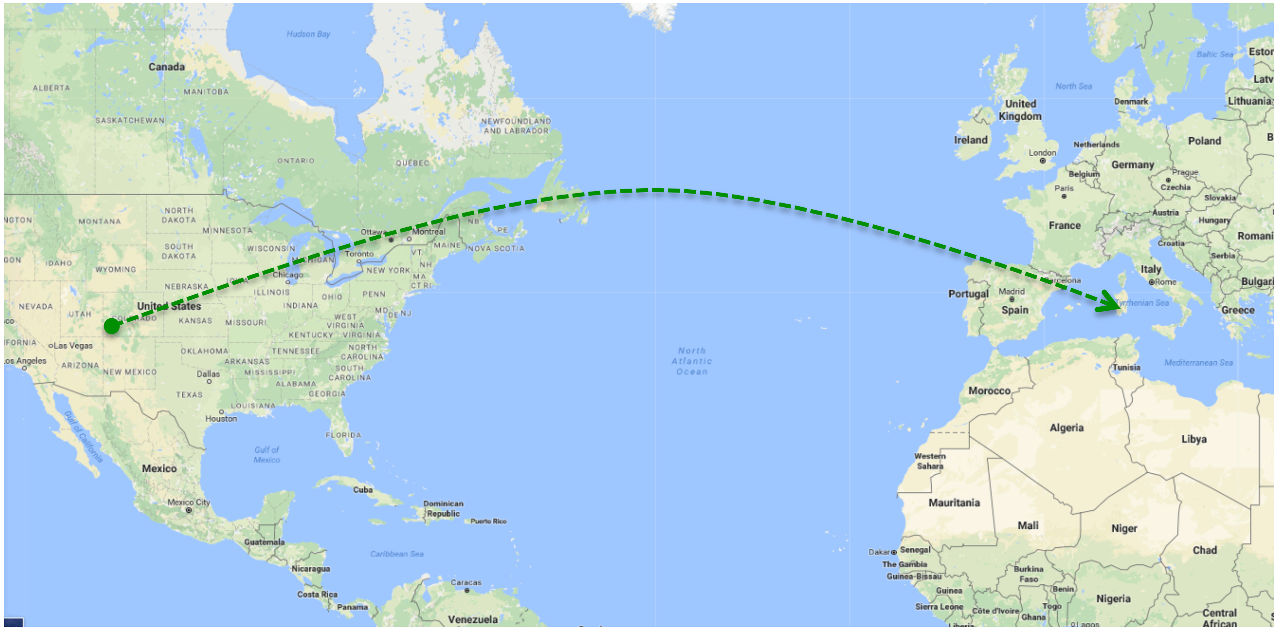
Motivation for the Aria project

Underground Argon: 2616 ± 43 kg×d exposure, after applying S2/S1 cut.
Background rejection power further enhanced!



Aria: Ar process and stable isotope production

The Aria project, located at the Seruci mine in Sardinia, has the aim to perform chemical purification of the UAr extracted from the Doe Canyon CO_2 wells at Cortez (CO) for the DS20k experiment.



It will be also the test bench to develop active depletion of ^{39}Ar from the UAr. Depletion of ^{39}Ar will be needed for the ARGO experiment.

Aria: Ar process and stable isotope production

Some uses of stable isotopes ^{13}C, ^{15}N and ^{18}O:

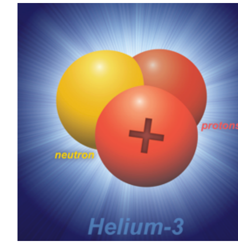
- **Nuclear medicine**: non radioactive, safe to use also in children and pregnant women as tracers.
- **Industrial and technological applications** (semiconductors, navigation systems, oil industry, nuclear power plants,…)

Nuclear Medicine (some examples):

- ^{13}C labeled urea used in breath tests to detect Helicobacter pylori infection
- ^{13}C for studying metabolic changes in the brain by MRI to diagnose neuropsychiatric disorders
- Study of metabolic transformations of drugs in pharmaceutical industry using ^{13}C, ^{15}N, ^{17}O and ^{18}O.

Such isotopes will be produced by Aria**,** entering in a market that is now constrained by supply and their costs dominated by the energy required for separation.

Application fields of ^{3}He isotope



Some ^{3}He relevant aspects:

- ^{3}He is present in traces (0.5-10 ppm) in ^{4}He.
- It is presently obtained from ^{3}H β-decay (tied to nuclear weapon programs)
- Very limited availability and very high cost
- Lack of a suitable technology to satisfy the market demand

1.

National and Homeland Security, Nuclear Non-Proliferation (through Neutron Detectors):

Given its very large cross section for neutron capture, **^{3}He-filled proportional counters** are the best performing detectors for neutrons. They are very effective for monitoring ports and terminals to prevent possible rogue smuggling of nuclear materials.

Their increase in use may prevent possible nuclear terror threats, this being one of the major concerns on National Security nowadays, as reported by the former US president Obama at the 2016 "Int'l Nuclear Security Summit".

Application fields of ^{3}He isotope

2.

Medical Care, Precision Lung MRI:

^{3}He can be hyper-polarized and, upon inhalation by patients, its distribution in lungs can be detected through an advanced Magnetic Resonance Imaging (MRI) scanner to produce extremely detailed anatomical and functional imaging of lung ventilation, characterized by their unprecedented precision [W. Happer et al., Phys. Rev. A 29, 3092 (1984)].

This tool for medical diagnostics was developed twenty years ago and has since been held back from large-scale deployment **due to the lack of availability of the ^{3}He isotope**. *It provides early and specific detection of metastatic cancer cells and other lung diseases*.

Application fields of ^{3}He isotope

3.

Ultra Low Temperature - Dilution Refrigerators and ^{3}He Refrigerators:

Dilution Refrigerators (DR) and ^{3}He refrigerators allow to reach temperature below 1 K and down to few mK. DR are the only systems able to reach very low temperature (2 mK) for an indefinite period of time. The high cost of ^{3}He makes all these refrigerators even more expensive. They are used, as examples, in the following fields:

- **Semiconductors** (Quantum Hall Effect, Quantum Dots, Single Electron Tunneling)
- **Superconductors** (Quantum Computing, Josephson Junctions, Flux Vortices)
- **Solid State Physics** (Heavy Fermion Systems, Metal Insulator Transition, Spin Glass, Mesoscopic Systems, Giant Magnetoresistance, Nanoelectronic Primary Thermometry)
- **Astrophysics**: Dark Matter, Neutrino Mass Measurement, X-ray spectroscopy (Low Temperature Detectors, Transition Edge Sensors, Ge or Si bolometers)

Application fields of ^{3}He isotope

4.

Future applications include the use of **^{3}He as fuel for 2nd and 3rd generation nuclear fusion plants**.

There is a great interest in ^{3}He because the ^{3}He-^{3}He (D-^{3}He) fuel cycle do not (almost) generate neutrons, whereas in the D-T fusion 80% of the energy is wasted in neutrons which are moreover difficult to contain.

Consequently, ^{3}He has also to be seen as a viable solution to achieve a 100% safe, clean and adequate way for producing the energy the humanity will need on the Earth in the next decades.

^3He separation with the SOPHIE Project

- This project has been designed by INFN/PU collaborators
- A proposal has been submitted to H-2020 - FET OPEN
- No funds up to now have been granted for its construction

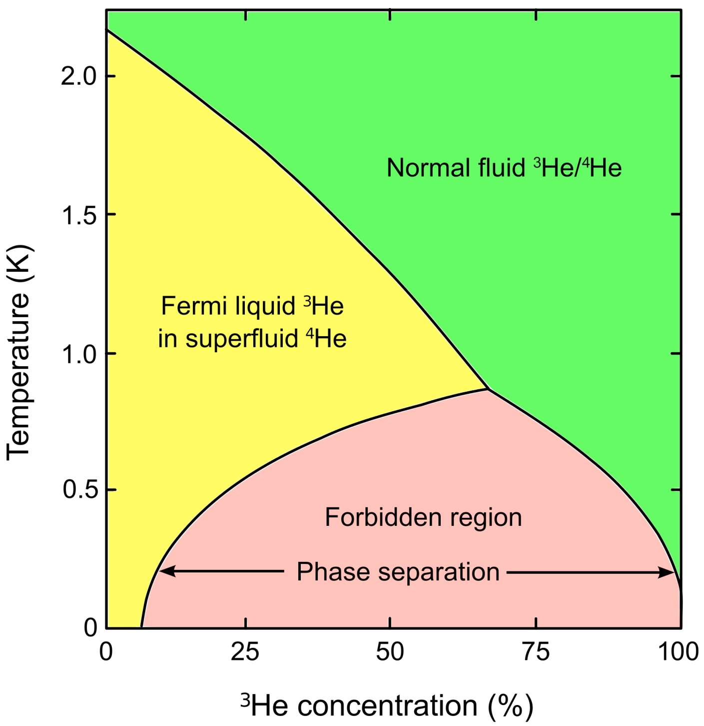
Three independent thermodynamic variables describe the properties of the $^3He/^4He$ mixture:

- Temperature
- Pressure
- ^3He concentration (or mole fraction)

At 1.35 K:

- 3He maximum concentration is 50%
- ^4He (^3He) vapour pressure is 2.13 (43.8) mbar.

As a consequence more than 95% of the vapour is ^3He and can then be collected and stored for all the required, already mentioned, uses.



^{3}He separation with the SOPHIE Project

The **SOPHIE** (**S**eparation by reverse **O**smosis **P**rocess for **H**elium-3 **I**sotope **E**xtraction) project in short:

- The novelty of this apparatus consists in separating ^{3}He and ^{4}He in a continuous mode, at a fast rate and at much cheaper costs allowing ^{3}He production on industrial scale with 95% concentration, 5% of ^{4}He and less than 0.01% of impurities (i.e. other gases).
- Of course, if/when requested, higher purity ^{3}He (>99%) is achievable lowering the operating temperature down to 1 K.
- The natural helium, presently extracted by the companies from gas wells, is already liquefied in situ at 4.2 K and this allows the ^{3}He extraction in a very cost effective way.
- **We look forward for this project to be funded soon!**

THE END