Direct Search for Dark Matter WIMPs with Depleted Liquid Argon at the Gran Sasso Laboratory:

Dark-Side

Aldo Ianni, DarkSide Collaboration

INFN Gran Sasso Laboratory

Padova, Sept. 18th , 2012

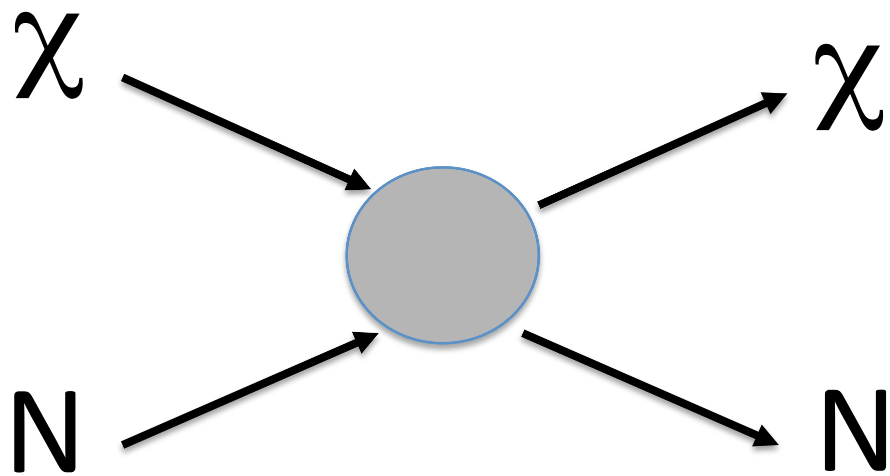
Evidence of Dark Matter

- Spiral galaxies rotation curves: $\Omega_{halo} \sim 10\Omega_{stars}$
- Clusters: galaxy motion, gravitational lensing and X-ray emission: Ω_{matter}~0.2-0.3
- CMB anisotropy: Ω_{matter}~0.27, $\Omega_{baryons}$~0.04
  - ~84% of mass in the Universe dark and non-baryonic
- Using early universe nucleosynthesis: $\Omega_{baryons}$~0.04
- Large Scale Structures:
  - Formation of structures by gravitational clustering
  - Comparison of observations with non-relativistic (cold) dark matter clustering agree well

WIMPs:
Weakly Interacting Massive Particles

- A general class of weakly interacting massive particles not from the Standard Model
- Assuming thermal equilibrium in the early Universe and non-relativistic decoupling, the energy density for these relic particles is predicted to be:
  - $\Omega_{\chi} \sim 10^{-36} cm^2 / \langle \sigma v \rangle$
  - annihilation cross section ~picobarns
  - relic abundance right order (i.e. $\Omega \sim 1$)
- This circumstance: a particle non-relativistic at decoupling with weak-scale mass and cross section which gives the right order for the relic abundance is given the name of **WIMP miracle**

Direct Search for WIMPs: nuclear recoil tagging



$$E_{recoil} = \frac{m_N M_\chi^2}{\left(m_N + M_\chi\right)^2} v^2 (1 - \cos\theta^*)$$

$$v \sim 300 \text{ km/s}$$

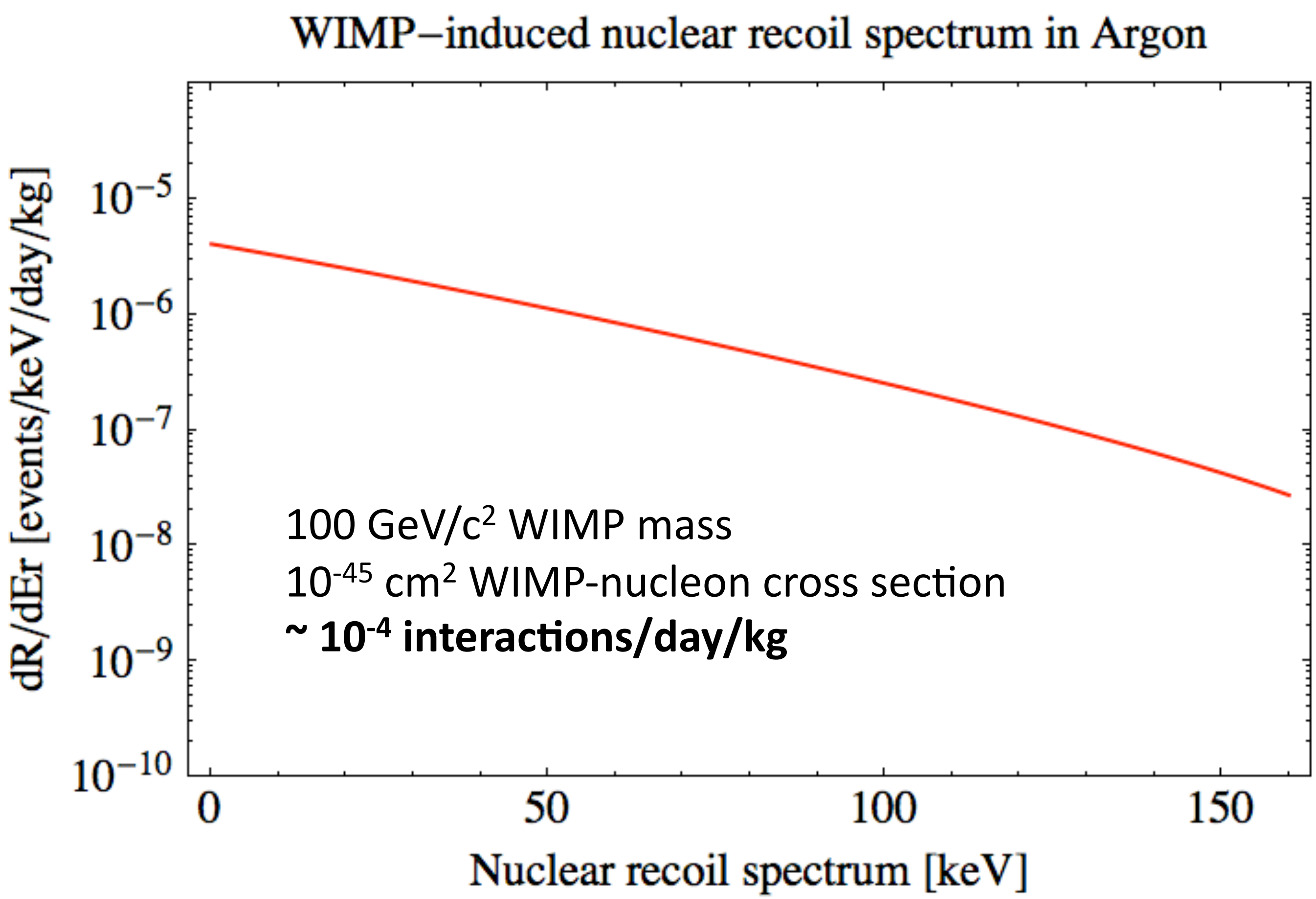
$$E_{recoil} \sim 1 - 100 \text{ keV}$$

$$\frac{dR}{dE} = N_t \frac{\rho_\chi}{m_\chi} \frac{m_N}{\mu_n^2} A^2 \sigma_{\chi n} F^2(E) \int_{v \geq v_{\min}(E)} d^3v \frac{f(v)}{v}$$

$$f(v) = \begin{cases} \frac{1}{N} e^{-\left(\frac{\left|v_\chi + v_{sun} + v_{Earth}\right|}{v_0}\right)^2}, & \left|v_\chi + v_{sun} + v_{Earth}\right| < v_{esc} \\ 0, & \text{elsewhere} \end{cases}$$

- 170 km/s < v_0 < 270 km/s
- 450 km/s < v_{esc} < 650 km/s
- ρ_χ ~ 0.3 Gev/cm^3
- F(E) = nuclear form factor
- f(v) = velocity distribution of WIMPs in the galaxy

Expected WIMPs Signal in LAr



Comments on expected WIMP signal

- No specific feature
- Low nuclear recoil energy
- 10-100 events for 1 ton-year exposure
- GOAL of WIMPs search:
  - If Dark Matter is made of WIMPs we need:
    - Strong suppression of background
    - As low as possible sensitivity to WIMP-nucleon cross section

Scintillation in LAr

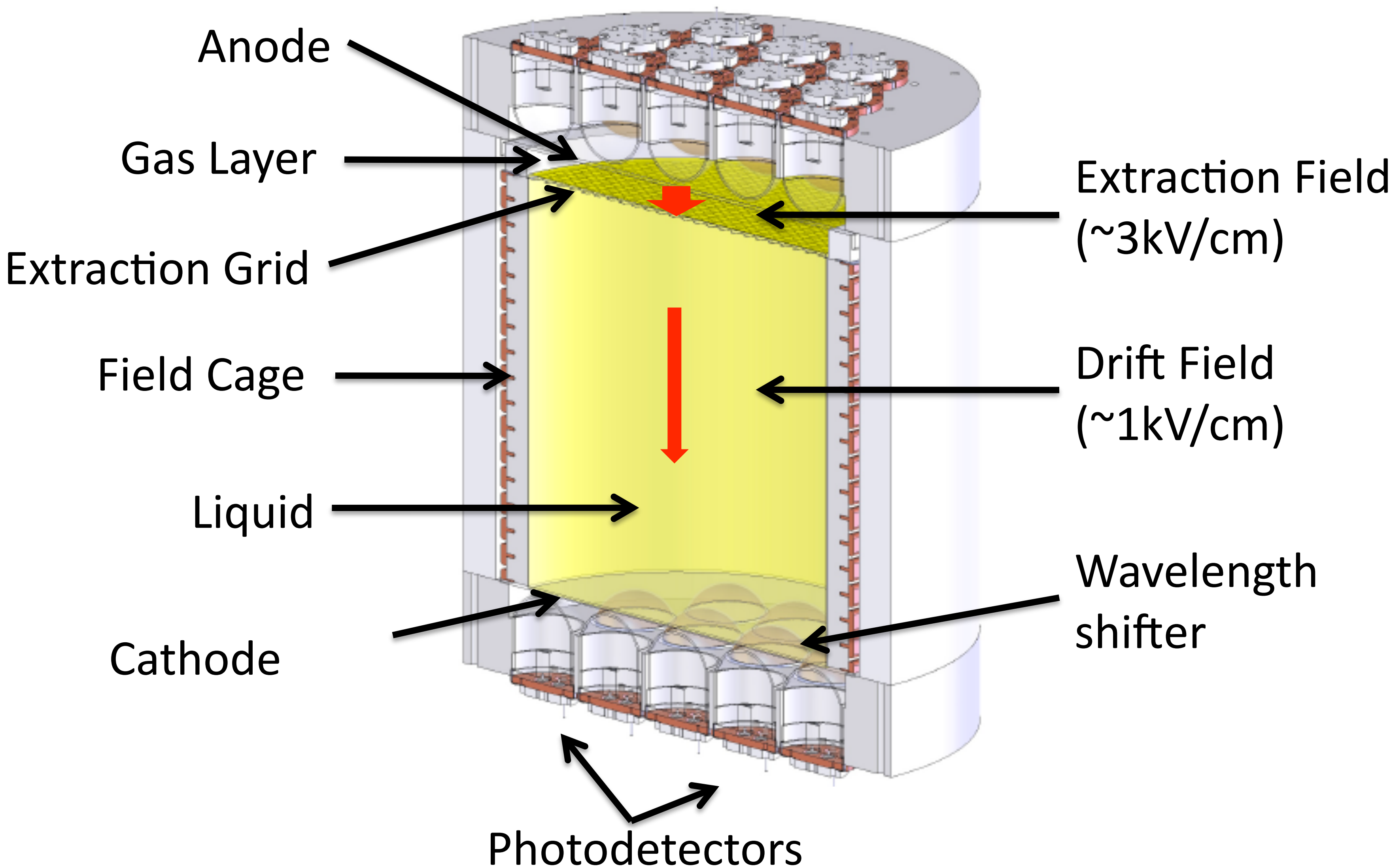
- Minimum ionizing particles produce ~ 4×10^4 γ/MeV
- Fast (~7ns) and slow (~1.6μs) decay components
- For nuclear recoil: fast component ~ 70%
- For electron recoil: fast component ~30%
- Scintillation light peaked at 128nm
- Need wavelength shifter to ~400nm to match PMTs Quantum Efficiency

Backgrounds for LAr

- β/γ radioactivity
- γ radioactivity from surface close to sensitive mass
- Radiogenic neutrons: (α,n) and spontaneous fissions
- Cosmogenic neutrons from muons

Neutrons can mimic a nuclear recoil

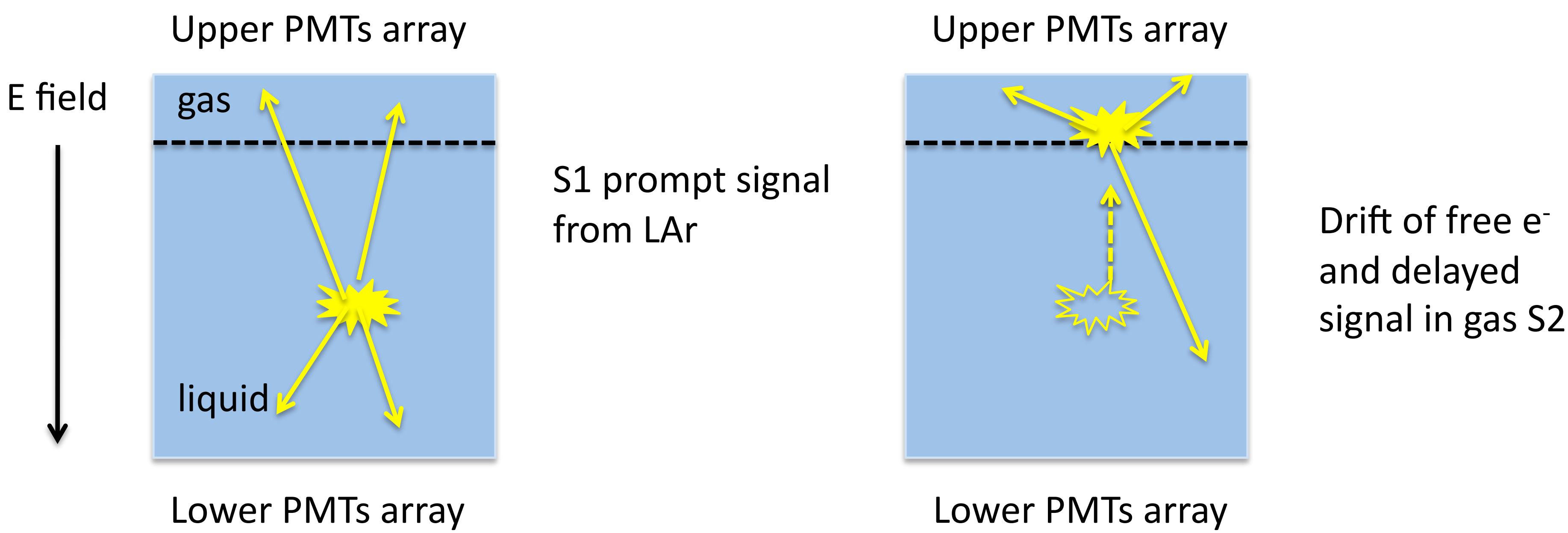
Double-Phase Argon TPC



Remarks on LAr target for WIMPs search

- **Advantages**
  - Good scintillator
  - Moderate cryogenic requirements: at 1atm liquifies at 87K
  - 1% abundance in atmosphere (but with ^{39}Ar see later)
- **Disatvantages**
  - Need waveshifter to ~400nm from 128nm
  - Must remove ^{39}Ar: use underground Ar (more difficult technology)

LAr TPC at Work [1]



S1 measures energy and time of event

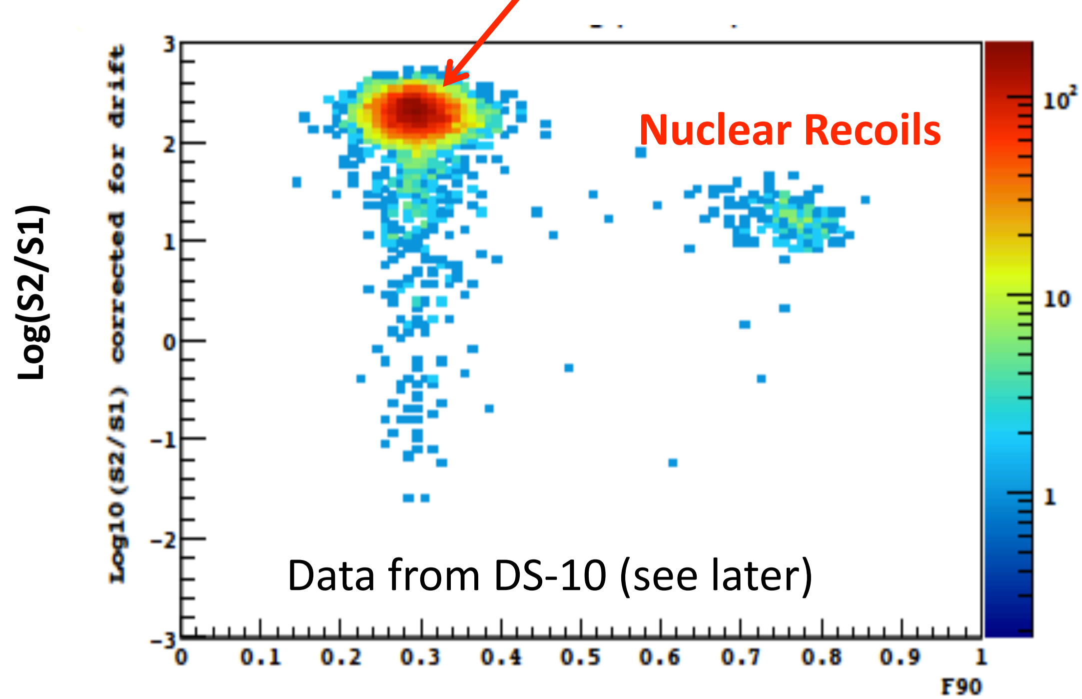
S2 measures position of event in LAr and is proportional to fraction of charge that escapes recombination

LAr TPC at Work [2]

Background reduction performed by exploiting

a) Pulse shape of S1 through a parameter which measures the fraction of fast to slow component in scintillation

b) S2/S1



The problem of ^{39}Ar

- Ar naturally present in the atmosphere at 1% level
- ^{39}Ar formed by cosmic muon interactions
  - $^{40}Ar(n,2n)^{39}Ar$
- ^{39}Ar is a β decay emitter with Q_β=565 keV and $T_{1/2}$=269 years
- In Ar from the atmosphere, ^{39}Ar is at the level of 1 Bq/kg
  - ~ 9×10^4 decays/kg/day
  - WIMPs(100GeV, 10^{-45} cm^2) ~ 10^{-4} events/kg/day

DarkSide Approach

- **Double phase TPC**
  - Exploit background rejection power
- **Low background technology**
  - Careful selection of materials
  - Assembling in Rn-free clean room
- **Active neutron veto**
  - Boron-loaded scintillator
- **Depleted Argon**
  - ^{39}Ar activity reduced to ~0.6% Bq/kg

Underground Argon [1]

- ^{40}Ar produced from ^{40}K
- The Earth is reach in ^{40}K in underground
- ^{40}Ar moves into the atmosphere and makes ^{39}Ar with muons interactions
- In underground ^{39}Ar is expected to be much less due to low muon flux
- However, ^{39}Ar underground can be produced by radiogenic neutrons interactions
  - $^{39}K(n,p)^{39}Ar$
- **Recipe**: go deep underground where surrounding rocks are poor in U and Th

Underground Argon [2]

- In exhaust stream gas (CO_2) of commercial mining facilities Ar at 400-600ppm level
  - In DS extraction site: CO_2 plant output, CO_2(96%)+N_2(2.4%)+He(0.4%)+Ar(0.06%)

- Make on-site preconcentration to ~40,000ppm, then cryogenic distillation at FNAL
  - After distillation: CO_2(~0)+N_2(<0.05%)+He(~0)+Ar(>99.95%)

- Purified depleted argon produced at 0.5kg/day

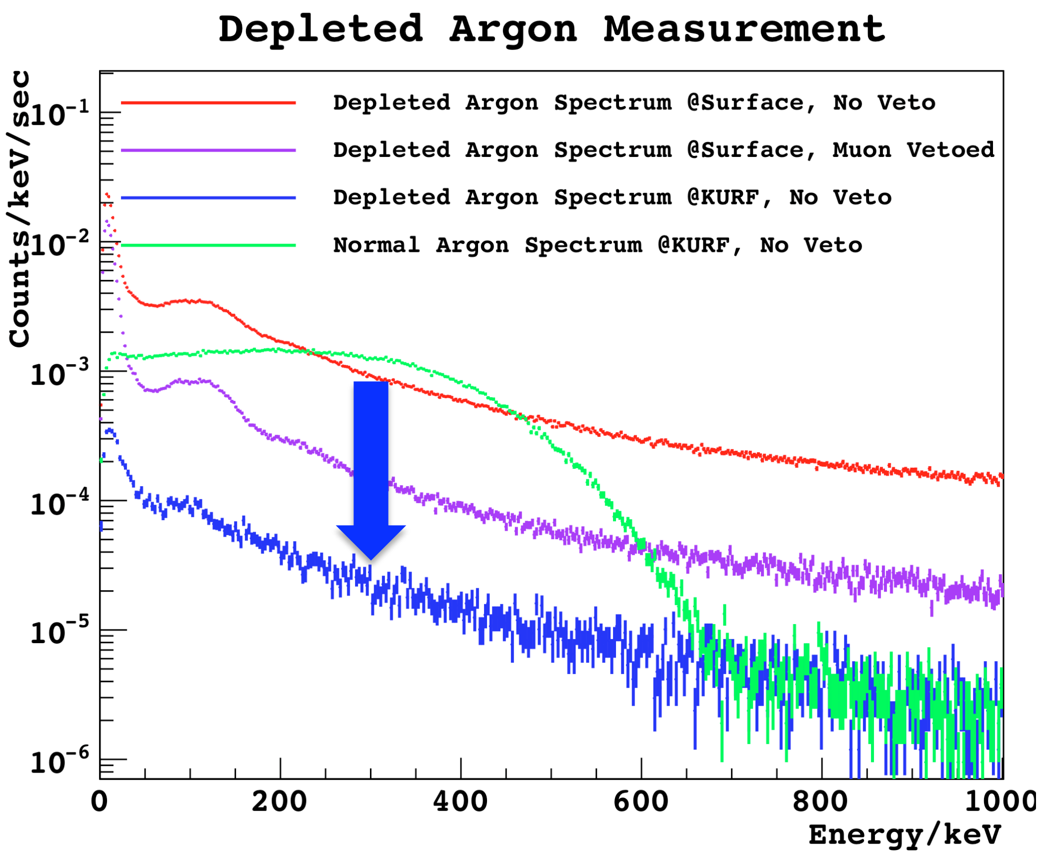
- ^{39}Ar depleted at <0.6% level wrt atmospheric level
  - ~500 decays/kg/day
  - For WIMPs ~ 10^{-4} interactions/kg/day

- Use LAr scintillation properties to perform background reduction
  - Prompt signal PSD shows: 90% n-recoil acceptance with $<10^{-5}$ e-recoil leakage

Underground Argon [3]

^{39}Ar depletion factor >100

In progress study with counting detector underground at KURF (1400 m.w.e.) Virginia, USA

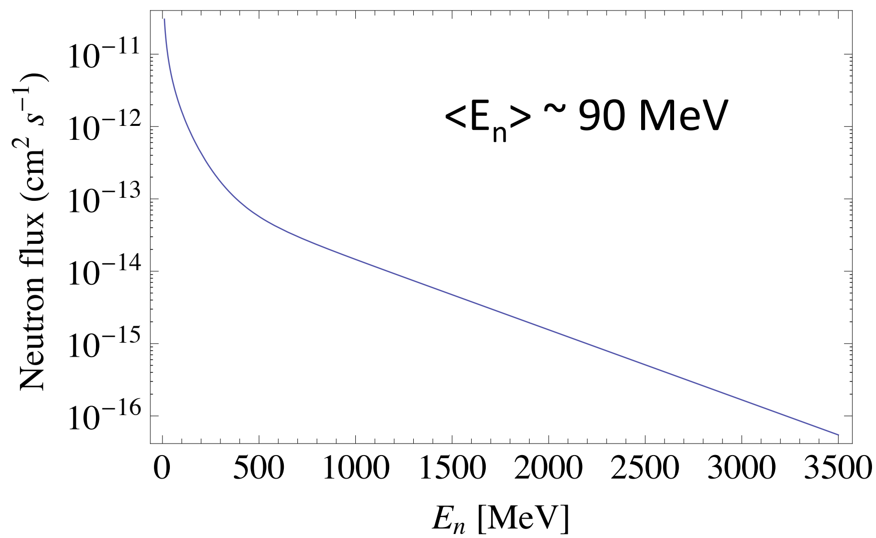


Neutrons from natural radioactivity

- Radiogenic neutrons
  - from (α,n) and spontaneous fission of heavy elements such as U and Th
  - energy ~ a few MeV (<10 MeV)
- Source in DarkSide:
  - PMTs (low background PMTs ~ few n/year/PMT)
  - Steel in cryostat and support structures
- **Recipe**:
  - Passive shielding effective for ~MeV energies but asks for more surrounding materials
  - Active veto

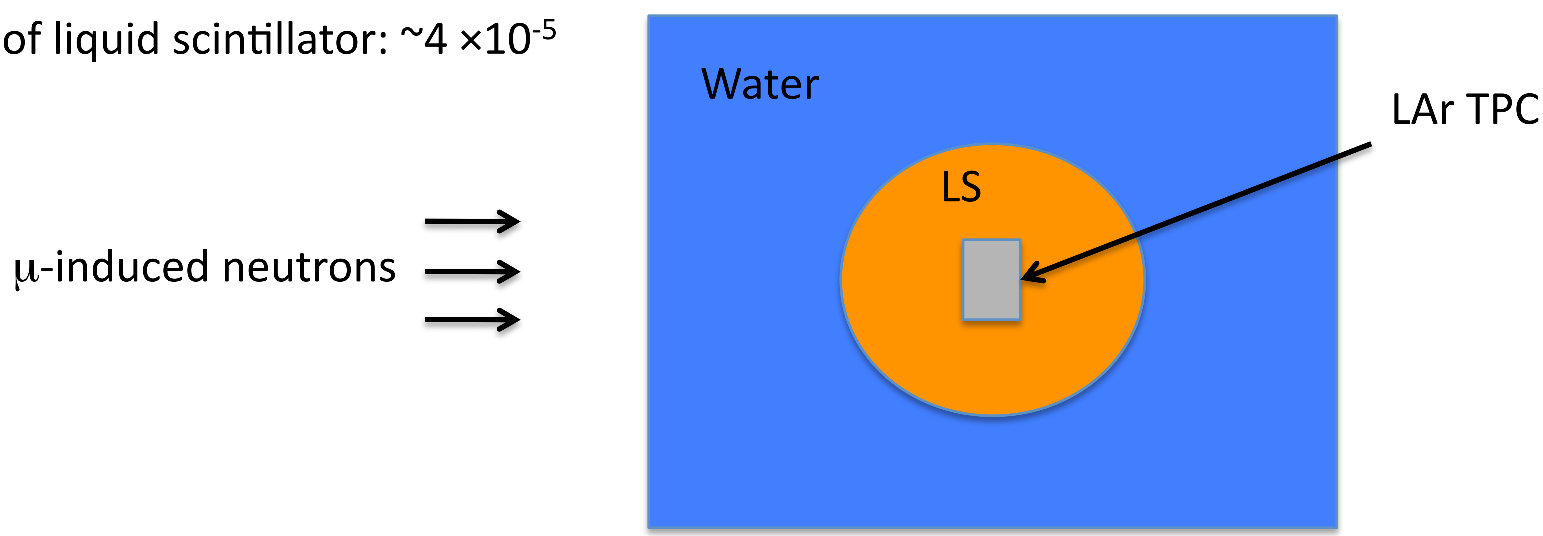
Cosmogenic Neutrons

- Flux at Gran Sasso lab:
  - ✓ 2.4 m^{-2} day^{-1}
  - ✓ 0.7 m^{-2} day^{-1} for > 10 MeV
- Expected rate ~ 3×10^{-33} /s/atom
- WIMPS rate ~ 10^{-34} /s/atom



- Neutrons from surrounding rocks reduced by shielding

✓In DS-50 3m of water ~ 10^{-3} and 0.04 from 1.5m of liquid scintillator: ~4×10^{-5}



Neutron Veto

- *Future Dark Matter Detectors @ LNGS,* F. Calaprice, WONDER, Gran Sasso, March 22, 2010
- *A highly efficient neutron veto for dark matter experiments,* A. Write, P. Mosteiro and F. Calaprice, NIM A 644 (2011) 18-26
- Make use of a boron-loaded radiopure liquid scintillator
  - $^{10}B+n \rightarrow {}^{7}Li+\alpha(1.474MeV)+\gamma(0.478MeV)$ 93.7% with σ=3837b
  - α energy is contained
  - capture time ~ 3μs
- 1m thick veto makes a reduction of 10^7 against external neutrons
- Neutrons from internal LAr target mass captured in 60μs in 1m thick veto with 99.5% efficiency
- Water Tank muon veto + neutron veto reduces cosmogenic background >> 10^3

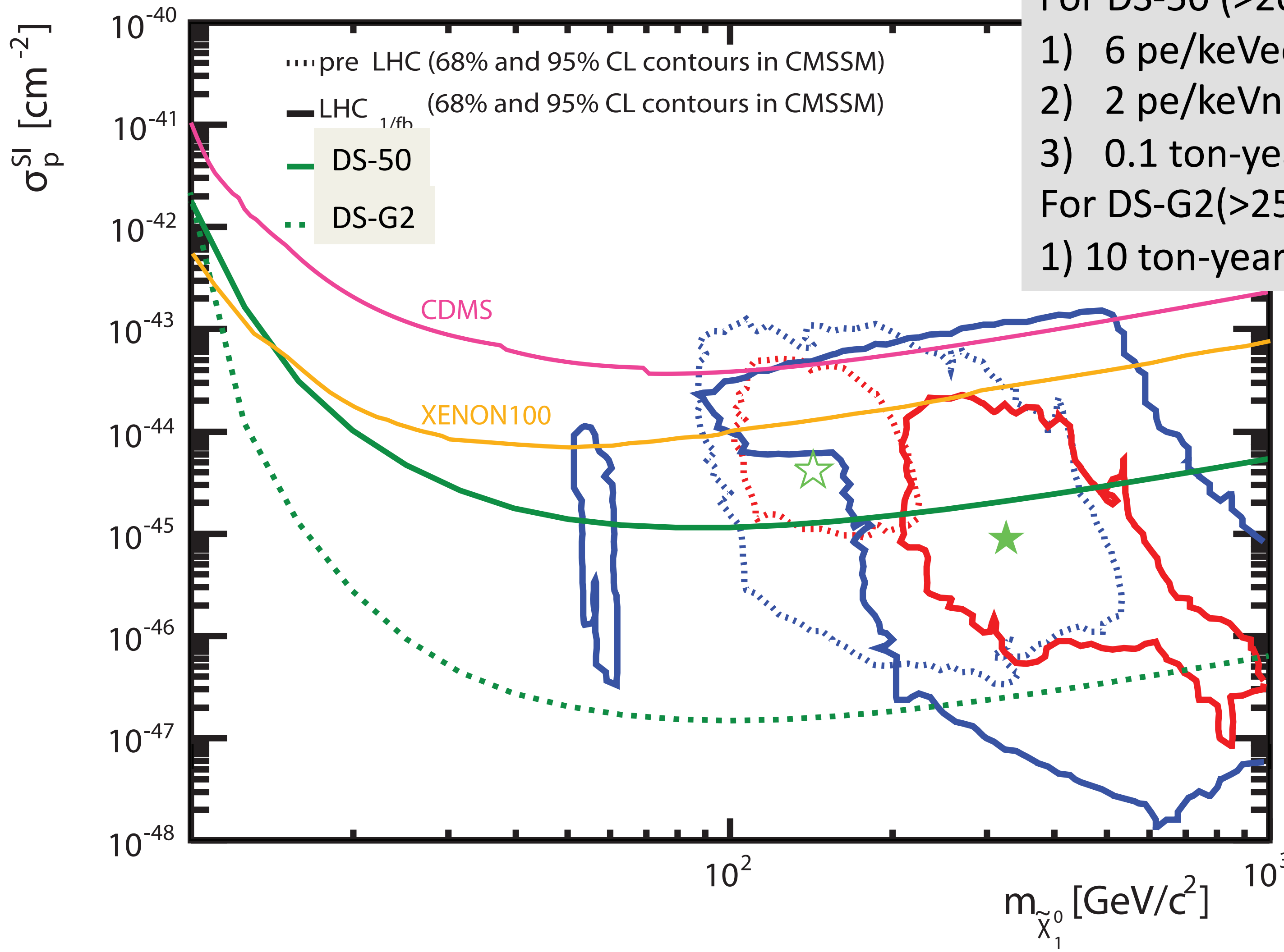
Estimated background in the DS neutron veto

- 30 tons boron-loaded scintillator in 1000 m^3 water tank, 100 PMTs
- Liquid scintillator
  - ^{14}C: ~4 Bq (Borexino level $^{14}C/^{12}C \sim 2\times10^{-18}$)
  - U+Th (1ppt): ~0.3 Bq
  - K(70ppb):~ 33Bq
- Stainless Steel Containment vessel: ~30 Bq (~1 mBq/kg in U and Th)
- External background < 1 Bq
- Inner Detector TPC < 1 Bq
- PMTs ~ 100 Bq
- Random coincidences ~ 160 Bq
- Total ~ 300 Bq which gives ~ 2% dead time in 1μs DAQ window

DarkSide Program

- **DarkSide-10**
  - a prototype detector with 10 kg of LAr
  - currently operating underground at Gran Sasso
  - test cryogenic technology with double phase TPC
  - test Light Yield and background rejection power
- **DarkSide-50**
  - 50 kg of depleted LAr for 10^{-45} cm^2 sensititivy for 100 GeV WIMP
  - currently under construction (ready by early 2013)
  - Test active veto concept and low background procedures
- **DarkSide-G2**
  - 3 tons target mass of depleted LAr
  - WIMP sensitivity 10^{-47} cm^2 for 100 GeV

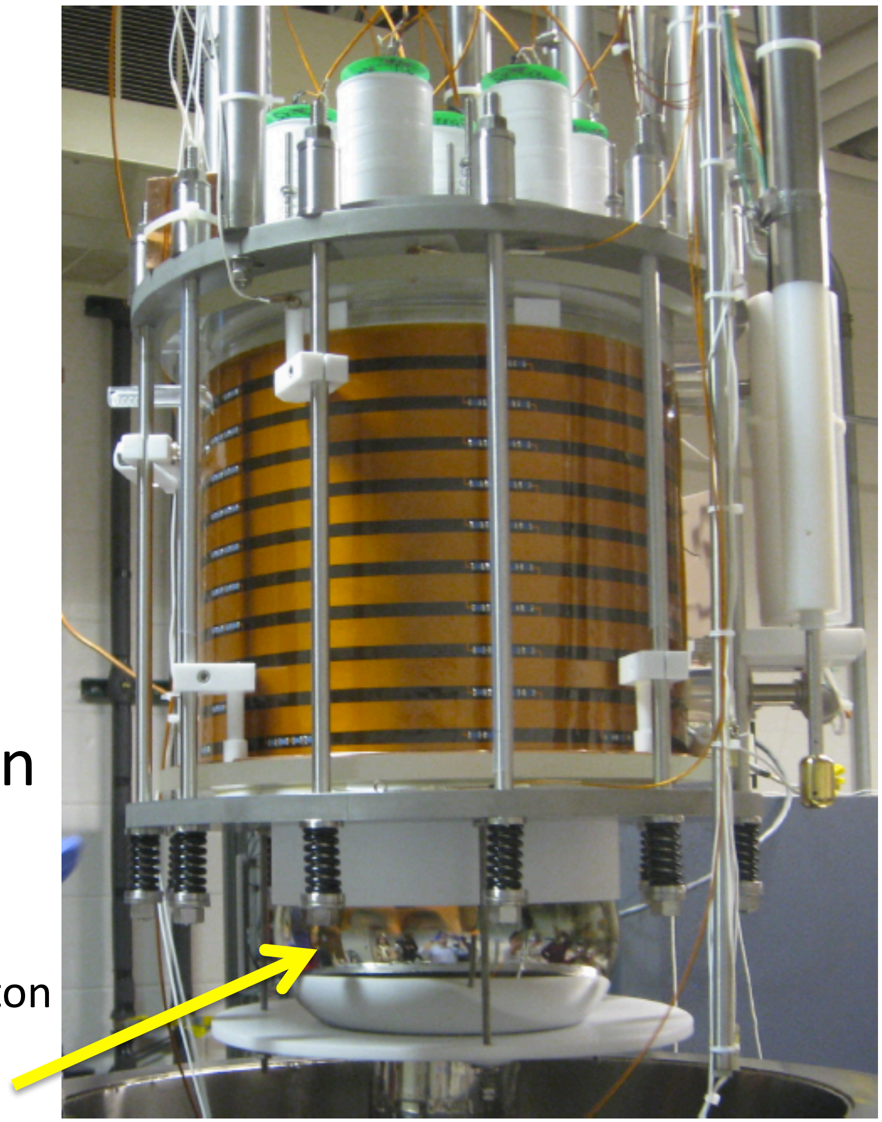
DarkSide WIMP Sensitivity



For DS-50 (>20keVnr):
1) 6 pe/keVee
2) 2 pe/keVnr
3) 0.1 ton-year
For DS-G2(>25keVnr):
1) 10 ton-year

DarkSide-10

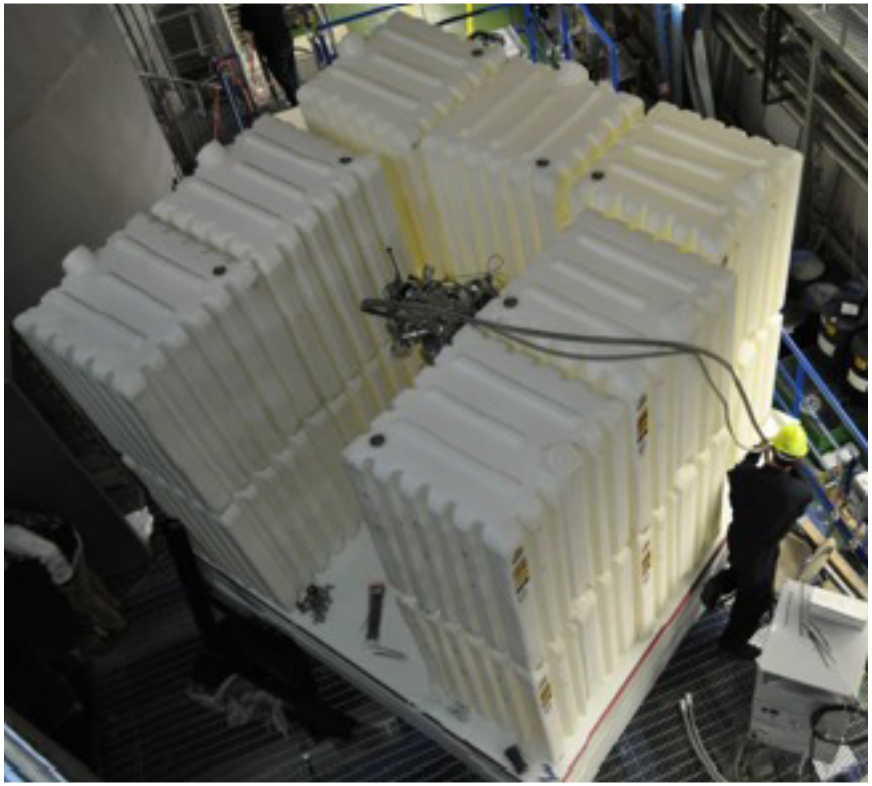
- Test DarkSide technologies
  - Control of gas layer
  - Charge drift and S2 light collection
  - **Light yield** (determined to be **~9 p.e./keVee** at zero field)
- Background suppression studies
- Experience operating an argon TPC



1 8” bottom PMT as in 1st test done at Princeton
Replaced by 7 3” PMTs at LNGS

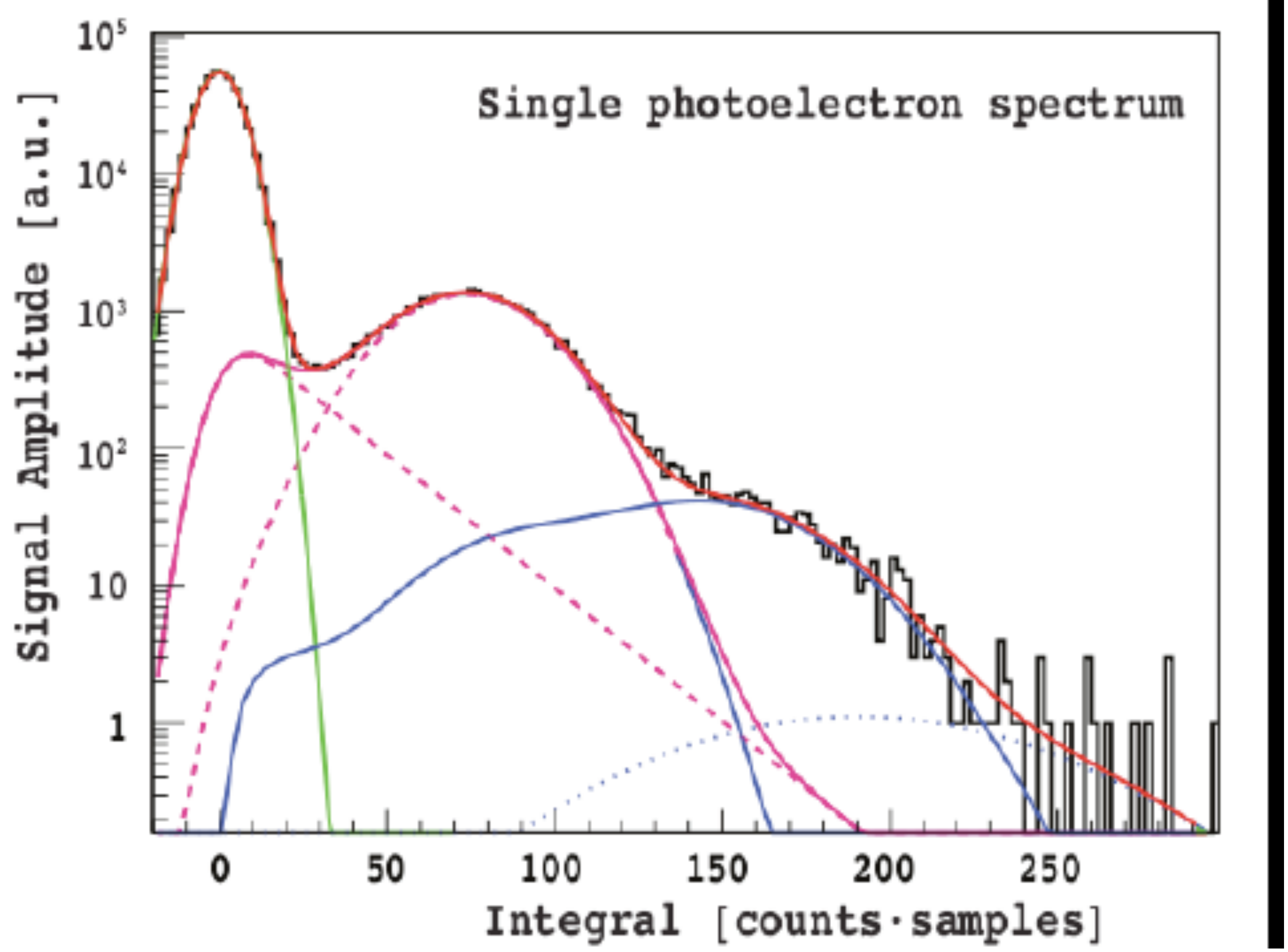
DarkSide-10 at LNGS

- In operation at Gran Sasso underground since summer 2011
- Water shielding to reduce background rate
- 15Hz with 4 PMTs trigger with water shielding
- Calibration with gamma and AmBe source



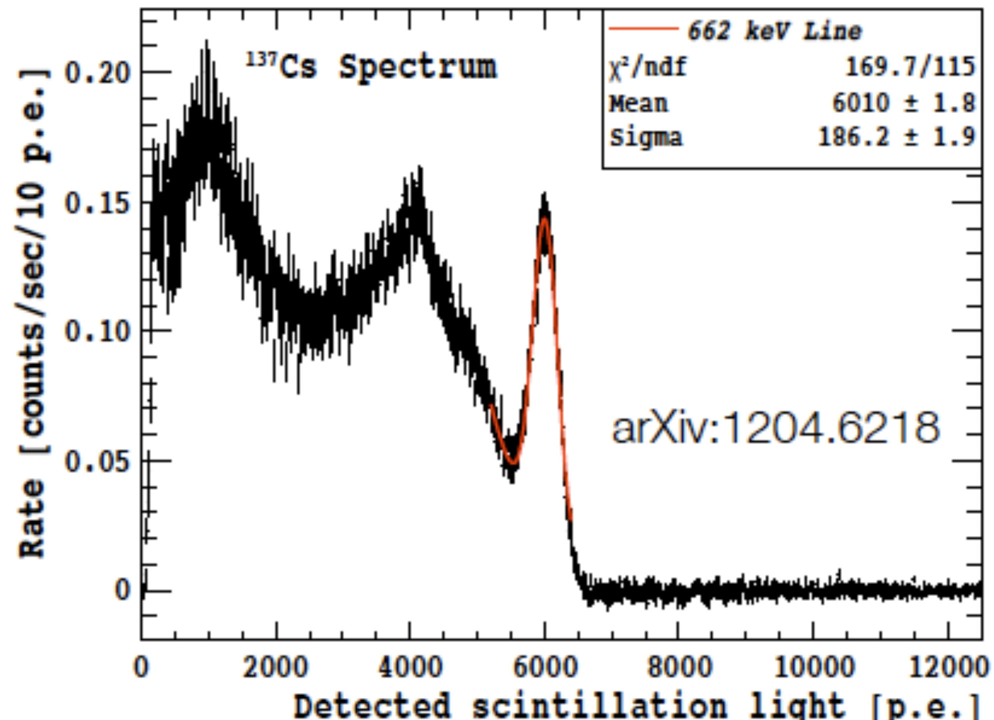
DS-10: PMTs calibrations

- 7 3” PMTs high QE at each end of sensitive volume
- QE ~ 30-36%



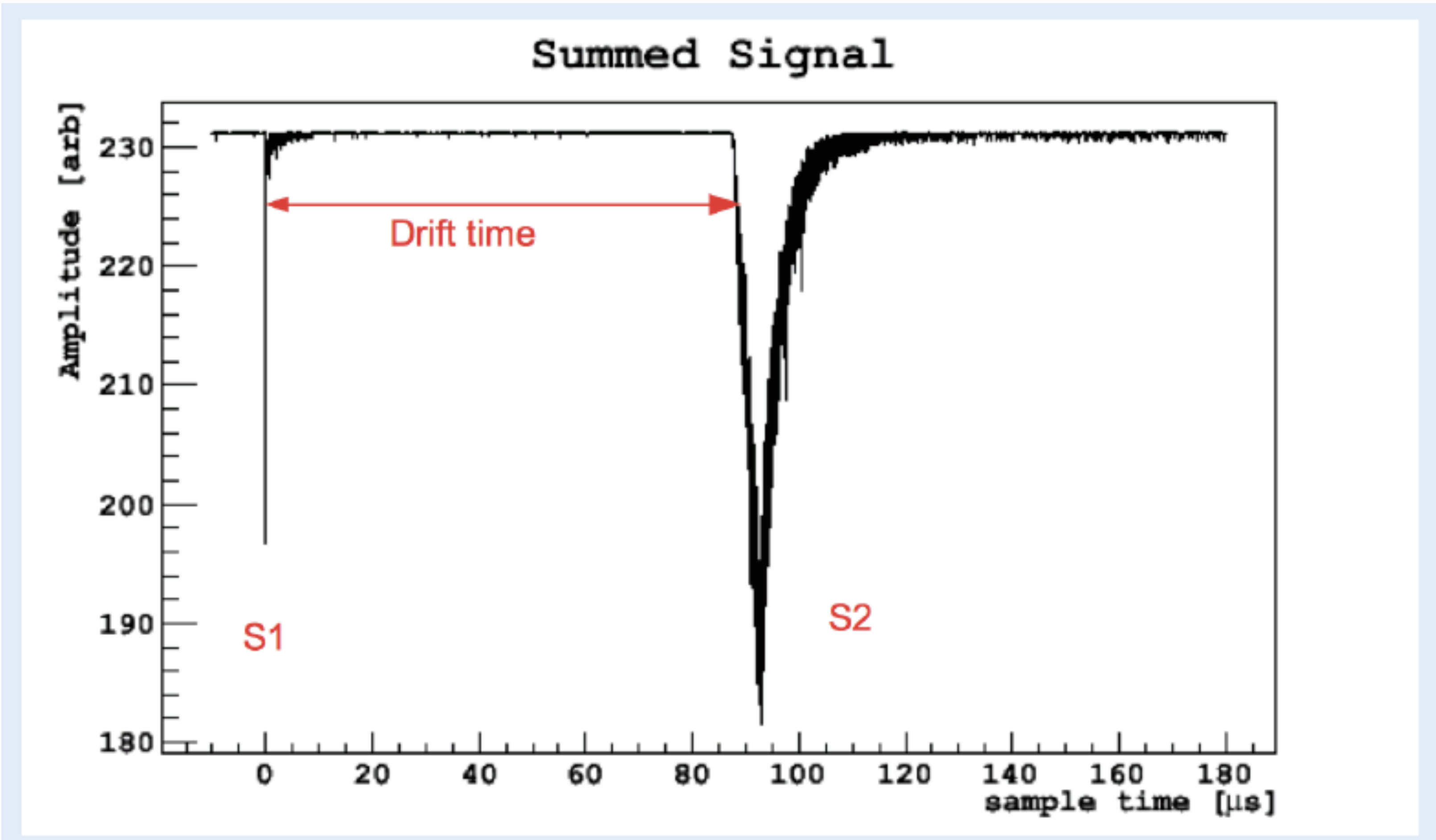
DS 10: light-yield

Light-Yield measured
by means of gamma sources
located outside the cryostat
vessel

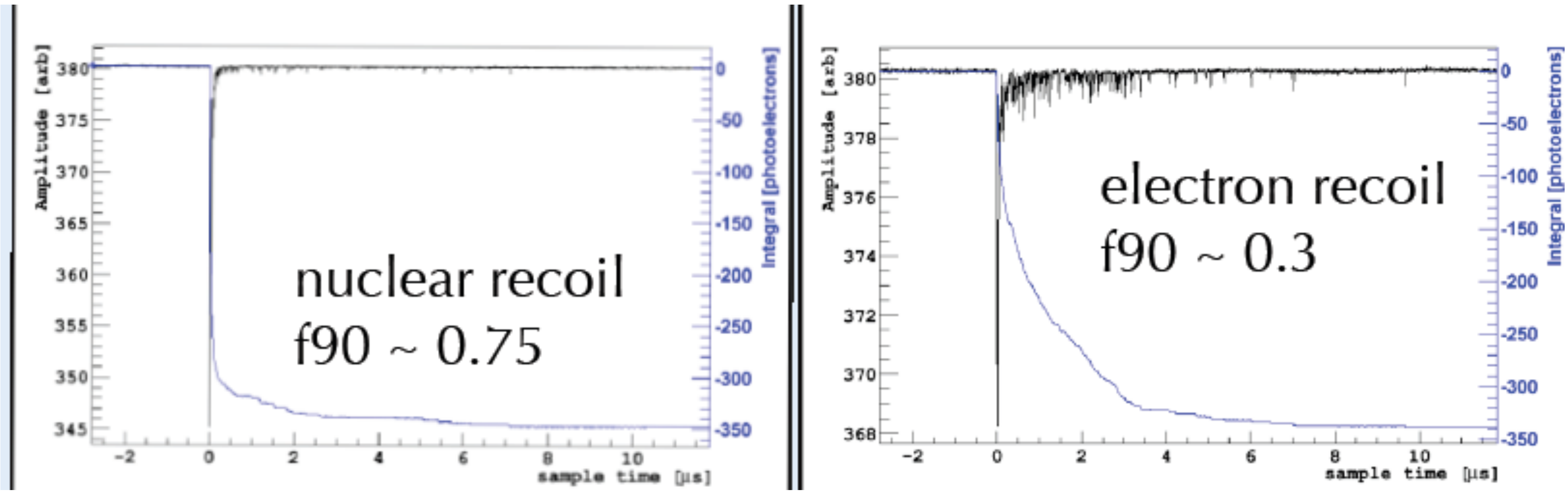


Energy [keV]	Light-Yield [p.e./keV]	Resolution (σ) [%]
122	8.87	5.2
511	8.78	3.4
662	9.08	3.1
1275	8.60	2.9
average	8.9±0.4	

DS-10: event w/ drift field

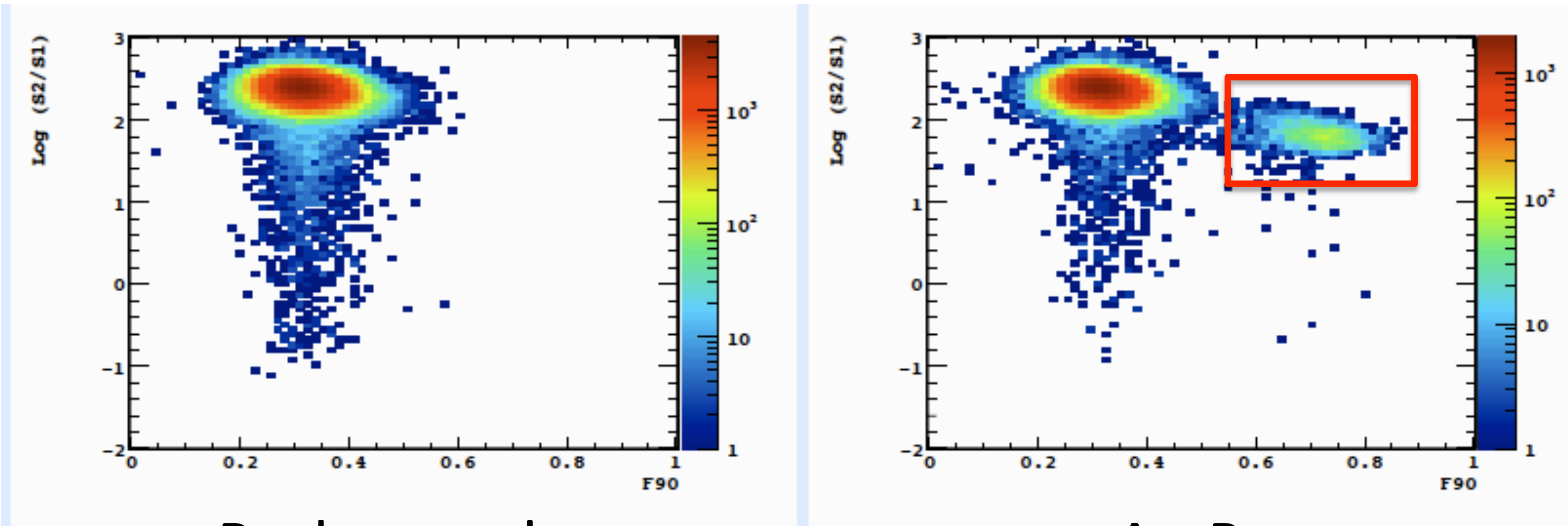


DS-10: PSD with S1 signal



- Figure of merit for PSD: f90 = fraction of S1 light which arrives before 90ns

DS-10: neutron calibration



Background AmBe

Data taken in TCP mode with AmBe source (10n/s) outside the cryostat.
Rejection power against threshold under study

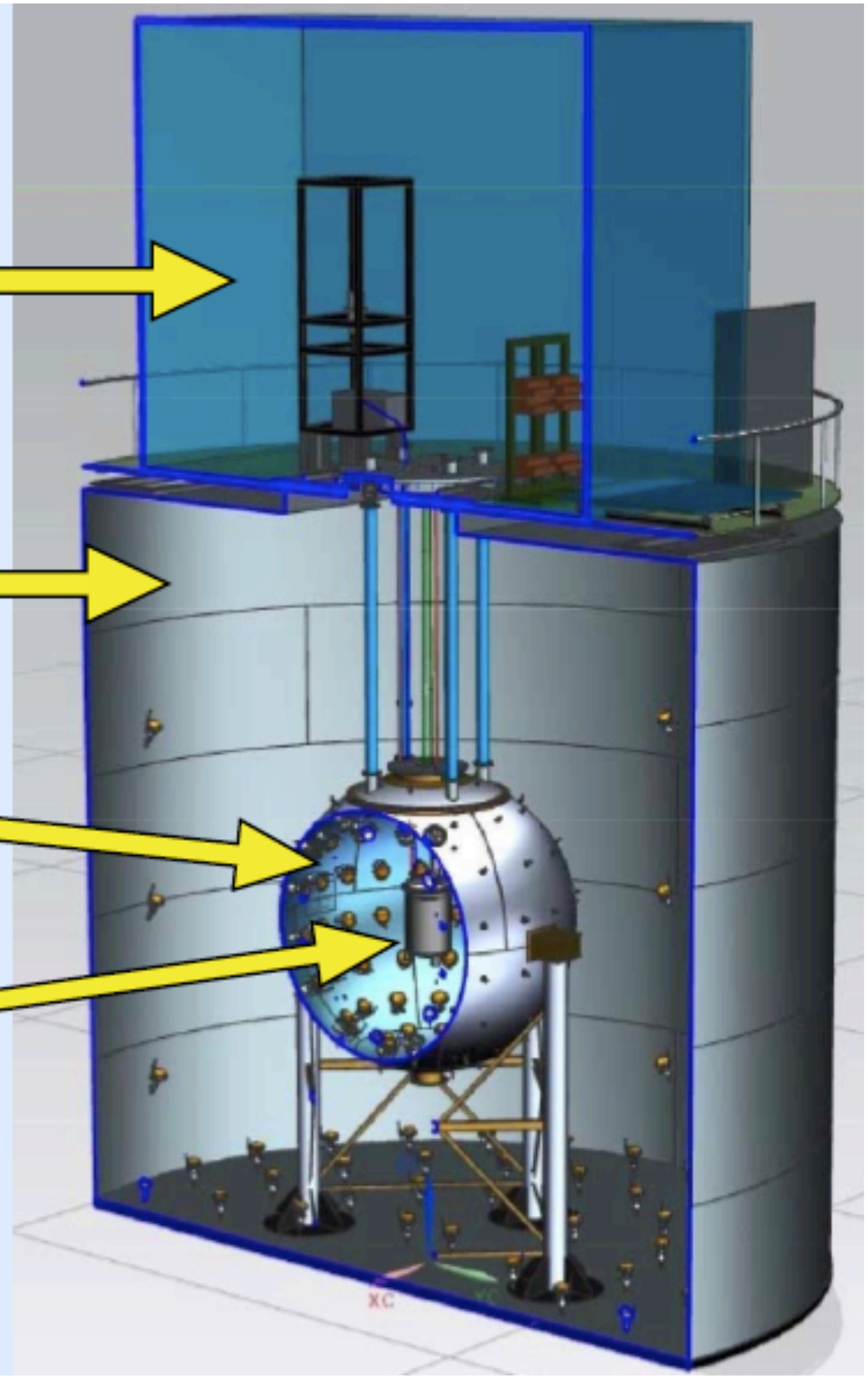
DarkSide-10: publications

- *Light Yield in DarkSide-10: a prototype two-phase liqid argon TPC for Dark Matter Searches*, DarkSide coll., arXiv:2104.6218
- *Study of the Residual ^{39}Ar content in Argon from Underground Sources*, DarkSide coll, arXiv:1204.6011

Dark Side 50

- 50 kg DLAr sensitive mass
- WIMP-nucleon cross section sensitivity $\sim 10^{-45} cm^2$
- Detector under construction
- Data taking expected in spring 2013
- First step toward 1 ton-scale detector

DS-50 layout



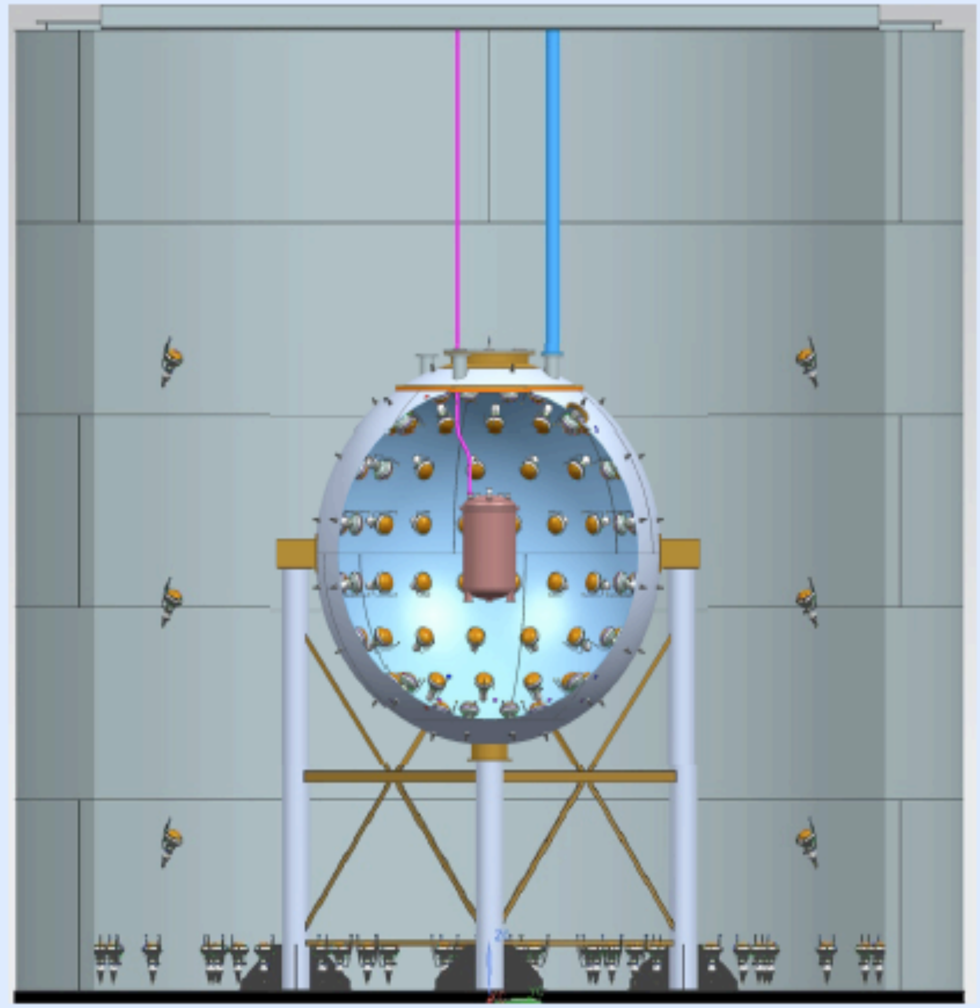
Radon-free clean room
Instrumented water tank
Liquid scintillator
Inner detector TPC
(Underground argon)

DarkSide-50 water tank

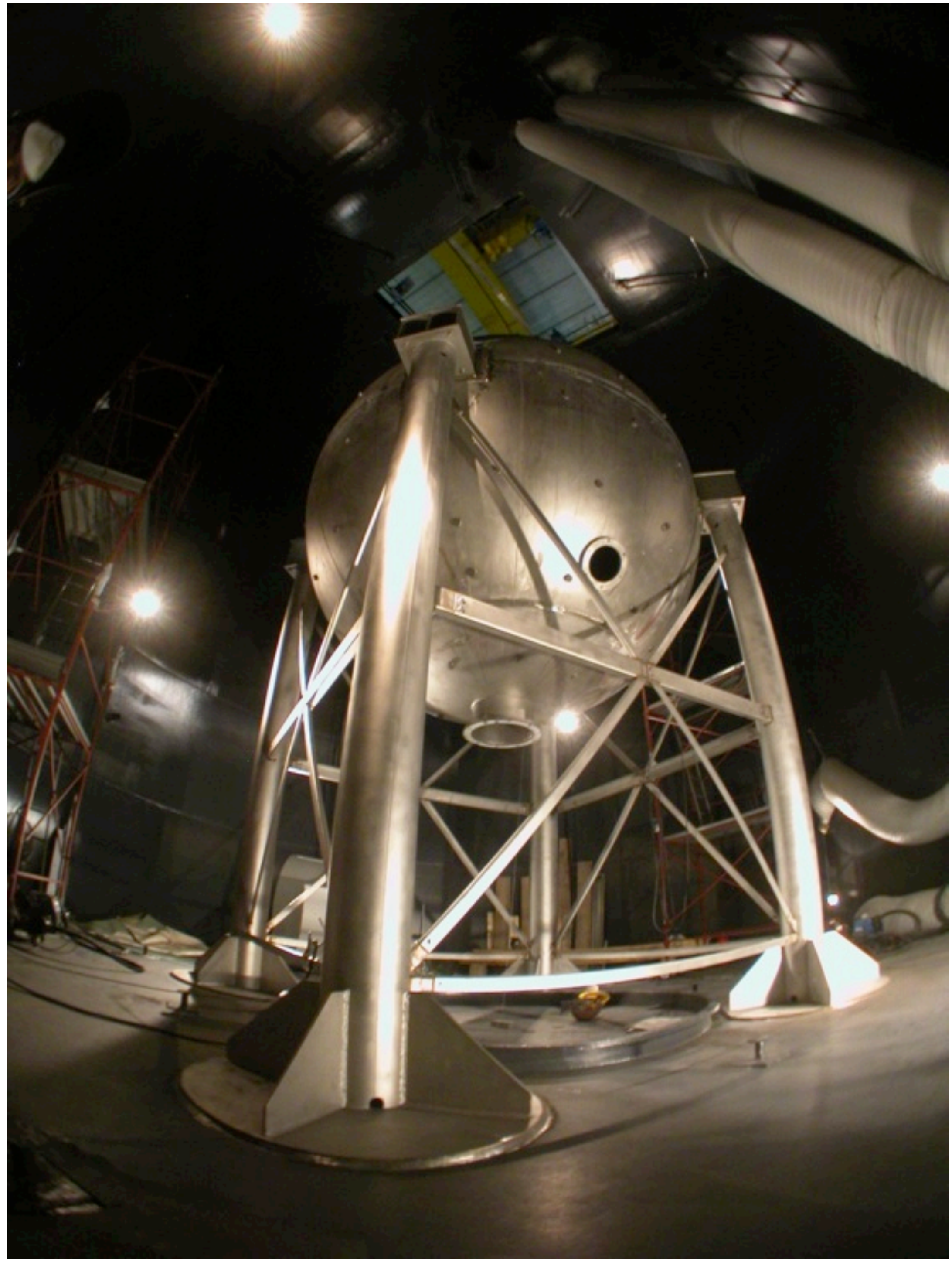
80 PMTs within Borexino CTF (11m dia. x 10 m high)

Acts as a muon and cosmogenic veto (~ 99% efficiency)

Provides passive gamma and neutron shielding



The Liquid Scintillator Contaiment Vessel for the DarkSide Neutron Veto as completed within the CTF water tank
(Hall C of LNGS)



Summary

- DarkSide detector designed to have very low background for direct WIMP search with LAr
- First use of active boron-loaded liquid scintillator neutron veto
- Make use of Borexino fluind handling and purification plants
- 10kg prototype in operation since summer 2011
- 50kg DS-50 full design detector in construction
- DS-50 commissioning expected early 2013
- DS-50 sensitivity ~ 10^{-45} cm^2

Darkside Collaboration

Augustana College – SD, USA
Black Hills State University – SD, USA
Fermilab – Il, USA
INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy
INFN and Università degli Studi Genova, Italy
INFN and Università degli Studi Milano, Italy
INFN and Università degli Studi Naples, Italy
INFN and Università degli Studi Perugia, Italy
Institute for High Energy Physics – Beijing, China
Joint Institute for Nuclear Research – Dubna, Russia
Princeton University, USA
RRC Kurchatov Institute – Moscow, Russia
St. Petersburg Nuclear Physics Institute – Gatchina, Russia
Temple University – PA, USA
University of Arkansas, USA
University of California, Los Angeles, USA
University of Houston, USA
University of Massachusetts at Amherst, USA