# Recent results from the DarkSide experiment

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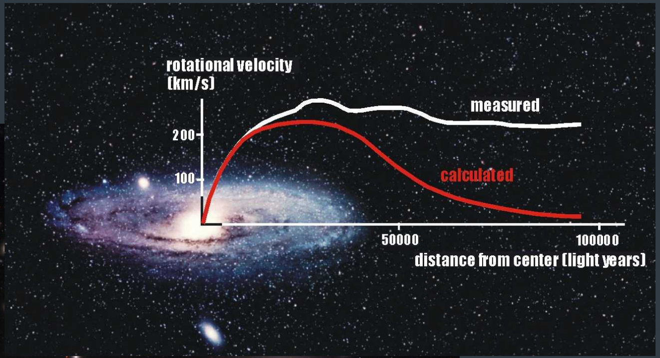
**Seminar @ LLR 12/04/2015**

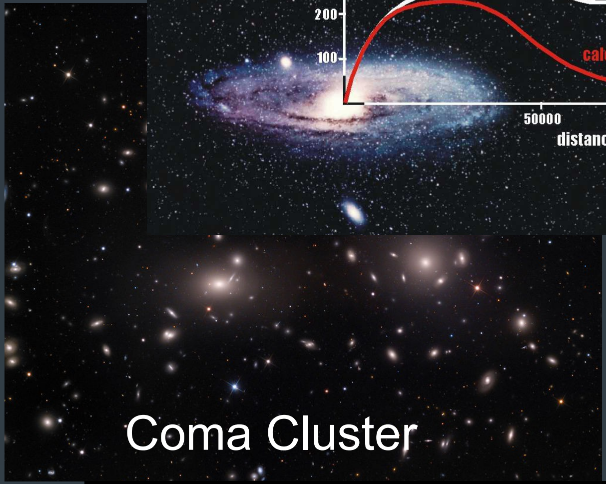
# Outline

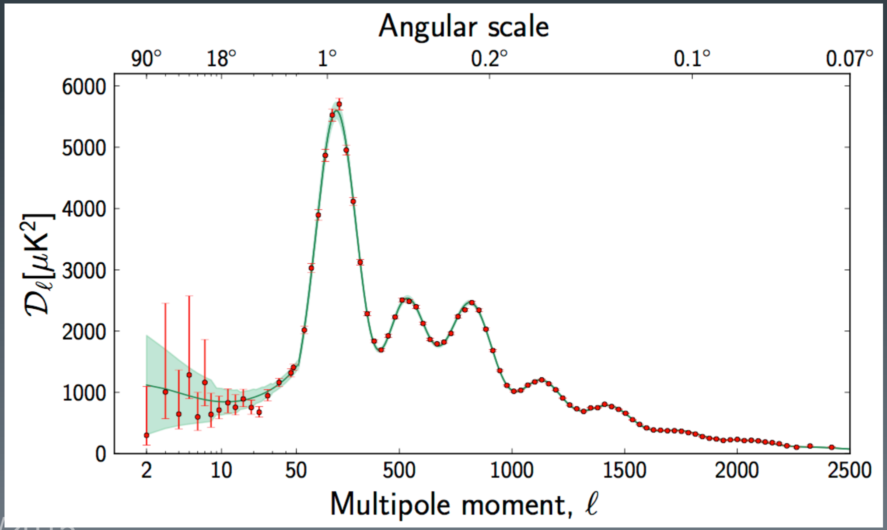
- Dark Matter and WIMP hypothesis
- WIMPs searches with noble liquids
- Darkside-50 detector
- Physics results
- Next steps

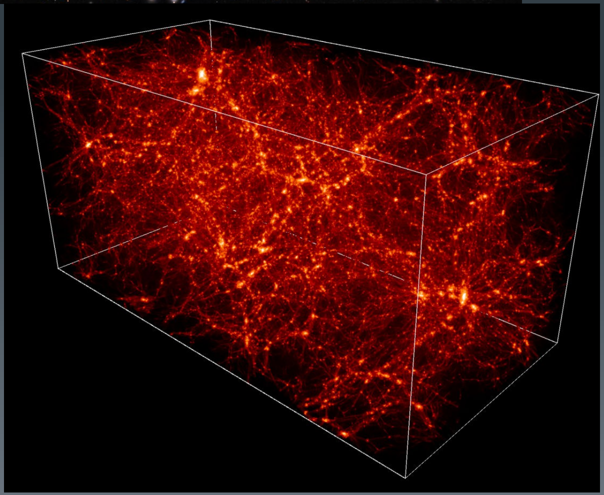
# Indications of Dark Matter

- Several compelling gravitational indications for Dark Matter from different sources
  - Galactic rotation curves
  - Large Scale structures
  - Acoustic peaks in CMB
  - Gravitational lensing



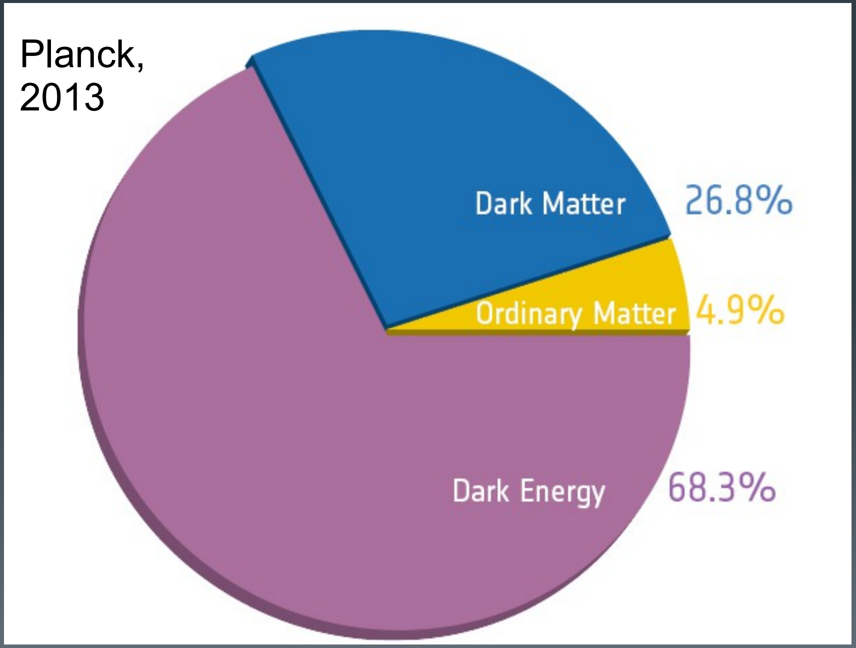



# Dark Matter and WIMPs

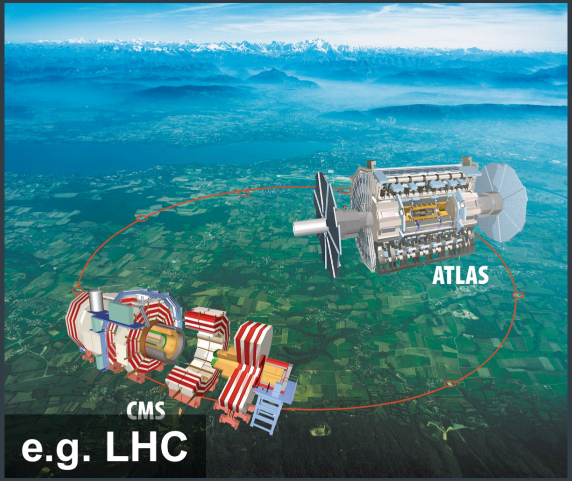
- The ordinary matter can make the ~5% of the Universe
  - 27% Dark Matter, 68% Dark Energy

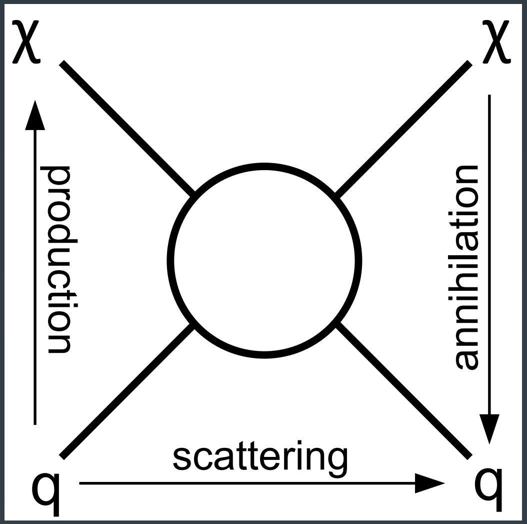



- Among the different candidates WIMPs (Weakly Interacting Massive Particles) are well motivated
  - Arise naturally in theories beyond the SM
  - WIMP miracle → relic density of the DM coincides with the self-annihilation cross-section of the weak force

# Dark Matter detection

Production of DM
at accelerators



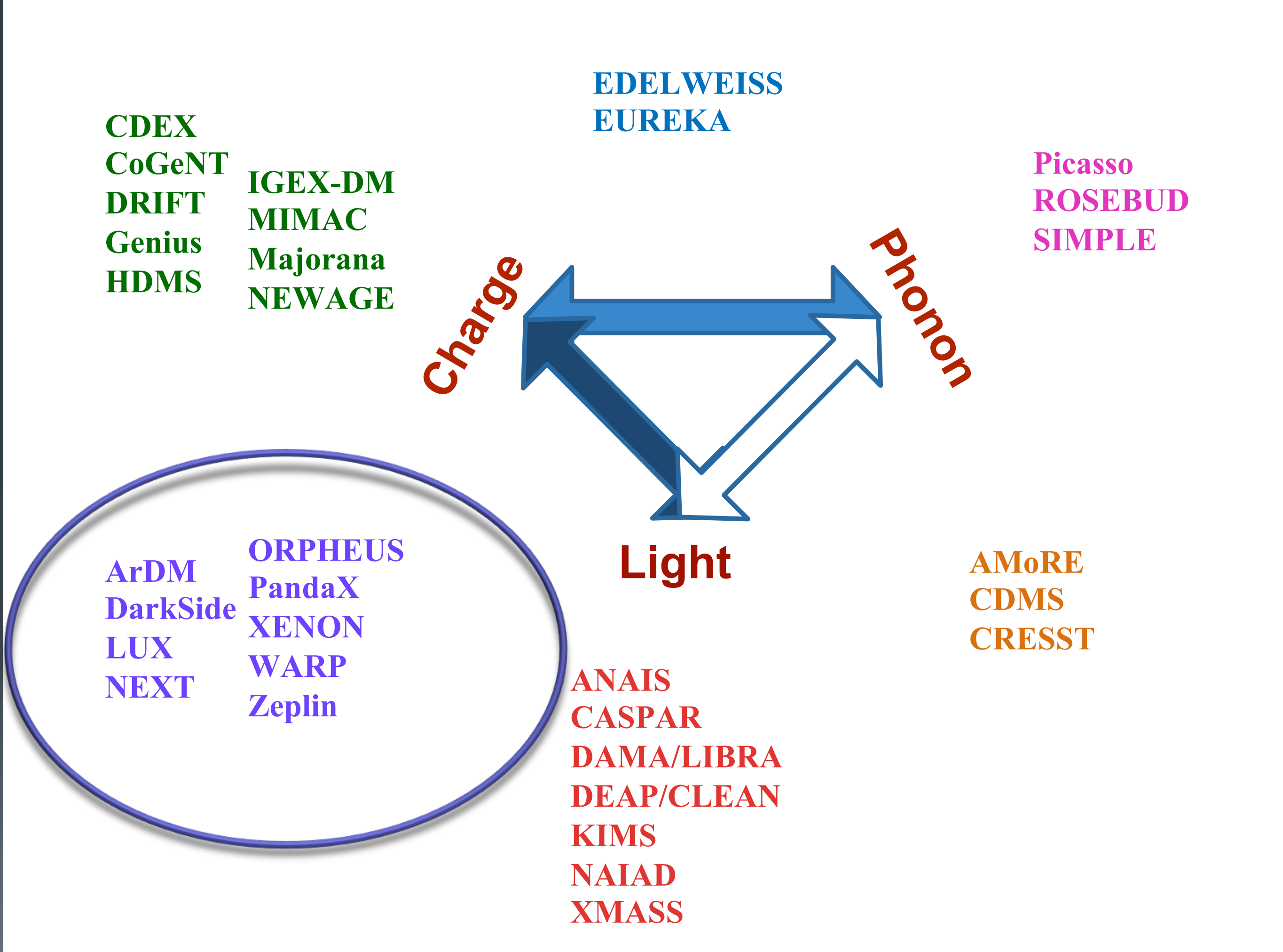




Indirect detection:
annihilation of DM

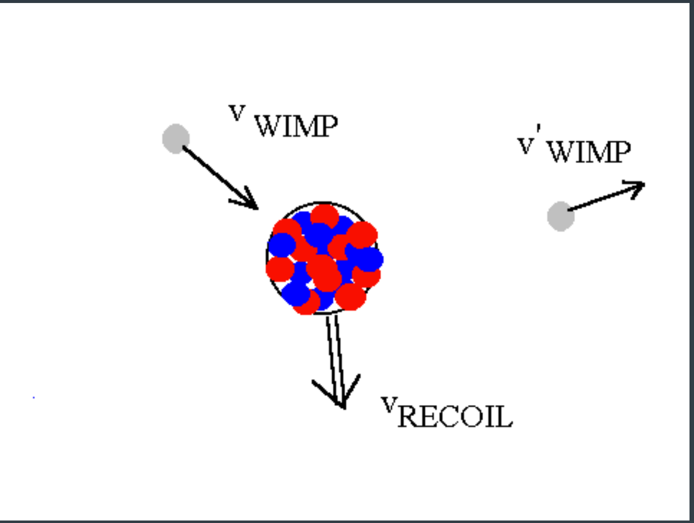


Direct detection:
scattering of DM

# Direct dark matter detection



# Dark Matter Direct Detection




Low rates (~1 ev/ton/yr @ $\sigma=10^{-47}cm^{-2}$) → large target masses

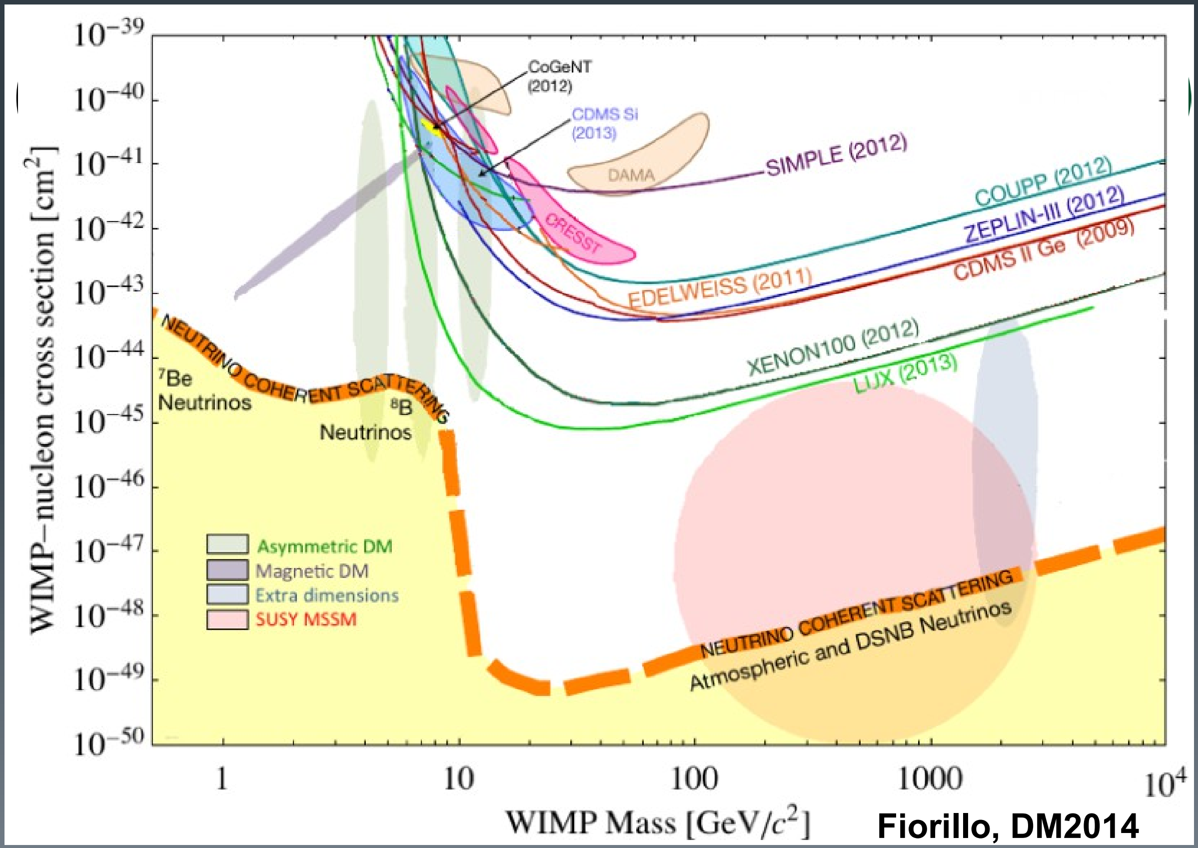
Low energy recoil → low detector thresholds

Background suppression

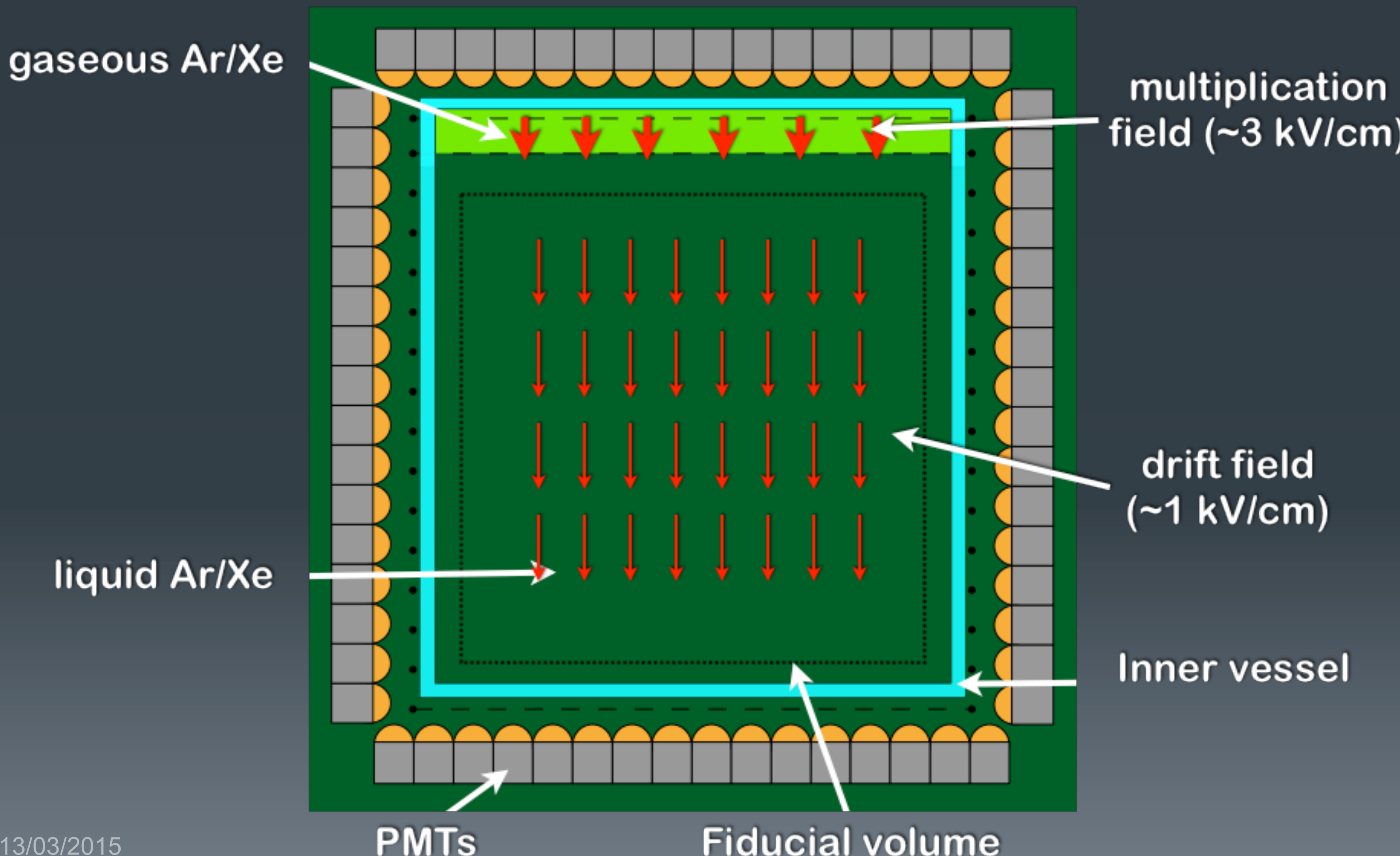
- ❑ Noble liquids TPC
  - ❑ large target masses with low thresholds
  - ❑ Deep underground
  - ❑ Passive and active shielding
  - ❑ Low radioactivity
  - ❑ Discrimination of electron recoils from nuclear recoils

# Noble Liquid TPCs

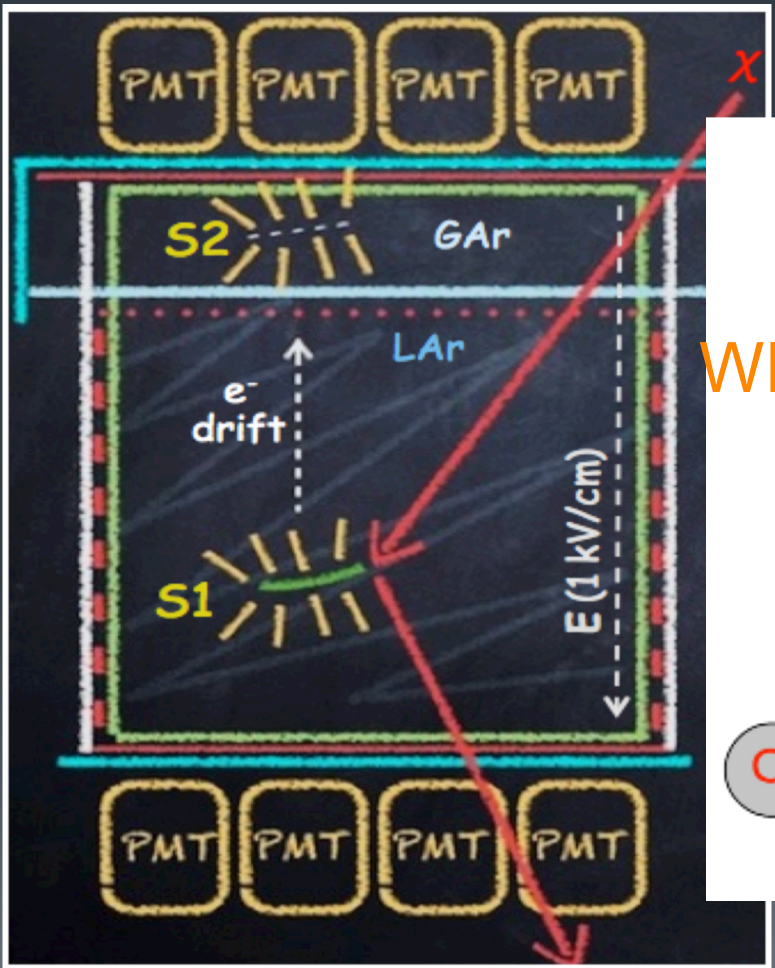
- Today the best limits for the WIMPs cross-section are obtained with Liquid Xenon Double Phase TPC (Xenon100 and LUX)

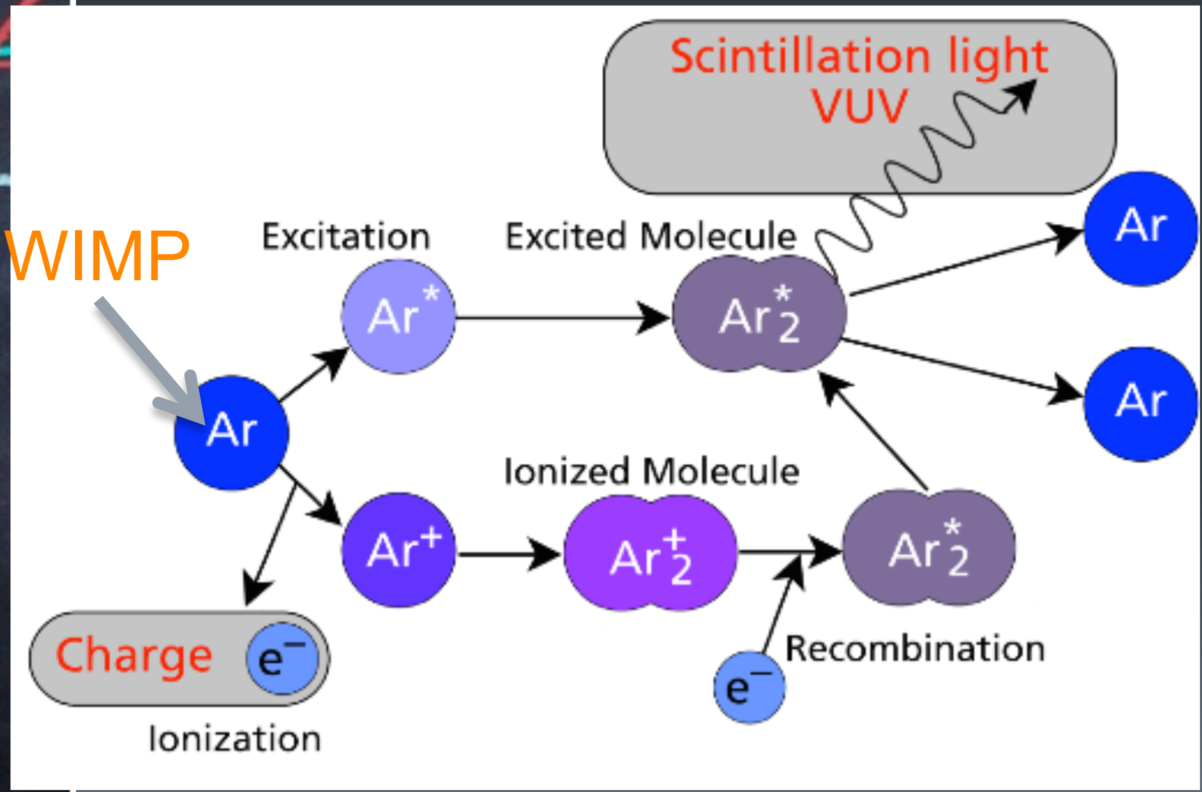


# Double Phase TPC



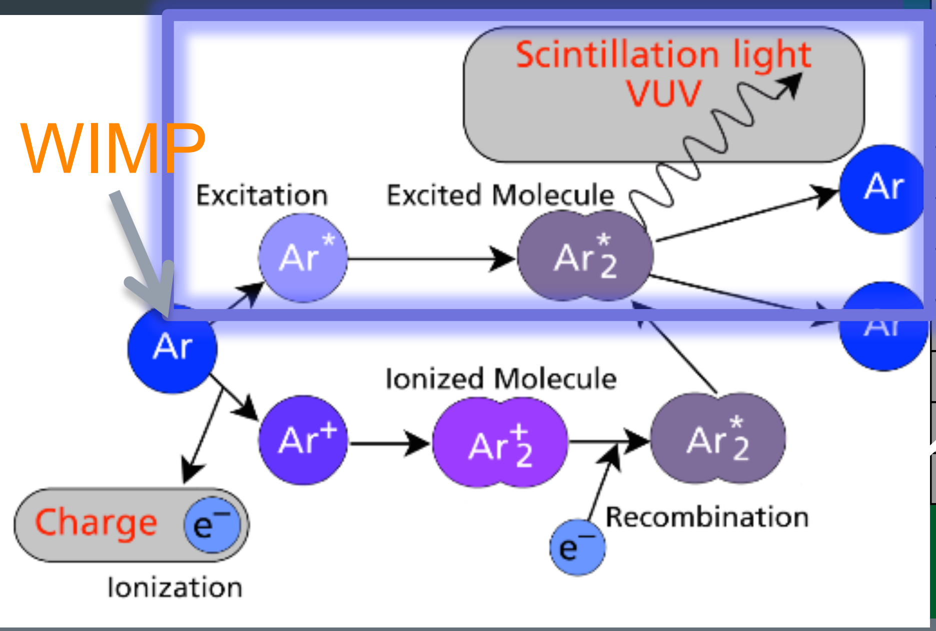
# WIMP scattering in Ar (or Xe)

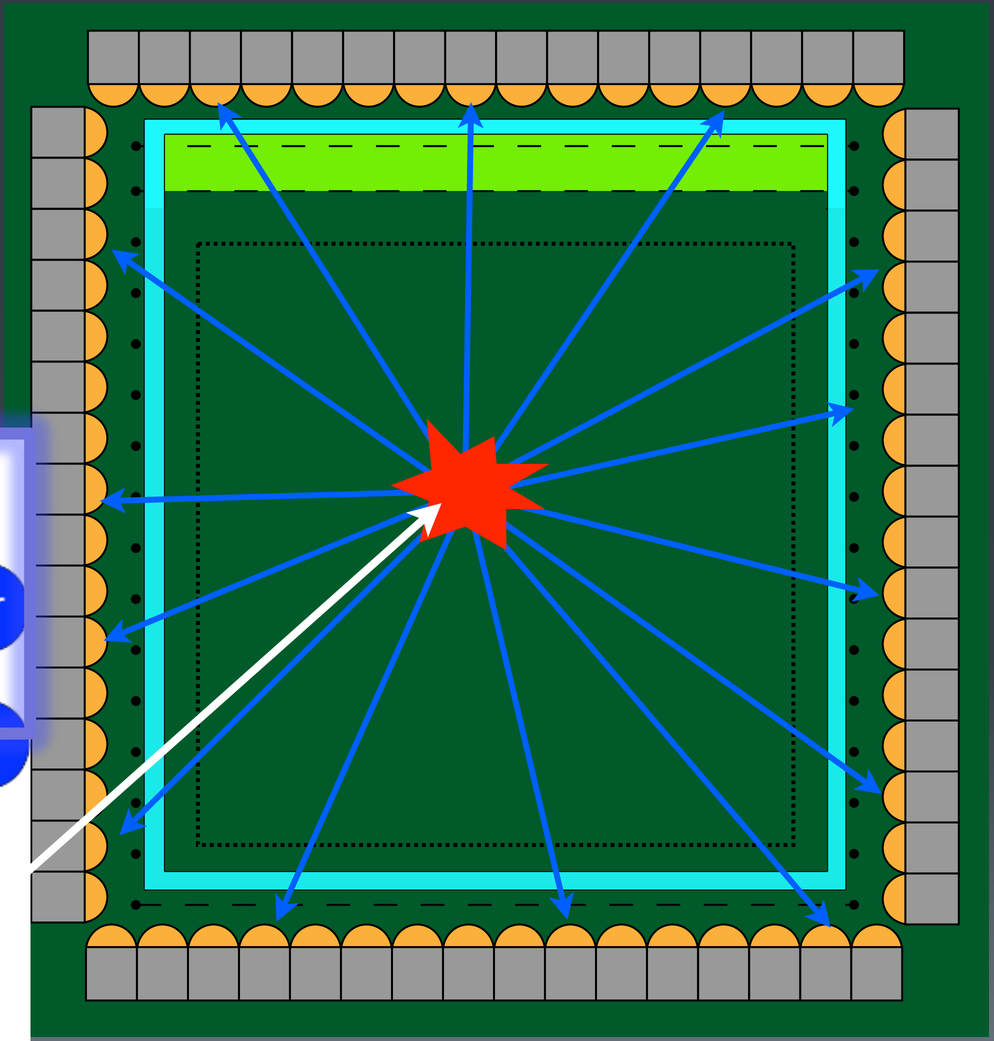


# What we see in the detector: Scintillation

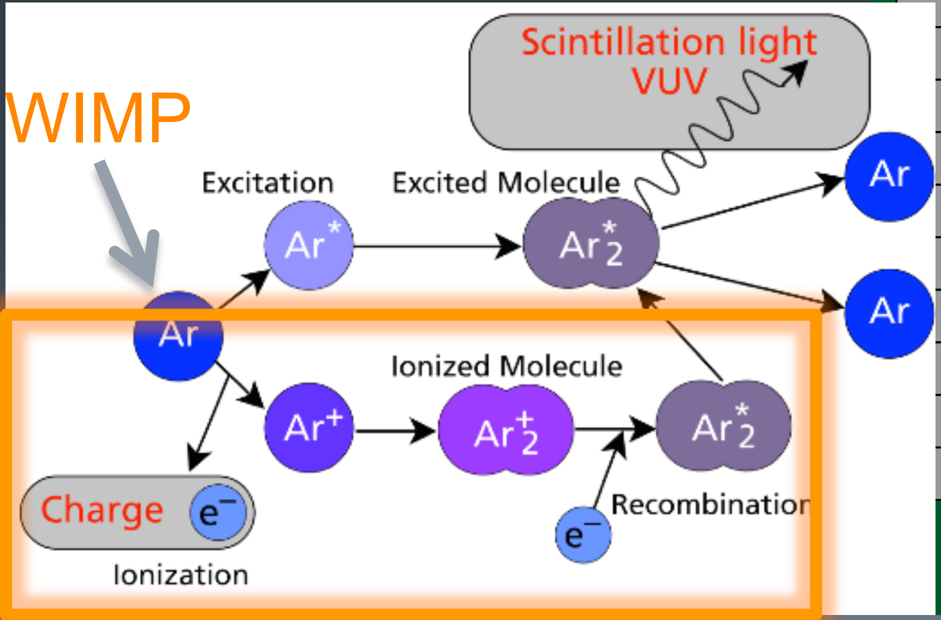
Primary scintillation photons emitted and detected on the PMTs → **S1**

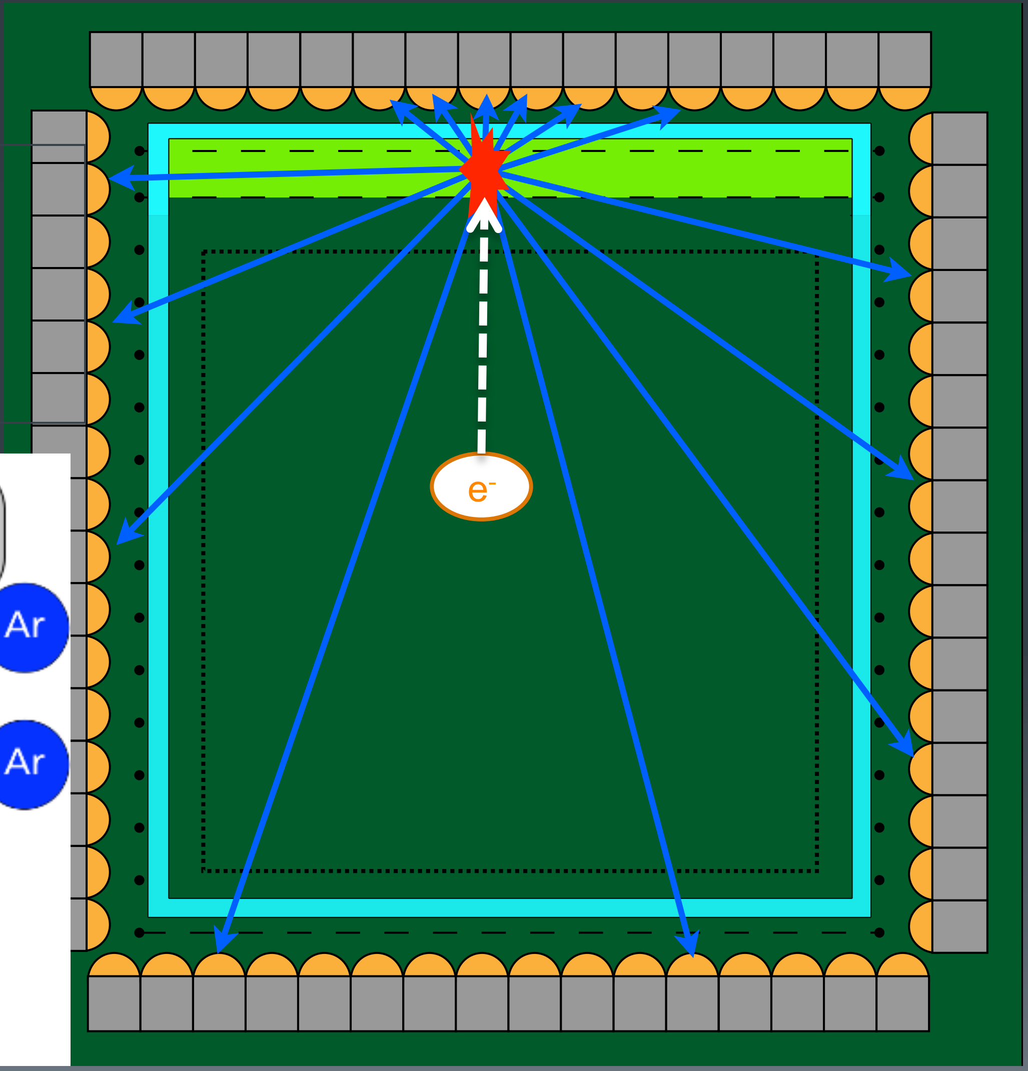


# What we see in the detector: Ionization

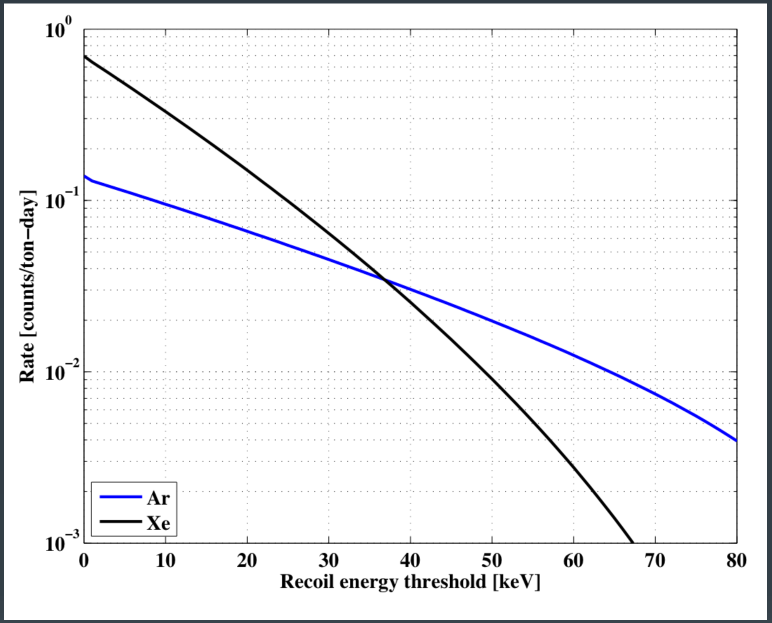
Electrons drift towards the top of the TPC and are extracted in the gas phase where they are accelerated emitting secondary light → S2



# Why Liquid Argon

- Relatively inexpensive and dense
- Easy to purify
  - Most impurities freeze out in colder liquids
- Ionization electrons:
  - High ionization (W=21.5 eV)
  - High electron mobility and low diffusion
- Scintillation photons:
  - Very high scintillation yields (40000 ph/MeV)
  - Transparent to its own scintillation
- Exceptional discrimination power
  - S1/S2
  - Pulse Shape Discrimination




- One problem
  - $^{39}$Ar contamination

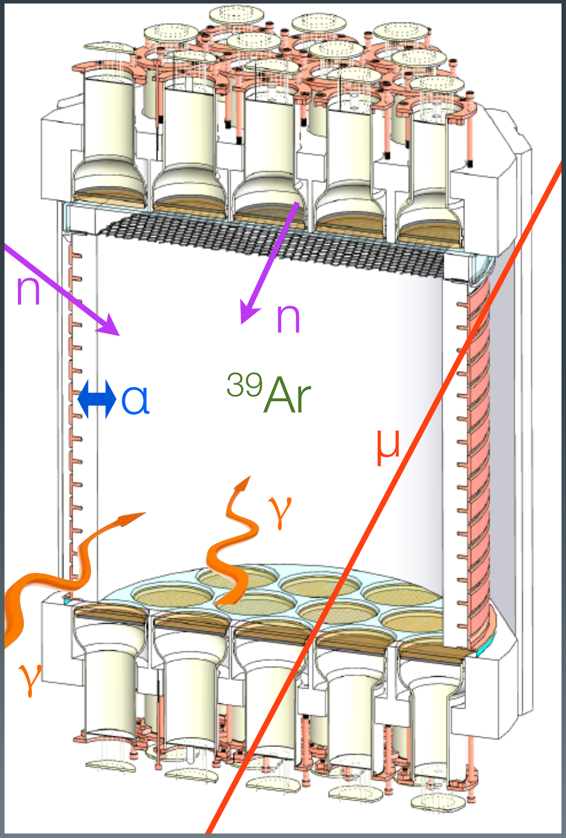
# WIMPs and Backgrounds

- Typical WIMPs rate ($M=100$ GeV, $\sigma_{SI}=10^{-45}$ cm$^2$) ~ $10^{-4}$ evt/kg/day
- A WIMP will produce a nuclear recoil in the TPC

Electron recoils:

$^{39}Ar \rightarrow 10^4$ evt/kg/day (atmospheric argon)

$\gamma \rightarrow 10^2$ evt/kg/day




Nuclear recoils:

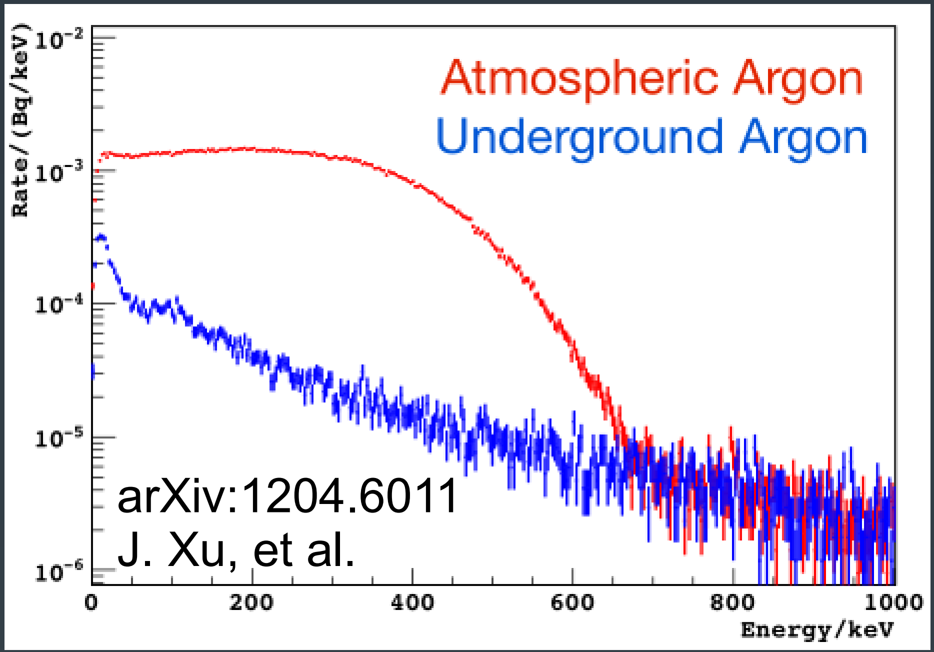
$\mu \rightarrow 30$ evt/m$^2$/day

$\alpha \rightarrow 10$ evt/m$^2$/day

Radiogenic neutrons $\rightarrow 6\times10^{-4}$ ev/kg/day

# Underground argon

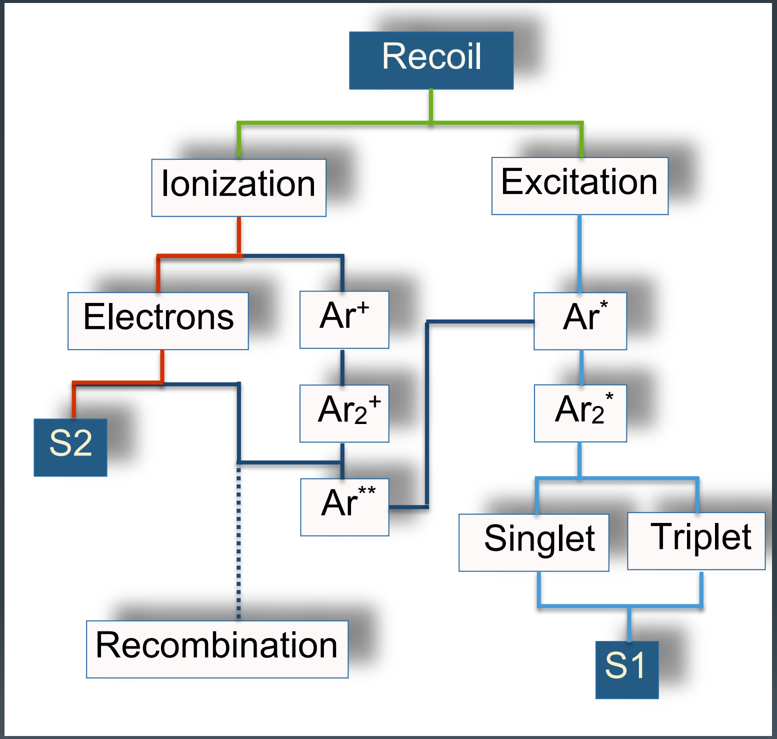
- In atmospheric Argon there is a small component of cosmogenic $^{39}Ar$ → β decay producing electron recoils with a rate of $10^4$ evts/kg/day
  - $^{39}Ar$/WIMPs ~ $10^8$
- Pile-up for large LAr detector




- Underground Argon do not contain $^{39}Ar$ (cosmogenic) → $^{39}Ar(UAr)/^{39}Ar(AAr)<1/150$
- We can build large LAr detectors using Uar
- Still $^{39}Ar$/WIMPs ~ $10^6$ → Need to discriminate ER from NR

# Pulse shape discrimination

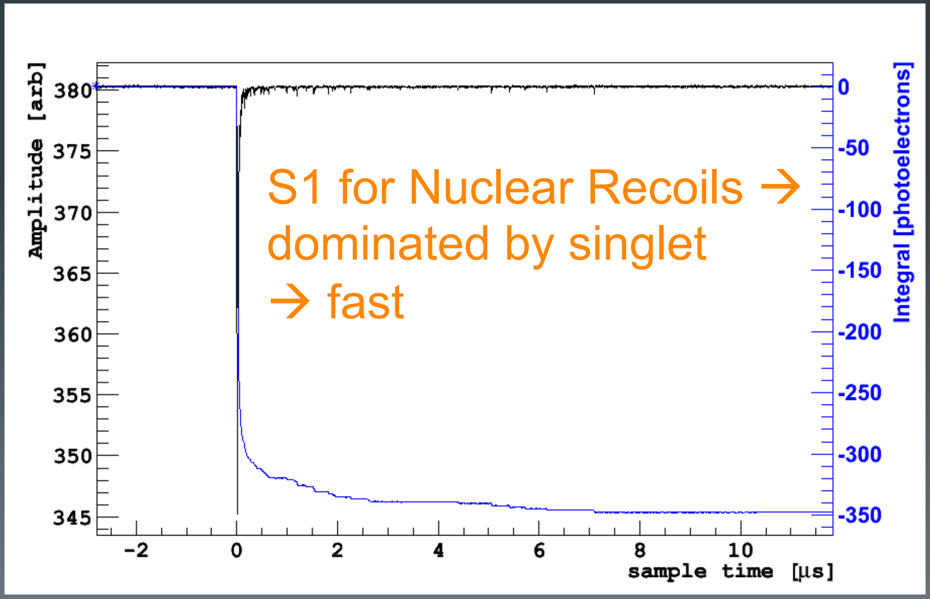
- What is unique in LAr is the capability of distinguish electron recoils from nuclear recoils thanks to the different shape of the scintillation signal
  - ER → most of the excitation goes in the triplet state (decay-time ~1600 ns)
  - NR → most of the excitation goes in the singlet state (decay-time ~7 ns)

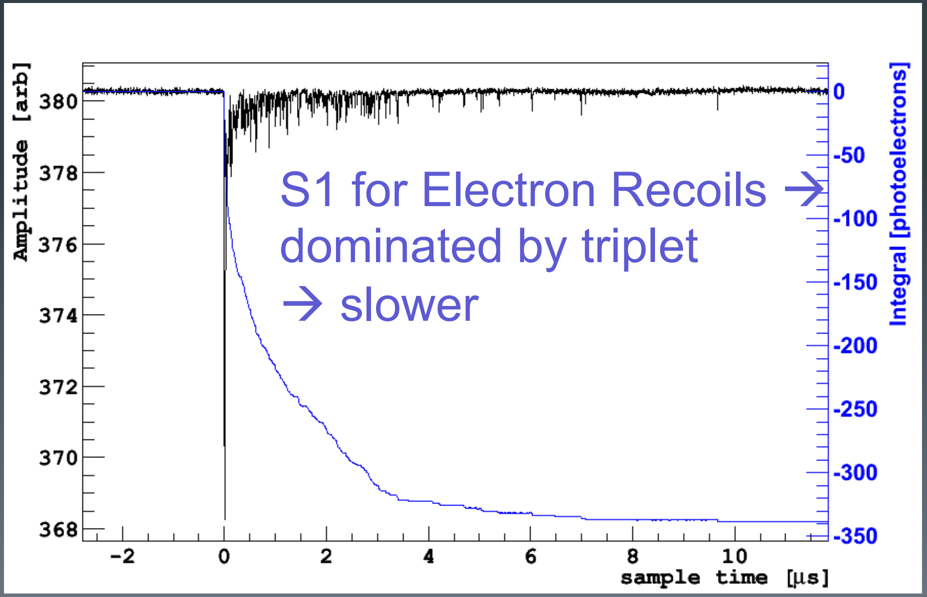



| | Singlet | Triplet |
|---|---|---|
| Time constant | ~7 ns | ~1.6 μs |
| Population ratio for Electron ionizing | 33% | $\boxed{67\%}$ |
| Population ratio for Nucleus ionizing | $\boxed{75\%}$ | 25% |

# Pulse shape discrimination

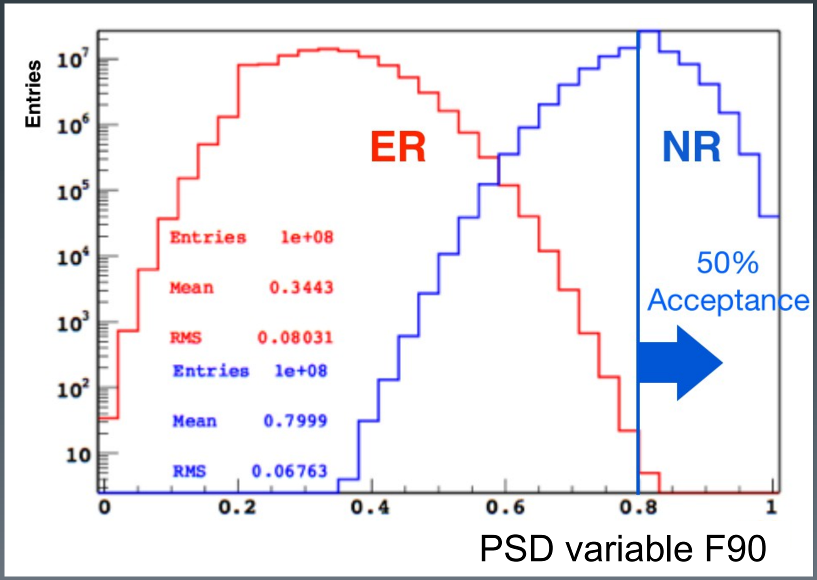
- The shape difference allow to distinguish with an exceptional power (>$10^8$) ER from NR
- This is a unique feature of LAr detectors
  - In Liquid Xenon the PSD is not possible (singlet and triplet have similar decay-time)
  - They can only distinguish ER from NR with S1/S2 → rejection power of $10^2$

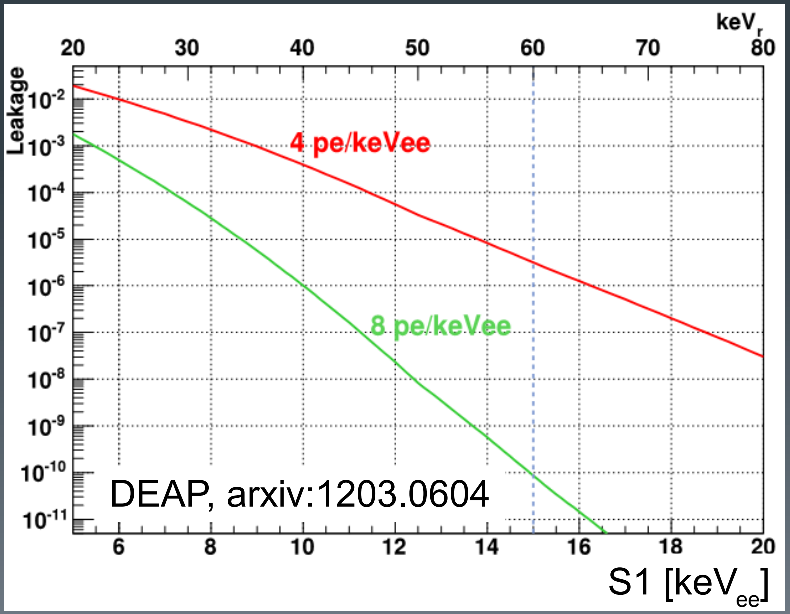


# Pulse shape discrimination

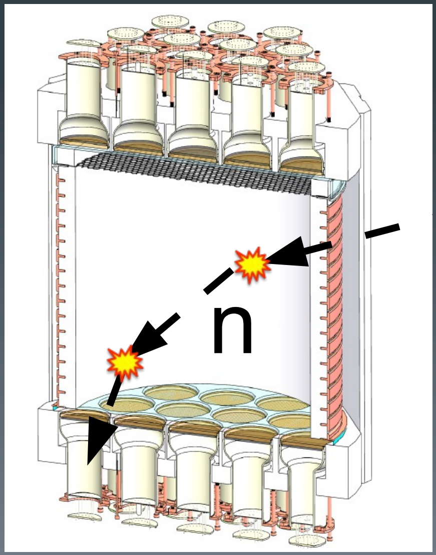
- $f_{90}$ → charge collected in S1 in the first 90 ns divided by the total S1 → fraction of singlet state
  - ~0.3 for ER, ~0.7 for NR
  - Fundamental to have large light yield (>7-8 pe/keVee)
  - Expect discrimination power > $10^8$ (for 60 keVr and 8 pe/ $keV_{ee}$ of light yield)

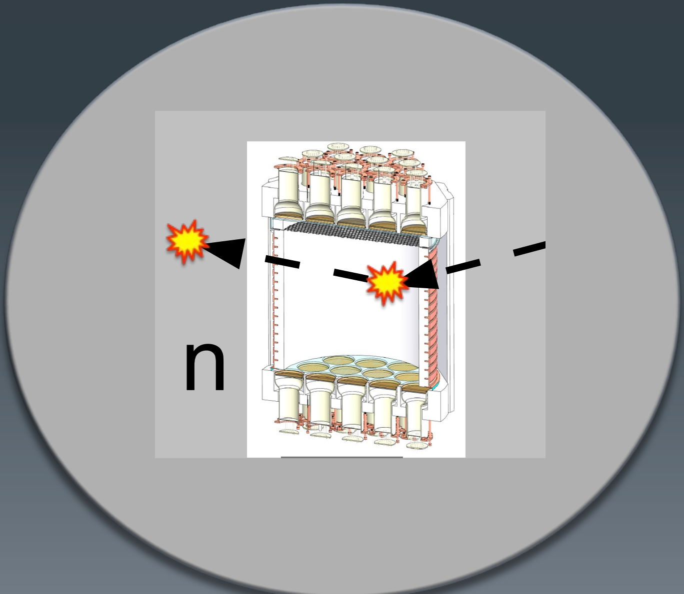


# Neutron Veto

- Once the ER have been rejected we are left with a background from neutrons producing NR similar to WIMPs
- Expected rate ~ $6\times10^{-4}$ evts/kg/day (WIMPs < $10^{-4}$ evts/kg/day)
- Can be distinguished either with multiple scattering in the TPC or using coincidence with a Veto
  - DarkSide is the first experiment with an active neutron veto



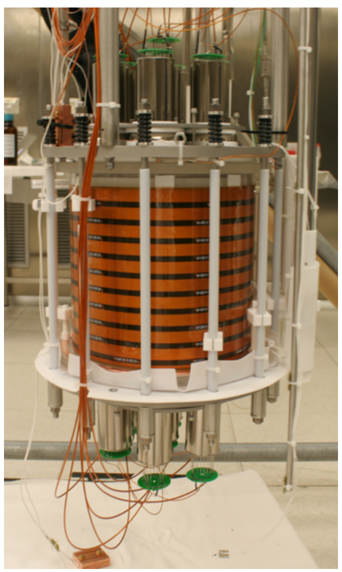
# The DarkSide physics program

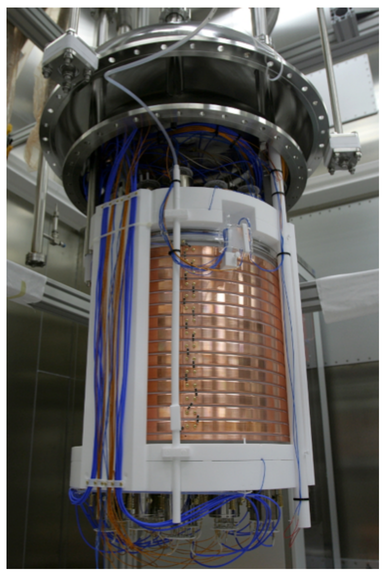
- Phased approach → goal to reach the neutrino floor

**DarkSide-10**
2011-2013

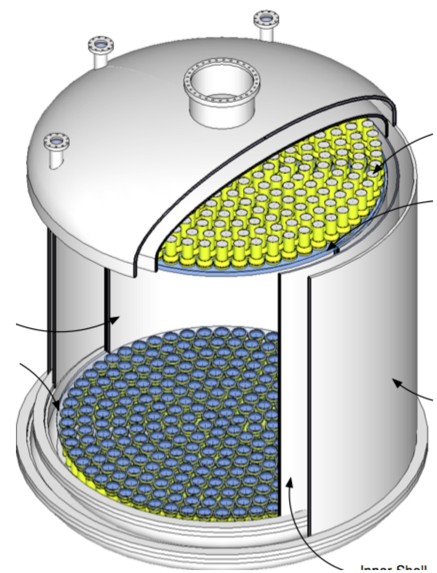
**DarkSide-50**
2013-2016

10 kg | 50 kg | 5 ton | 100 ton





**$\sim 10^{-45}$ cm$^2$**



**$\sim 10^{-47}$ cm$^2$**

?

**"neutrino floor"**
**$\sim 10^{-48}$ cm$^2$**

# DarkSide collaboration

ITALY

INFN Laboratori Nazionali del Gran Sasso – Assergi
Università degli Studi and INFN – Cagliari
Università degli Studi and INFN – Genova
Università degli Studi and INFN – Milano
Università degli Studi Federico II and INFN – Napoli
Università degli Studi and INFN – Perugia
Università degli Studi Roma Tre and INFN – Roma

USA

Augustana College – SD
Black Hills State University – SD
Fermilab – IL
Princeton University – NJ
SLAC National Accelerator Center – CA
Temple University – PA
University of Arkansas – AR
University of California – Los Angeles, CA
University of California – Davis, CA
University of Chicago – IL
University of Hawaii – HI
University of Houston – TX
University of Massachusetts – MA
Virginia Tech – VA

FRANCE

APC – Paris
LPNHE – Paris
IPHC - Strasbourg

CHINA

IHEP – Beijing

POLAND

Jagiellonian University – Krakow

Ukraine

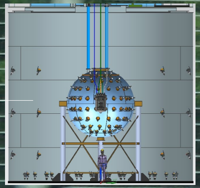
KINR, NAS Ukraine – Kiev

RUSSIA

Joint Institute for Nuclear Research – Dubna
Lomonosov Moscow State University – Moscow
National Research Centre Kurchatov Institute – Moscow
Saint Petersburg Nuclear Physics Institute – Gatchina

# What is DarkSide-50?

a two phase liquid argon (LAr) detector,
within a neutron veto,
within a muon veto,
under a mountain



… and all because of backgrounds



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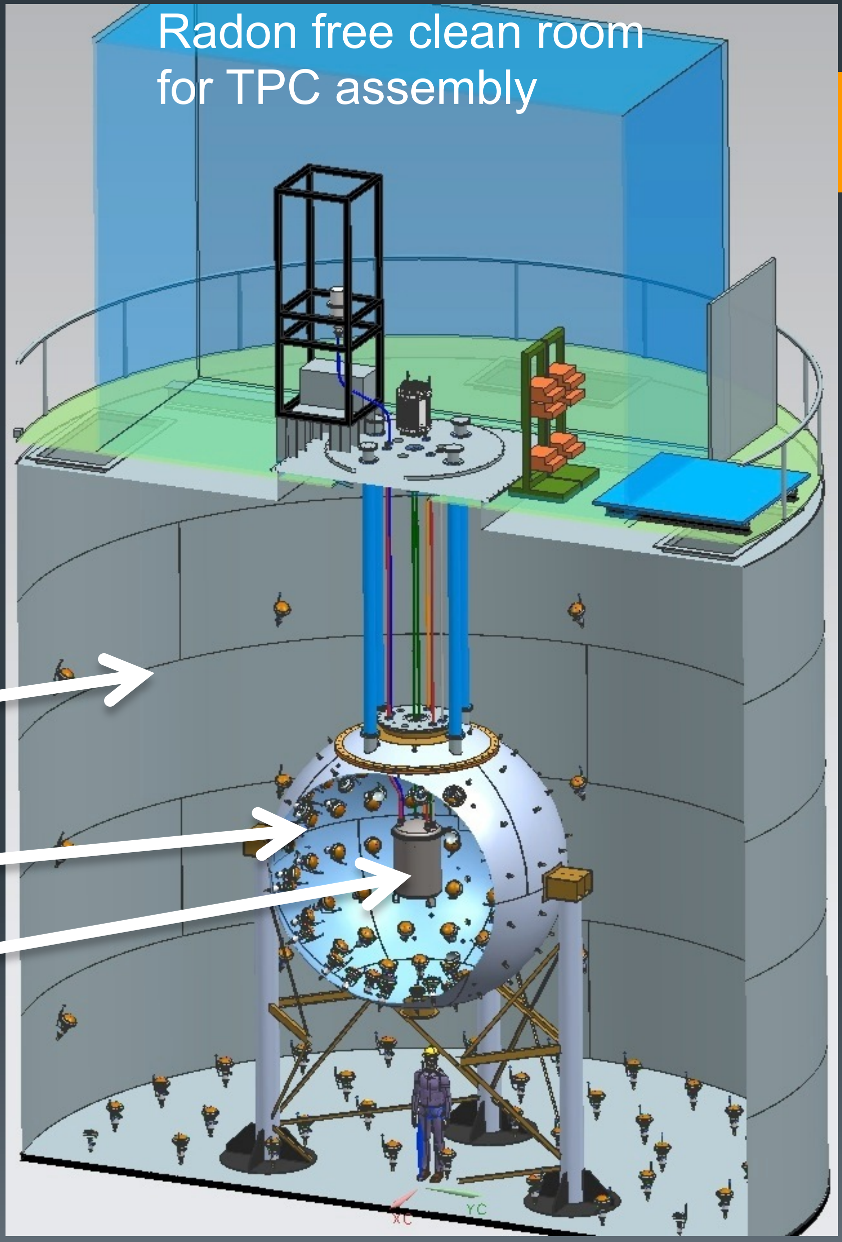
# DarkSide-50

- Experiment installed in the Gran Sasso Laboratory → passive shielding
- 2 vetoes system
  - Water Cerenkov muon veto
  - Liquid scintillator veto (active background measurement)
- Double phase TPC with 50 kg of liquid Argon
- Started data taking in January 2014 with Atm. Ar



# DarkSide-50 goals

- Demonstrate that double phase Liquid Argon TPC is the best technique for Direct Dark Matter Searches

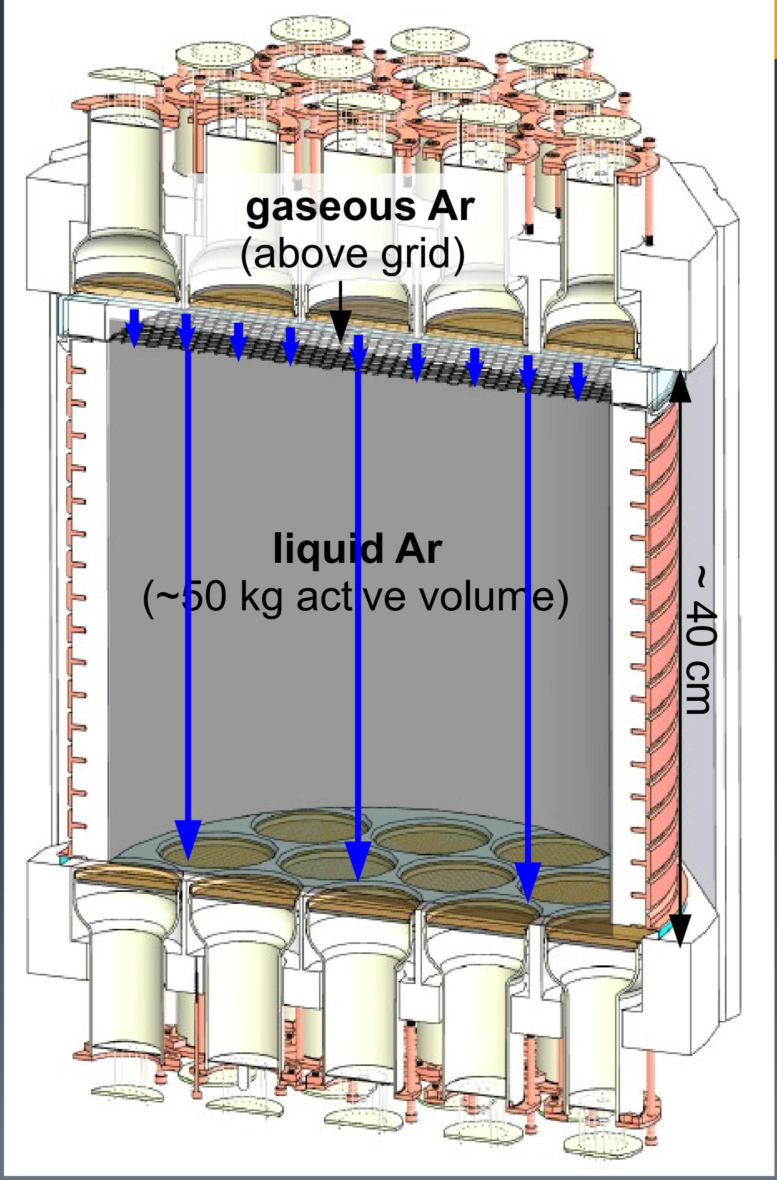
**Background reduction**
Depleted Underground Argon
Low background materials
Active Shields against neutrons and muons

**Background identification**
Pulse Shape Discrimination
S1/S2 discrimination
Measure neutron flux in borate scintillator
Position reconstruction

Demonstrate the potential of the technology for multi ton background-free detector

# DarkSide TPC

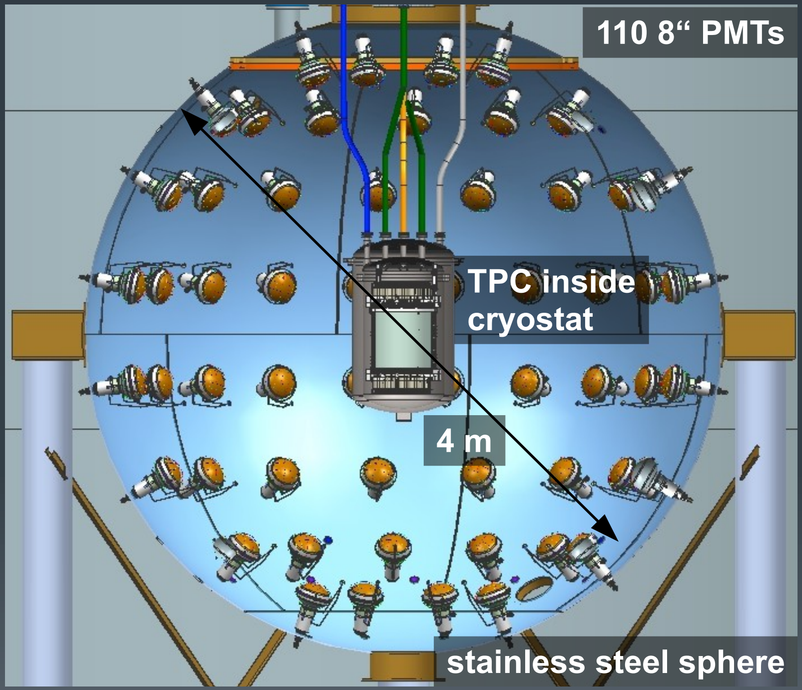
- 50 kg active mass of UAr (37 kg FV)
- 19 top + 19 bottom High Quantum Efficiency 3” PMTs (R11065)
  - Main source of neutron background (1neutron per year)
- 36 cm height, 36 cm diameter
- All inner surfaces coated with TPB (used to shift wavelength of Ar scintillation from 128 nm to 420 nm)
- Low field (0.2 kV/cm) in the Liquid phase to maximize the S1 light yield
- 2.8 kV extraction field
- Electron lifetime ~ 10 ms and drift velocity of ~1 mm/μs



# DarkSide vetoes

- Liquid Scintillator Veto
  - 30 ton boron-loaded liquid scintillator detector, 2 m sphere
  - 110 low-radioactivity PMTs
  - Tag neutrons from TPC to measure the neutron flux
- Muon Veto
  - 1 kton ultra pure water
  - ~10 meters, 80 PMTs
  - Tag cosmogenic neutrons

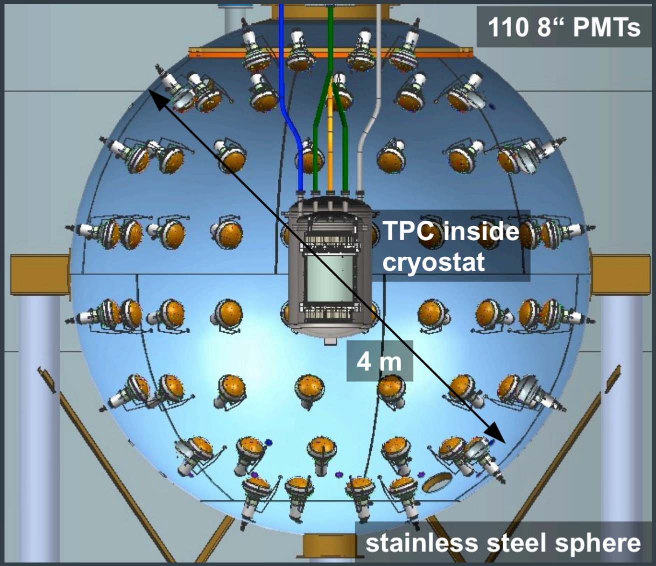
Most of the neutrons are produced in the PMTs and cannot be distinguished from WIMPs in the TPC

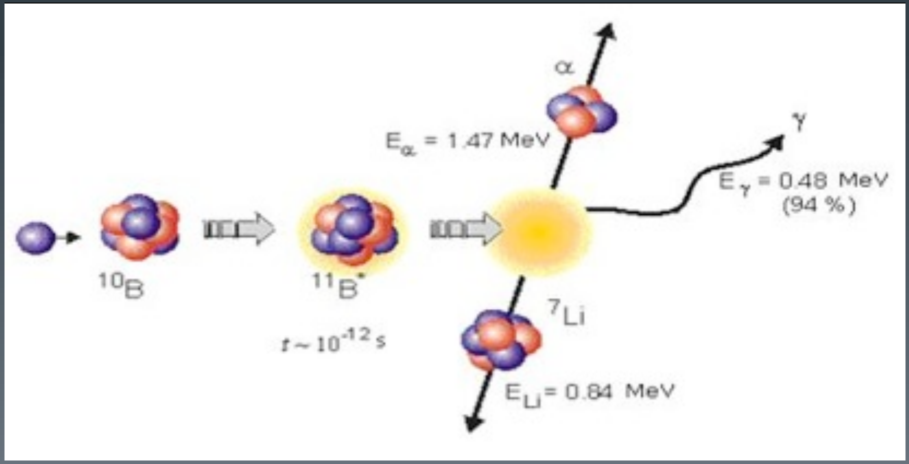



Expected veto efficiency >99%
Both vetoes are designed to host a ~5 ton TPC

# Borated Liquid Scintillator veto

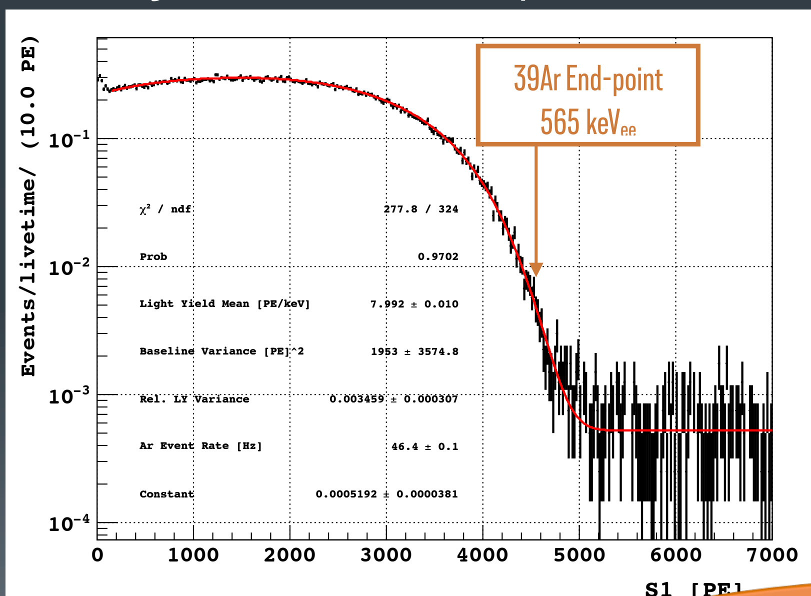
- High neutron capture cross section on $^{10}B$ allow for a compact veto size
- Neutrons are captured and emit a 1.5 MeV $\alpha$
  - Quenched to ~ 50 $keV_{ee}$ → easy to detect with high efficiency
  - Expect > 99% efficiency in tagging neutrons

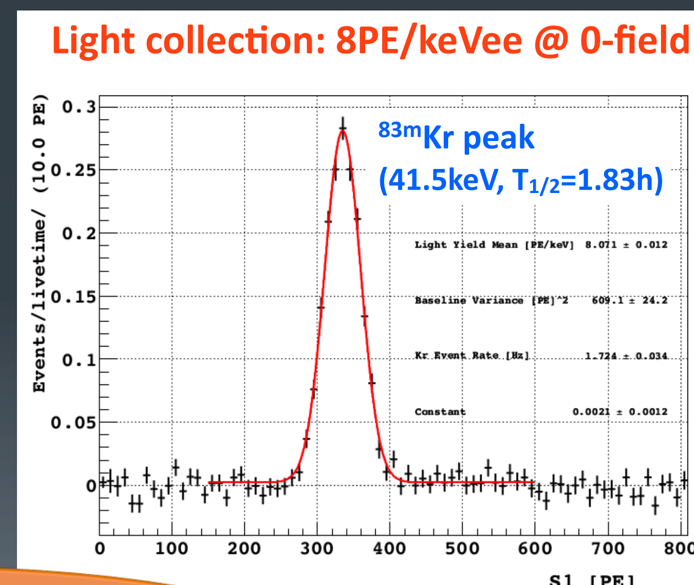


# Electron recoils calibration

- One crucial parameter for DS-50 is the light yield → pulse shape discrimination power critically depends on the number of collected photoelectrons
- Measured using the $^{39}$Ar end-point (E=565 keV) and injected $^{83m}$Kr (E=41.5 keV)

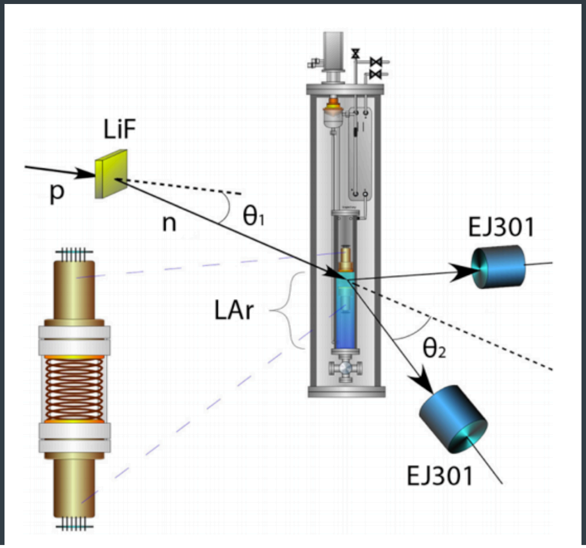


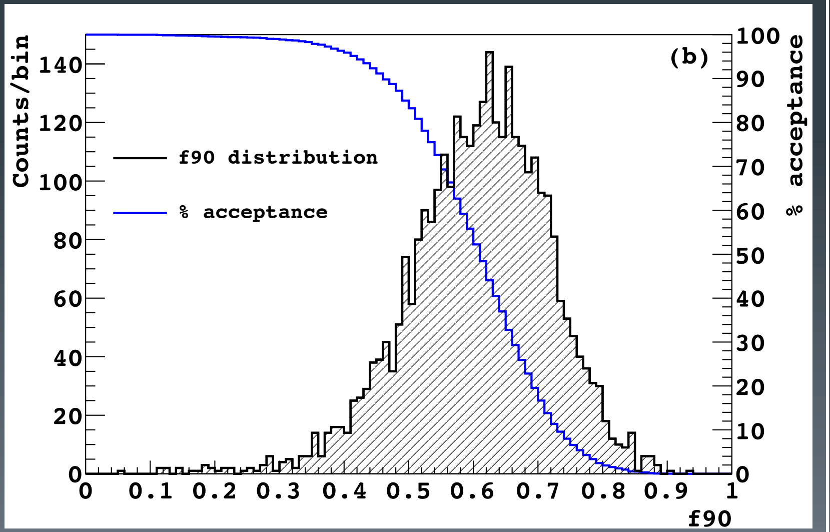



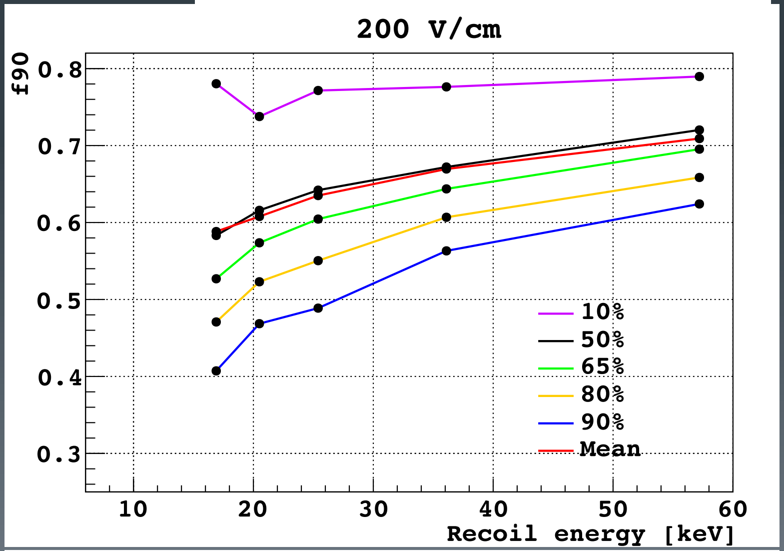

7.9 pe/keV at null field
7.0 pe/keV at 0.2 V/cm

# Nuclear recoils calibration

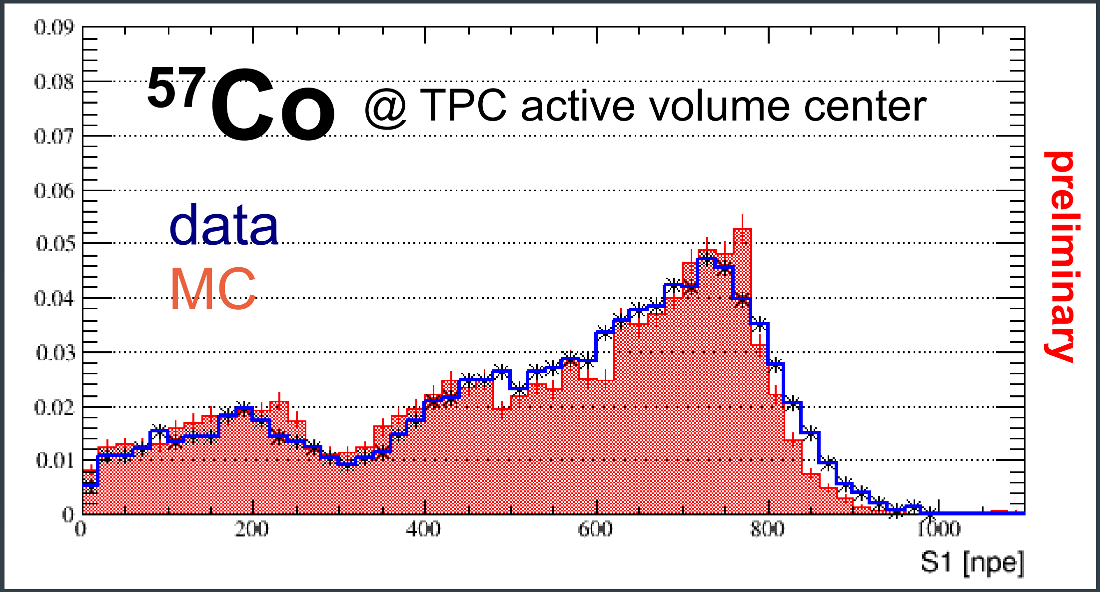
- Calibrate the response to NR is more difficult → need to have single scatter in the TPC
- SCENE: small TPC exposed to a neutron beam to measure scintillation produced by single scatter nuclear recoils of known energy



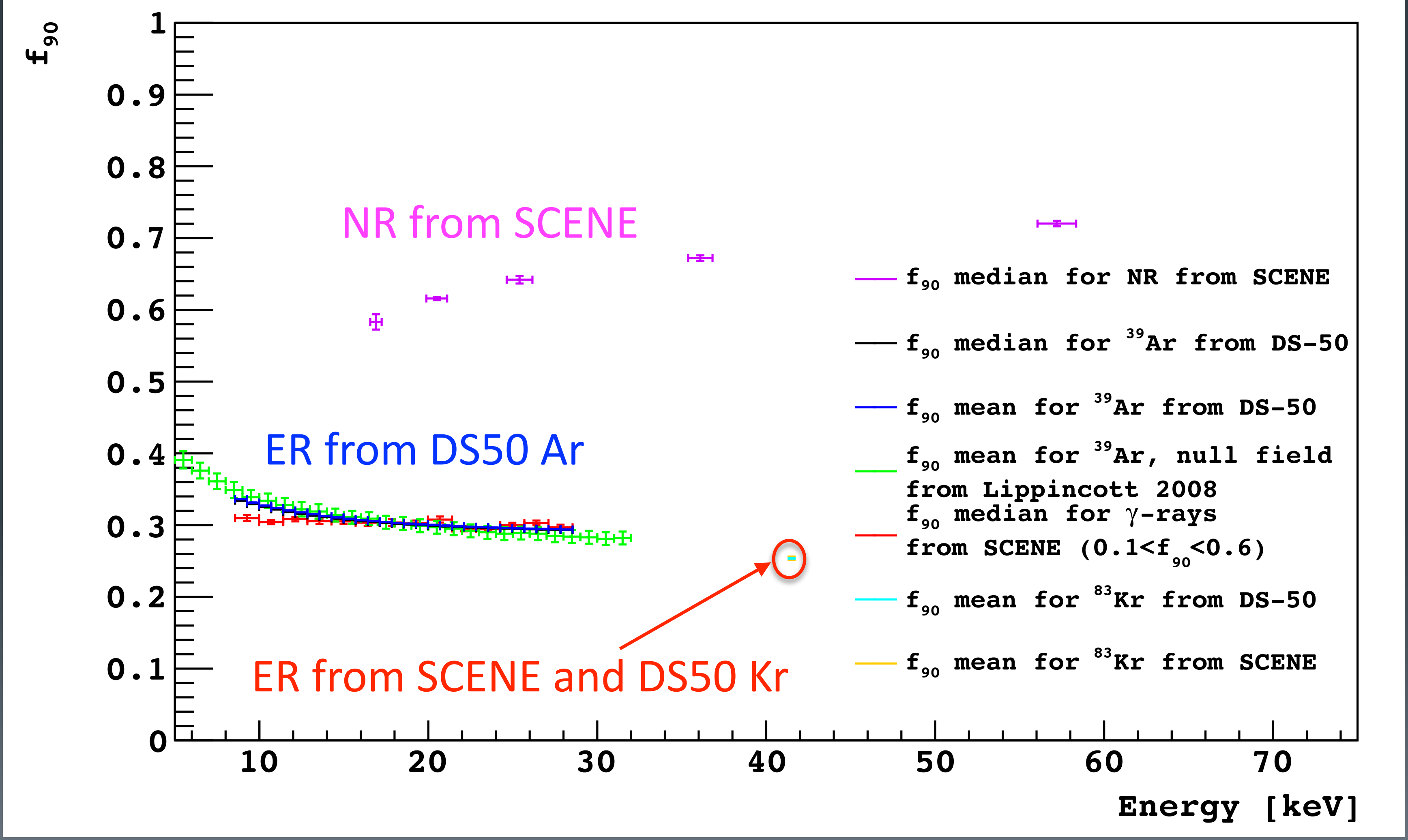



# On-going calibration




- Extensive calibration campaign with γ and neutron sources recently completed
- Data compared with a Geant4 based MC simulation → developed by French groups for DS-50
- %-level agreement

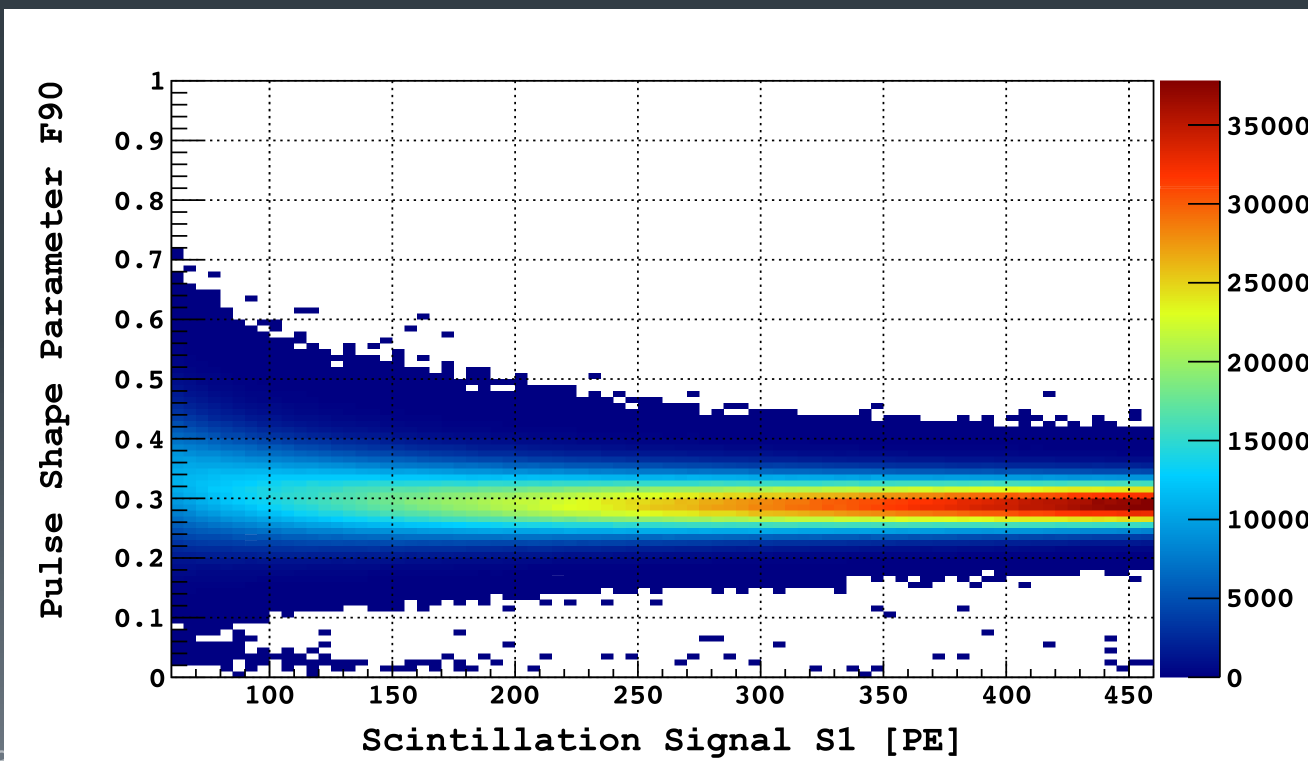
# f90 for nuclear and electron recoils



# First DarkSide-50 results

Published on PLB 743, 456 (2015)

- 2 months of data with Atmospheric Argon
- Collected ~$1.5 \times 10^7$ events of $^{39}Ar$
- Enormous statistics of ER to prove the Pulse Shape discrimination → correspond to 20 years with Underground Argon

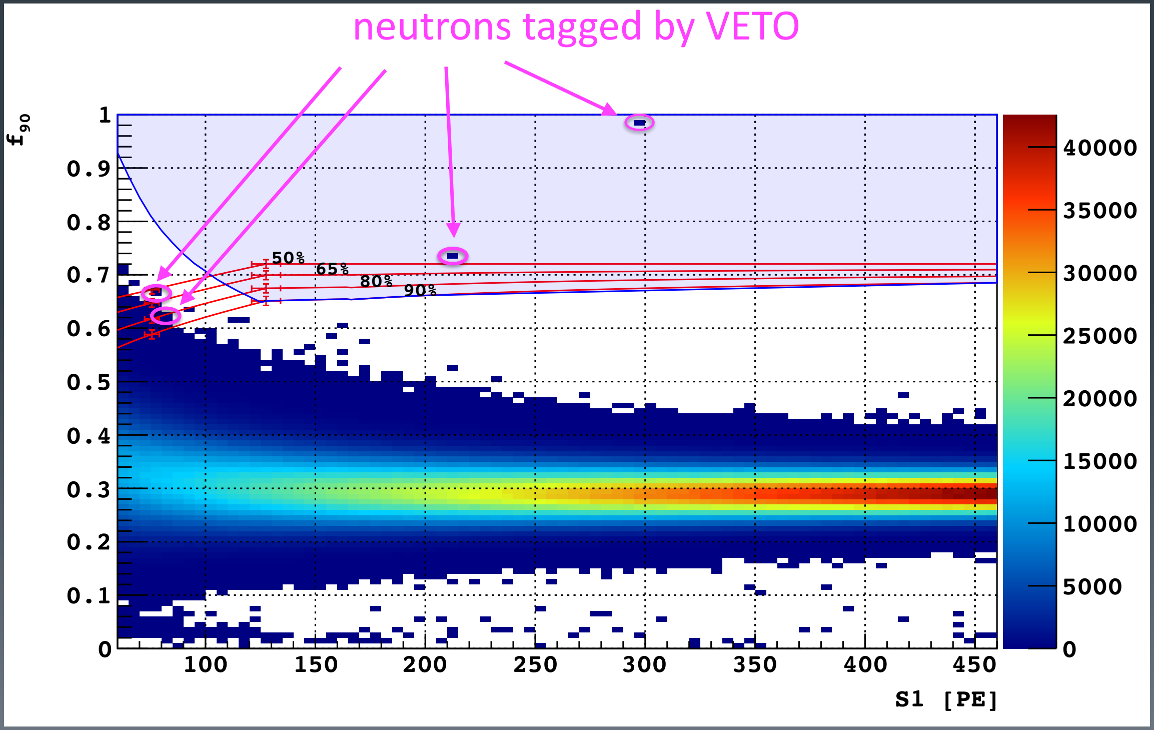



Event distribution after all quality cuts

- Single hits in TPC
- Without coincidences in the vetoes

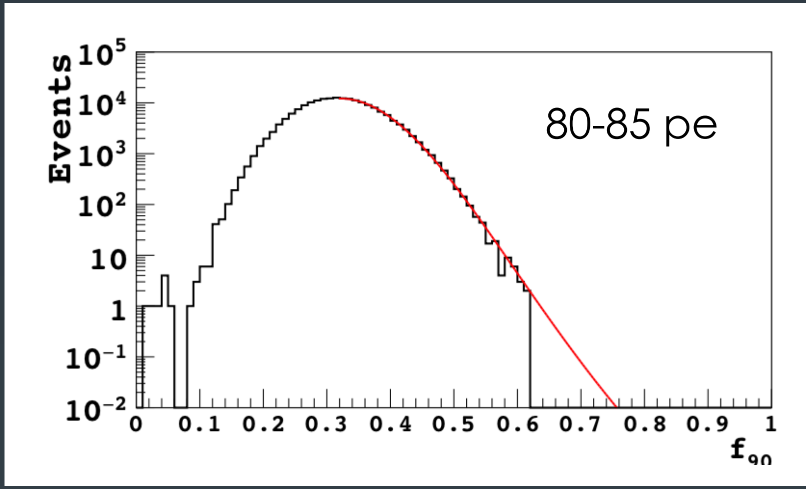
# The importance of the veto

- DarkSide is the only experiment in the field with a veto system
- Expected veto efficiency to tag neutrons → 99.5%
- During the first two months of data taking 4 events were tagged in the neutron veto → all with f90>0.6

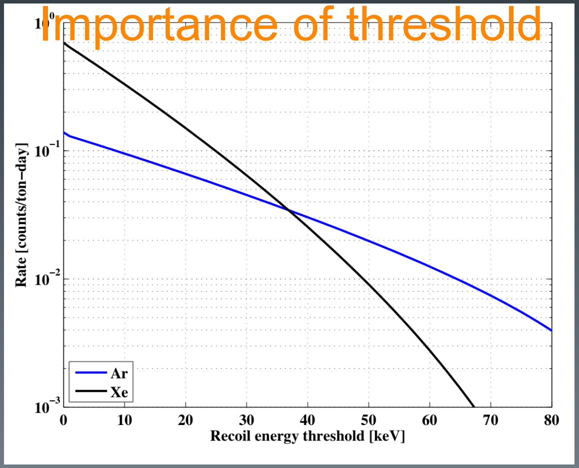


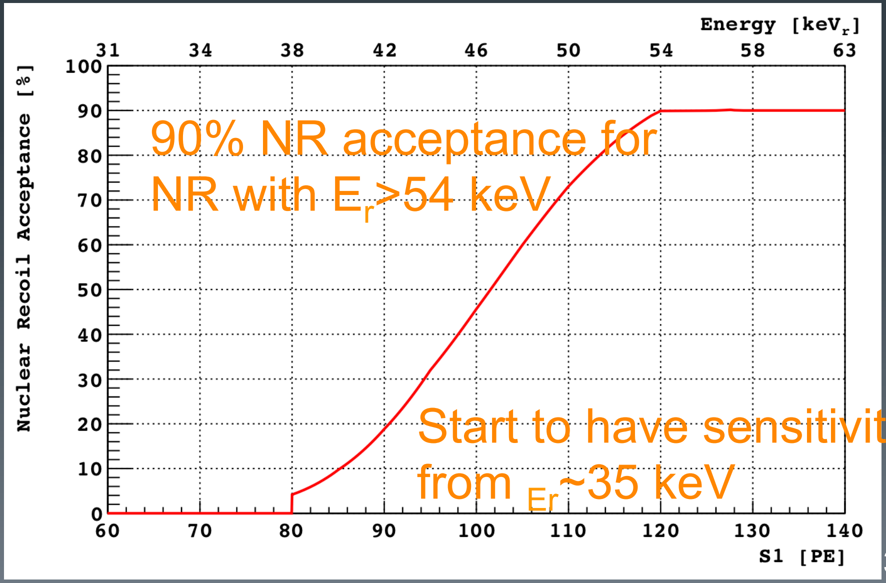
# WIMP acceptance band

- Define the WIMP acceptance band to have <0.01 ER entering the WIMP search region in a 5 pe window
- $f_{90}$ from the $^{39}$AR spectrum, fit with a two gaussian ratio model in bins of S1




Numbers of recoils vs recoil energy → Importance of threshold



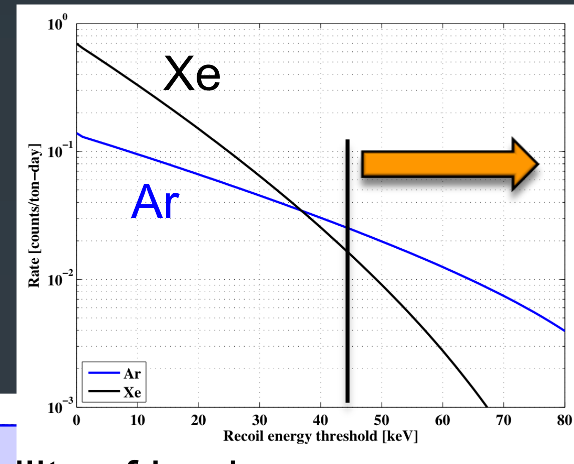



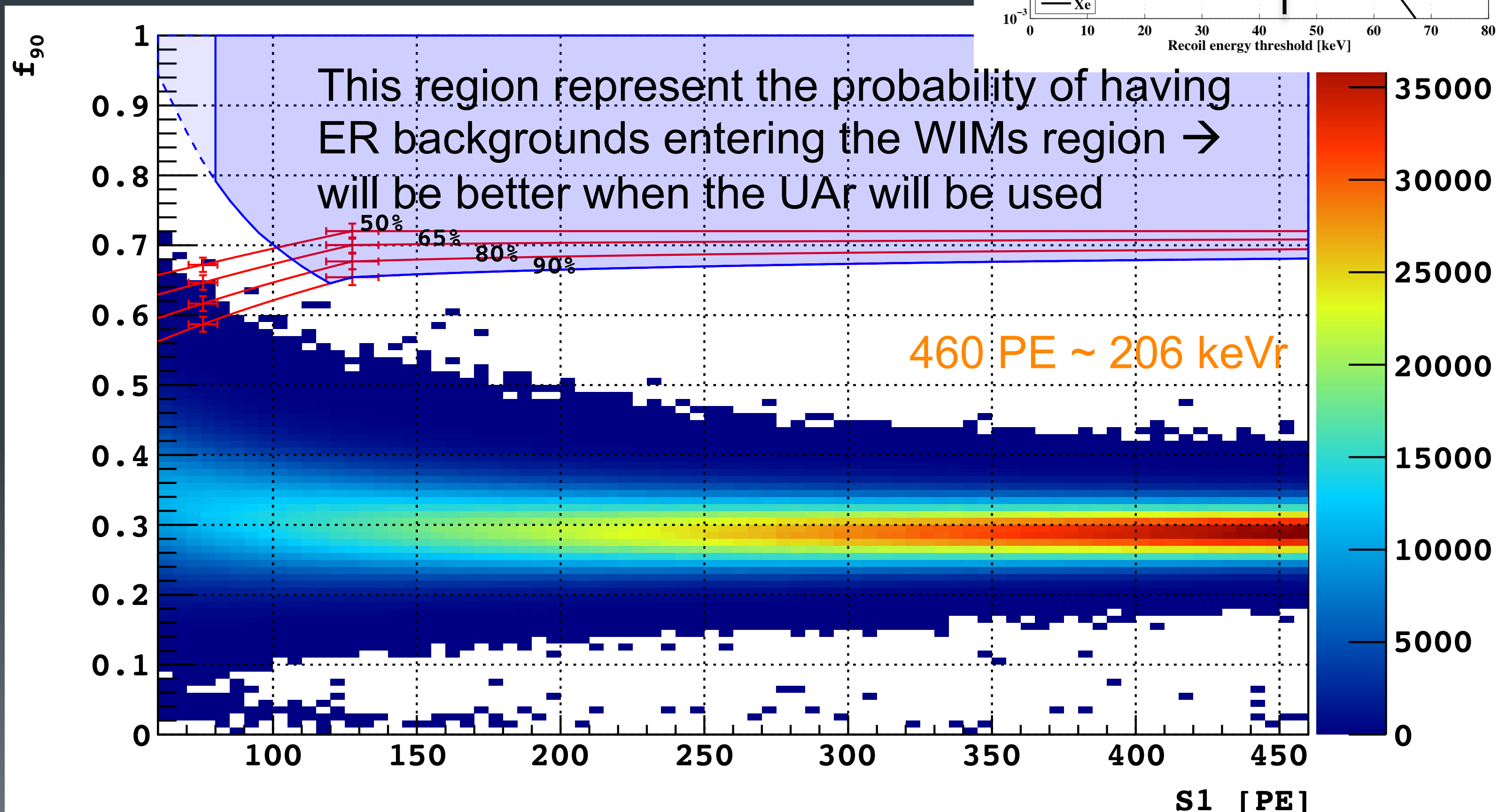

90% NR acceptance for NR with $E_r$>54 keV

Start to have sensitivity from $E_r$~35 keV

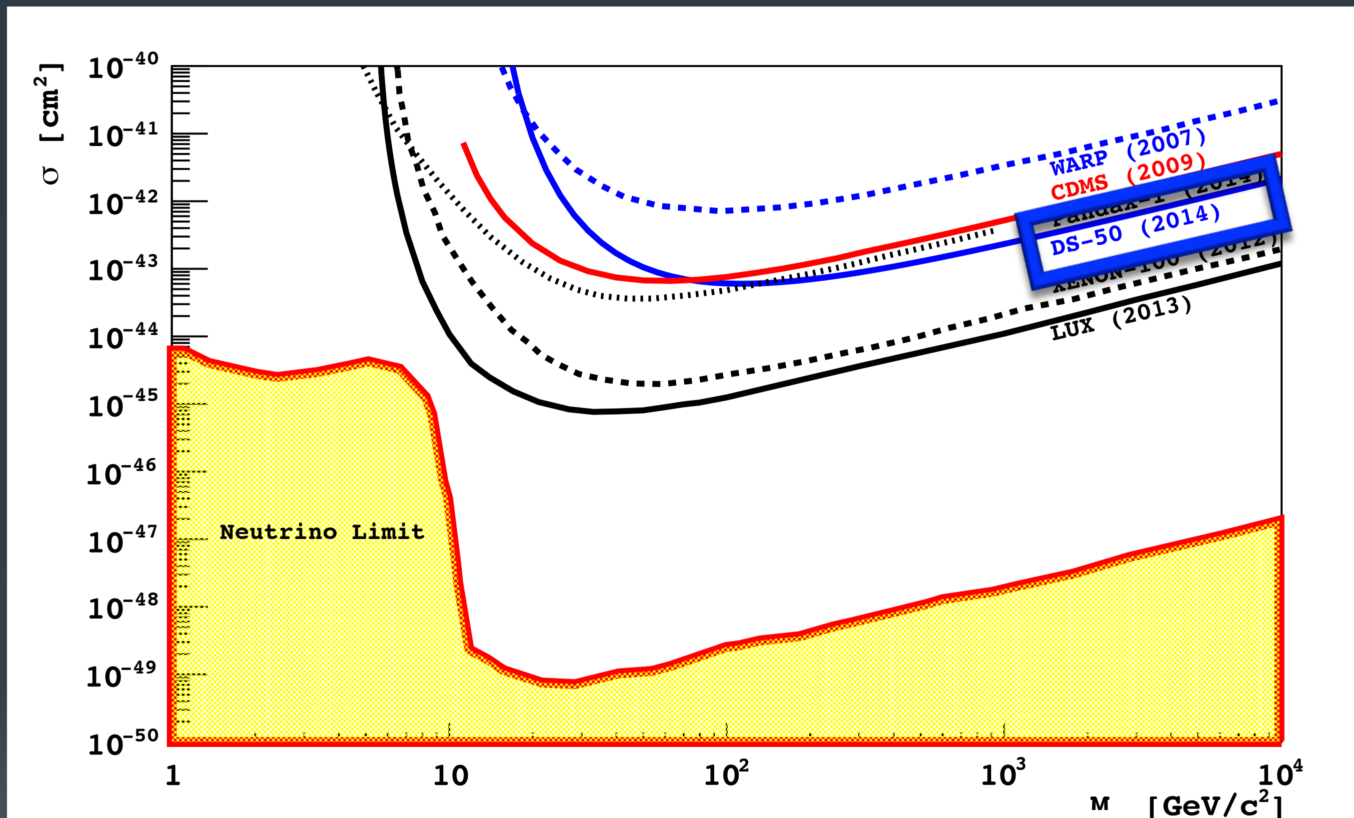
# WIMP search region

80 PE ~ 38 keVr
(from SCENE)



# WIMPs limit

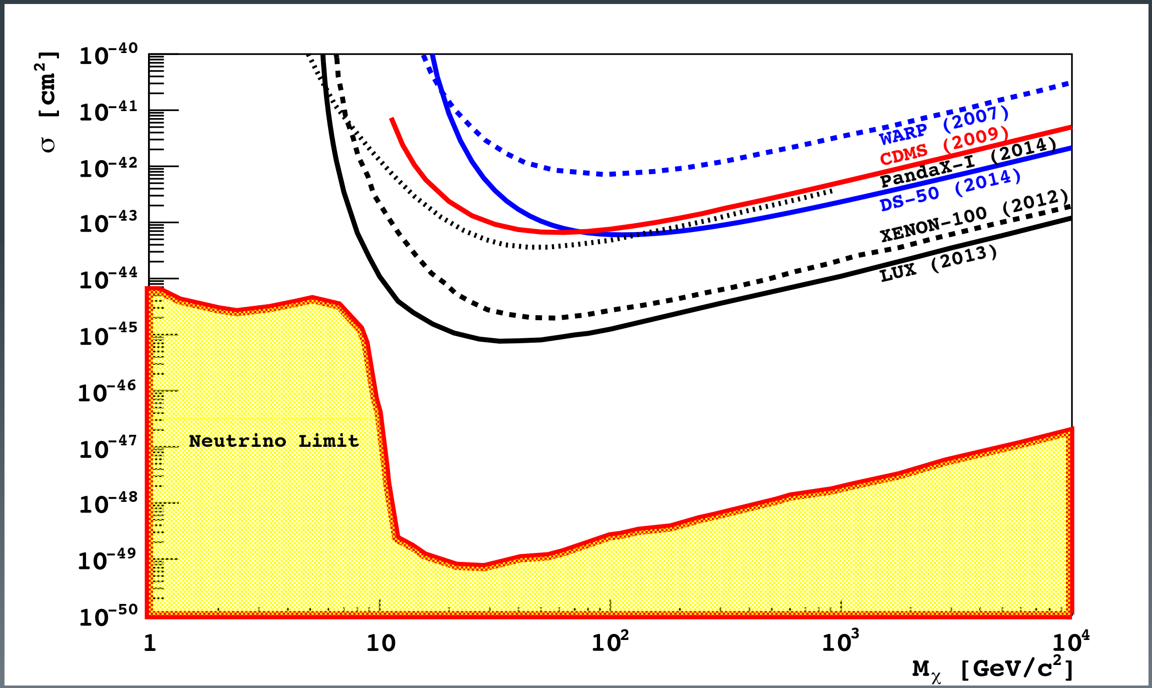



$\sigma < 6.1 \times 10^{-44}$ cm$^2$ for 100 GeV WIMP mass

- No events observed in the WIMPs search region → limit on spin-independent cross section of $6.1\times10^{-44}$ cm$^2$ for M=100 GeV/c$^2$
- Most sensitive dark matter search with Argon as target

# The future

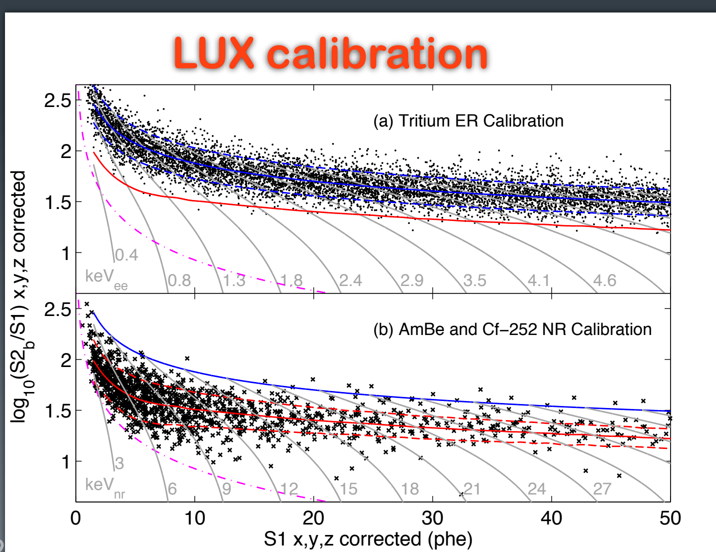
- Today limits from Xenon experiments are better than the ones from Argon
- But before reaching the neutrino floor we still need to gain 5 order of magnitudes
- Which is the best technology to reach $\sigma \sim 10^{-49}$ cm$^2$?

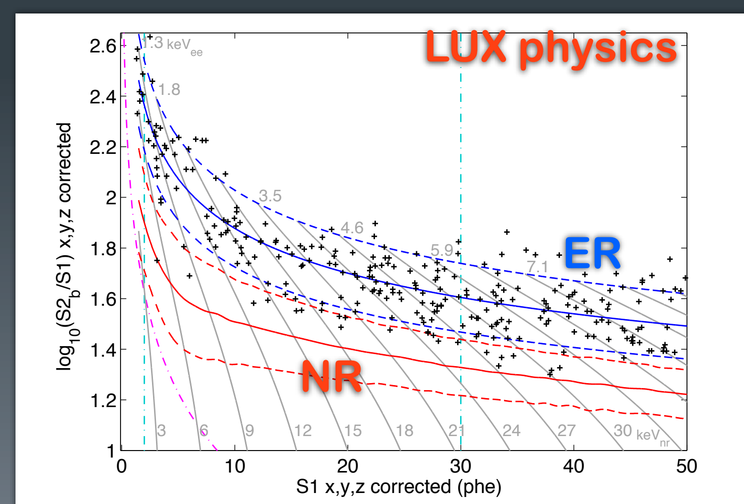


# Xenon experiments

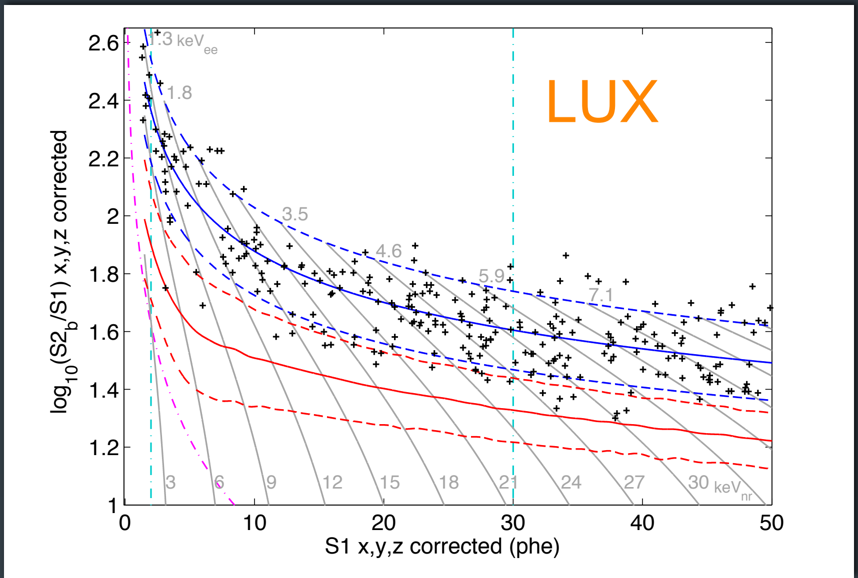
- Xenon based experiment cannot distinguish ER from NR with Pulse Shape Discrimination
  - Need to use S1/S2 ratio → discrimination power ~ 100
- Liquid Argon can reach PSD > $10^8$ → background free!

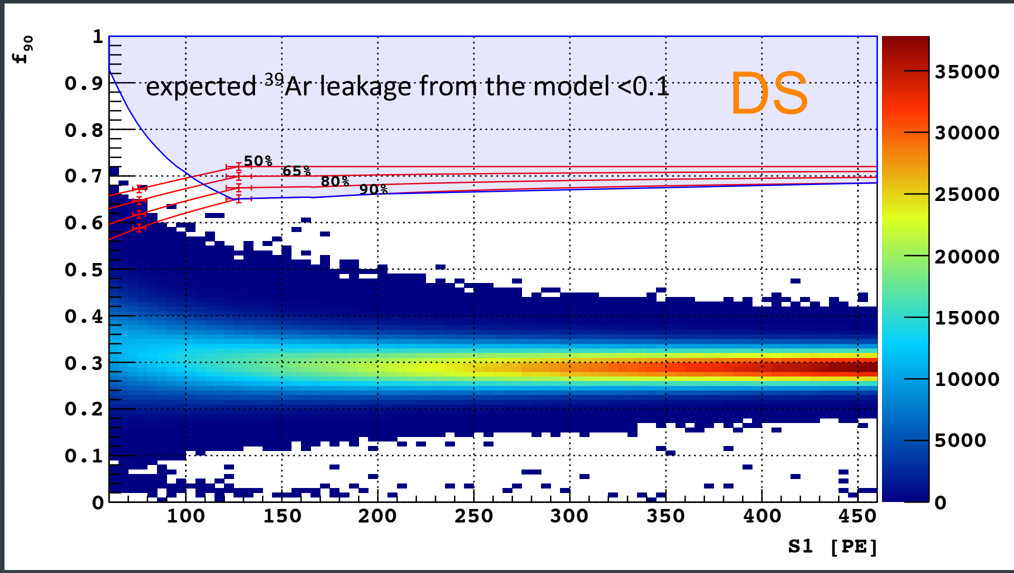
LUX → 0.6 ER events expected below NR mean, some more observed close to the NR mean
Will get worst with larger Xenon detectors



# ER background in LXe and LAr

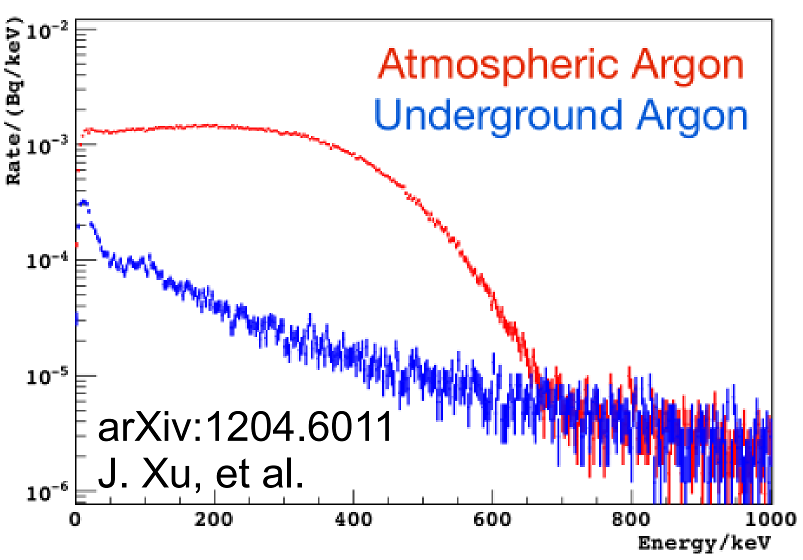



- LXe → Electron Recoils close to the NR mean
- LAr → no ER leaking in the NR region (not even taking the 90% acceptance line for the NR)
  - DarkSide results obtained with 50 days of AAr → correspond to more than 20 years of running with UAr

# Underground Argon

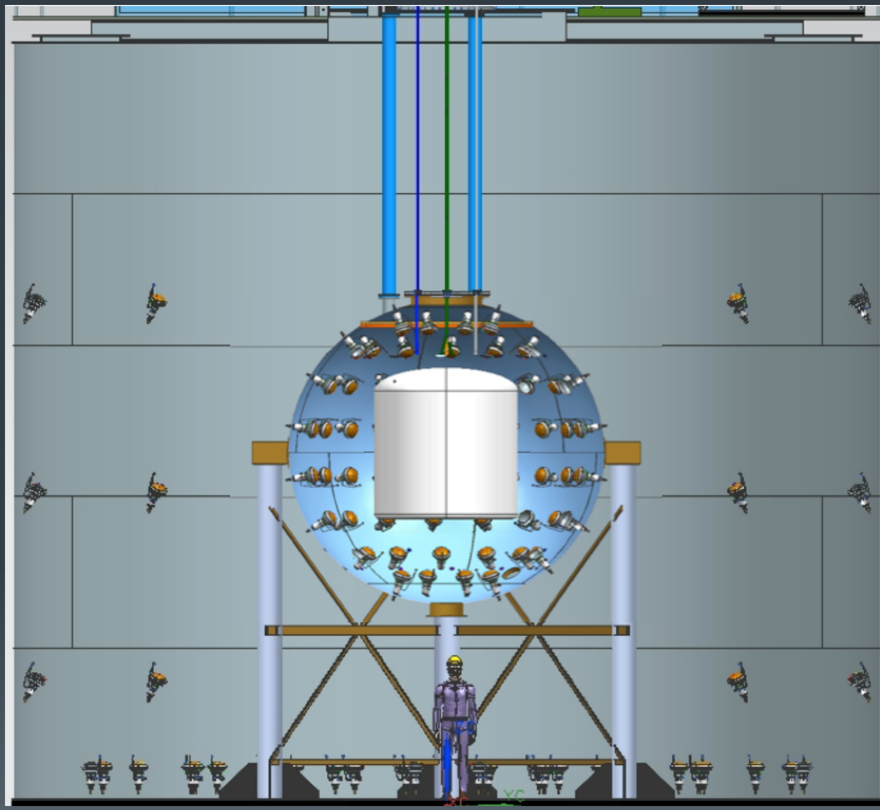
- Underground argon is extracted from a mine in Colorado
- All necessary UAr for DarkSide-50 (150 kg) has been extracted and shipped to Gran Sasso
- DarkSide-50 is now filled with UAr
- 3 years of data taking foreseen




- $CO_2$ wells in SW Colorado (near Cortez)
- Contains ~500 ppm Argon
- $^{39}$Ar activity < 0.65% of atmos. argon (arXiv:1204.6011)

# Ton-scale experiment

- Build a ton-scale Double Phase LAr TPC ready for taking data in 3-4 years
- An LOI will be presented at the Gran Sasso Laboratory in April
- Water and Scintillator veto will be the existing ones
- The TPC will be replaced with a larger TPC instrumented with SiPM
- Intermediate step toward the final DM experiment able to reach the neutrino floor (~100 ton)

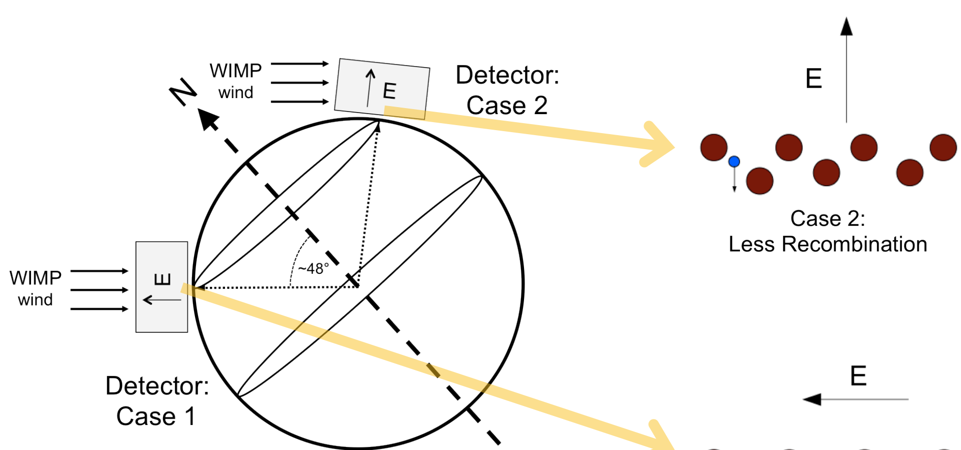


# French contributions in DarkSide

- APC, LPNHE and IPHC are part of the DarkSide collaboration and involved in the efforts for the next generation detector
- For DarkSide-50 we have written and we are responsible for the Geant4-based MC simulation of the experiment
  - The MC includes geometries with larger detector and is being used to assess the sensitivity of future DarkSide detectors
- Contribute to the analysis of DarkSide-50 with Underground Argon → new results expected soon
- ANR proposal to study directionality of NR

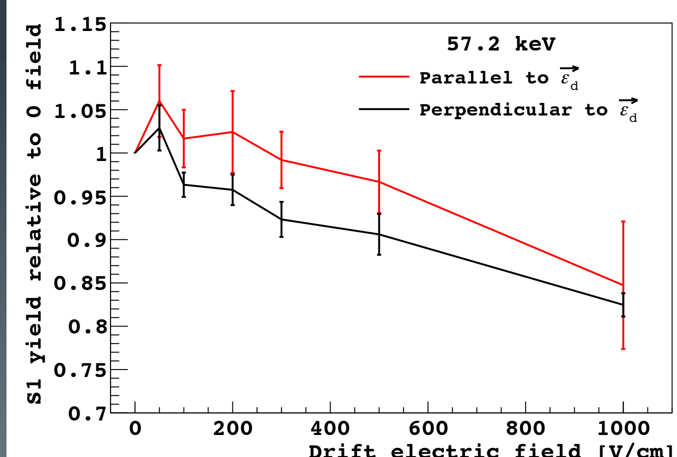
# Directionality with LAr

- For a given recoil energy S1 and S2 are different if the recoil is parallel or perpendicular to the drift field because of the different  recombination probability
- If confirmed this effect might allow to distinguish isotropic neutrons recoils from WIMP that have a preferred direction
- ANR project including APC, IPHC, IPNO and LPNHE to build a small TPC and expose it to the IPN neutron beam




When a nuclear recoil is parallel to the electric field, as in Case 1, there will be more electron-ion recombination since the electron passes more ions as it drifts through the chamber.

**Angular dependence from SCENE**




http://arxiv.org/abs/1406.4825

# Conclusions

- DarkSide-50 has produced the first physics results with Atmospheric Argon (PLB 743, 456 (2015)
  - Best WIMP limit with LAr as target
  - Excellent Pulse Shape Discrimination
    - $1.5 \times 10^7$ ER → none of them in the WIMP search region
    - No background in 20 years of running with UAr
- DarkSide-50 is now filled with Underground Argon
  - Results on $^{39}Ar$ contamination expected soon
  - Take data for 3 years to produce WIMP limits
- Design study for a intermediate detector on-going
  - Final goal is to build a 100 ton LAr detector to reach the neutrino floor
- Active French community participating to data analysis of DarkSide-50 and to the design of the next generations

# Back-up slides