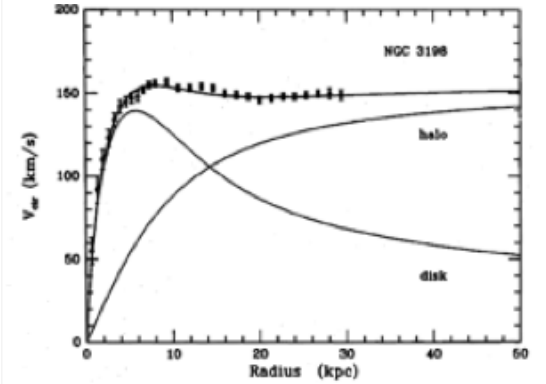
Direct Dark Matter Search with Liquid Argon

D. Franco

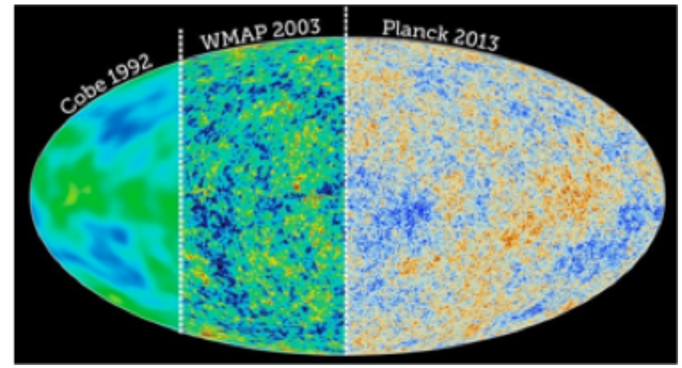
NCNJ – December 2018

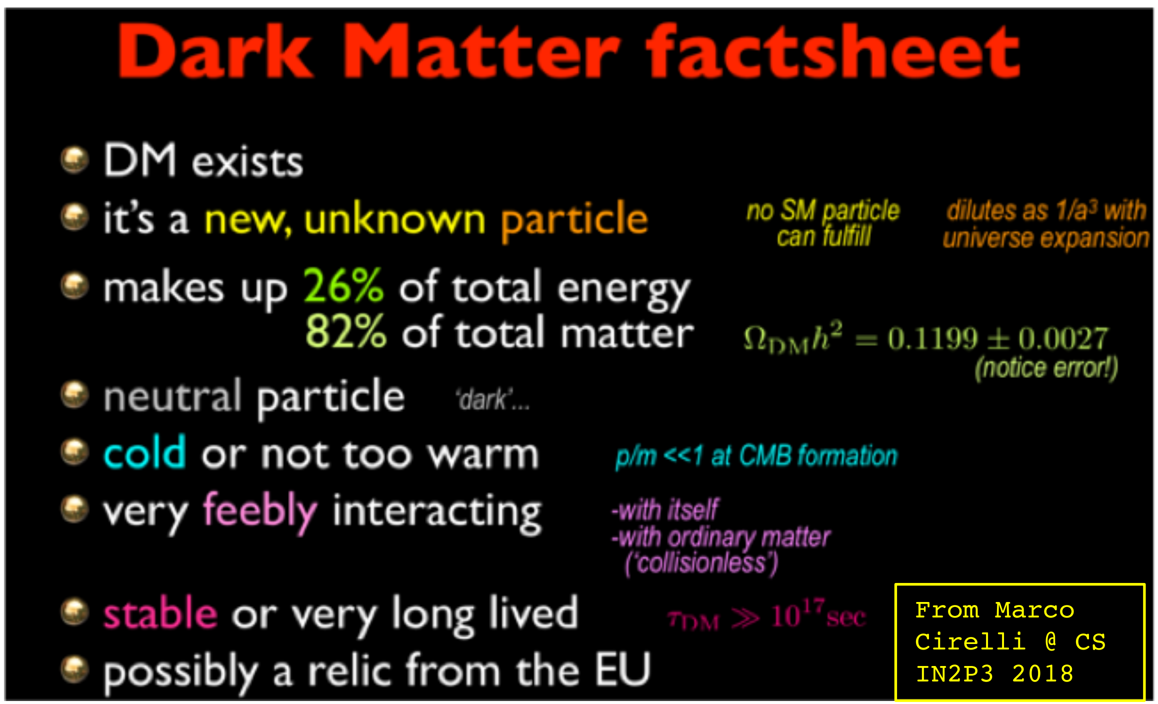
galactic rotation curves



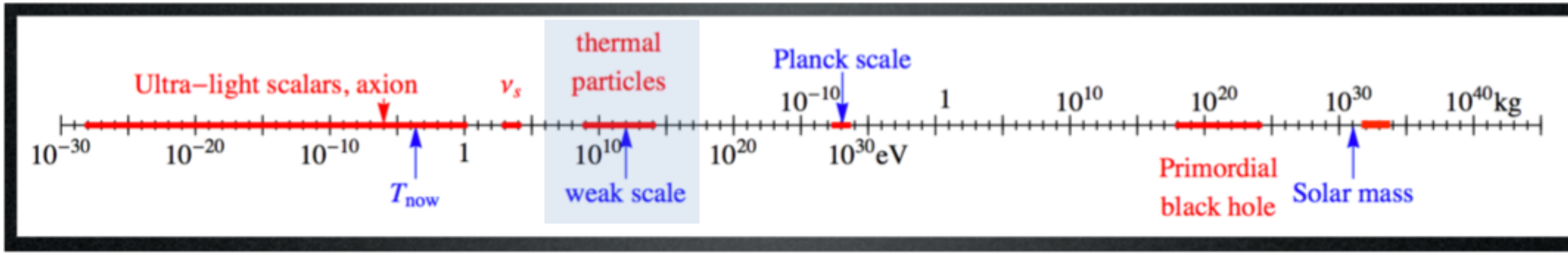
Weak lensing

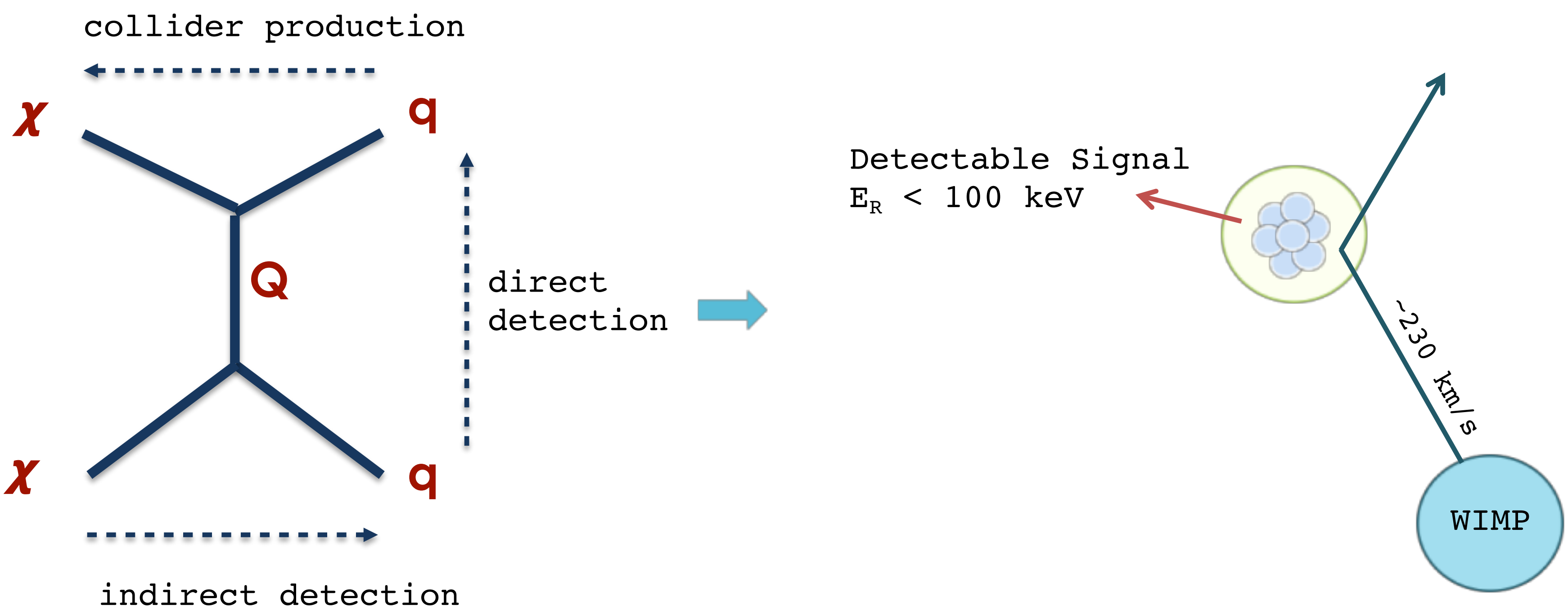
Precision cosmology





« only » 90 orders of magnitude



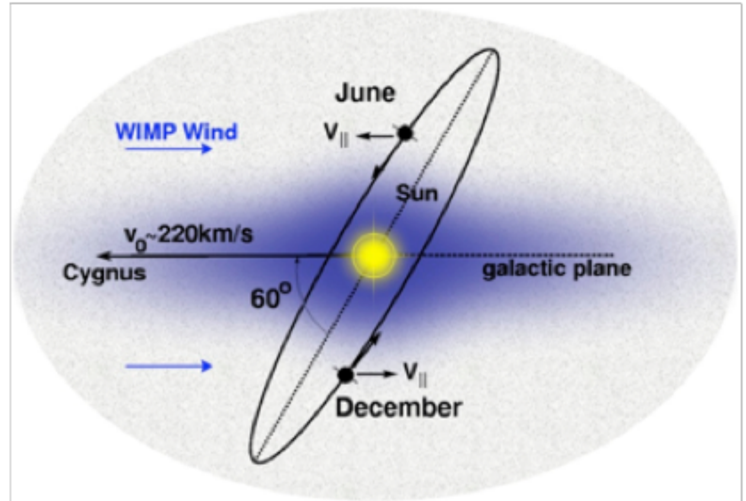


Observables: Characteristic Features

Annual Modulation

Earth rotation around the Sun => **largest speed** of the dark matter particles in the Milky Way halo relative to the Earth around **June 2nd** and **smallest in December**

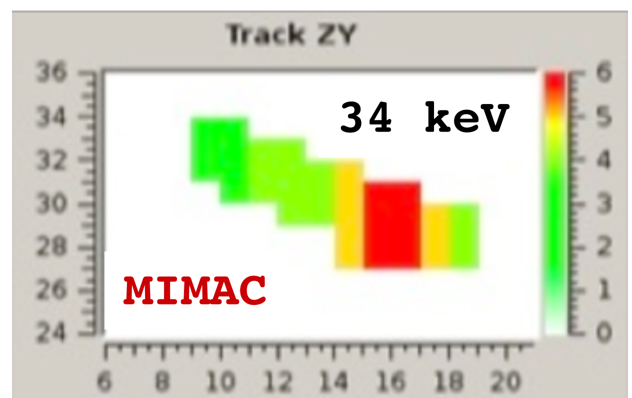
Expected seasonal variation at **2-10%** level



Directionality

The recoil rate, in the Galactic rest frame, is **highly anisotropic**: the rate in the **forward direction** is roughly an order of magnitude larger than that in the backward direction

10 WIMP events could be **enough to reject isotropy** (Green & Morgan, Phys. Rev. D81 061301, 2010)



Observables: the Rate

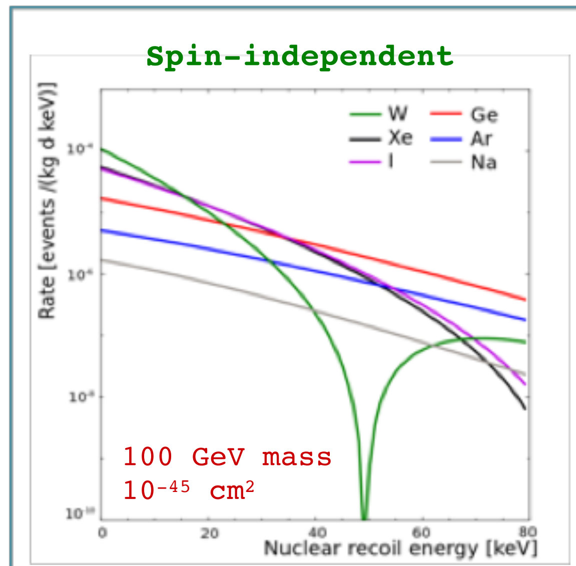
Event rate proportional to:
- Number of target nuclei
- Local WIMP density
- Elastic cross section

$$R \propto N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \cdot \langle v \rangle$$

For instance:
- liquid argon target
- 100 GeV WIMP mass
- $\sigma = 10^{-47}$ cm^2

=> 1 event/ton/year

In case of positive observation, measurements with **multiple targets** are needed

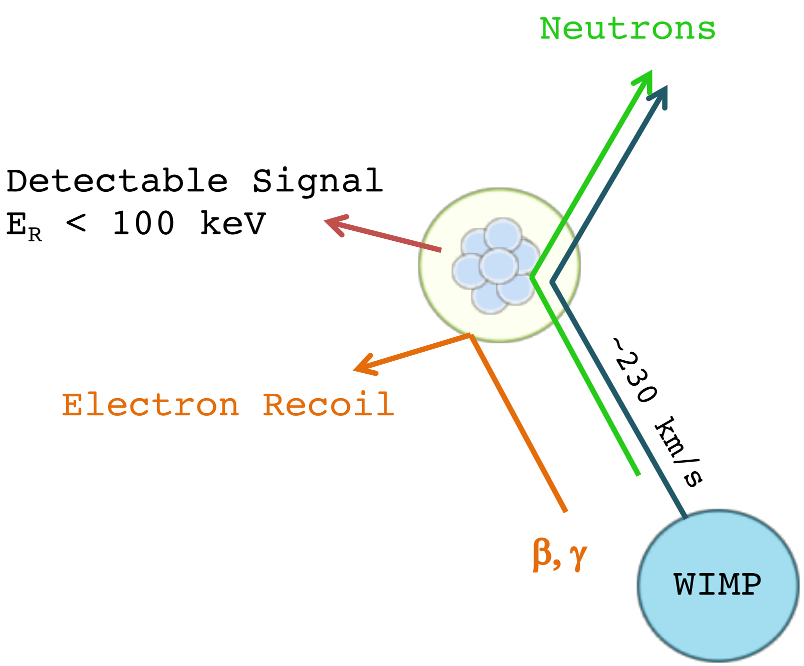


Backgrounds and Detector Requirements

Cosmic rays and cosmogenic isotopes

Natural (^{238}U, ^{232}Th, ^{235}U, ^{222}Rn,…) and anthropogenic (^{85}Kr, ^{137}Cs,…) **radioactivity**

Neutrinos (solar, atmospheric, diffuse supernovae)



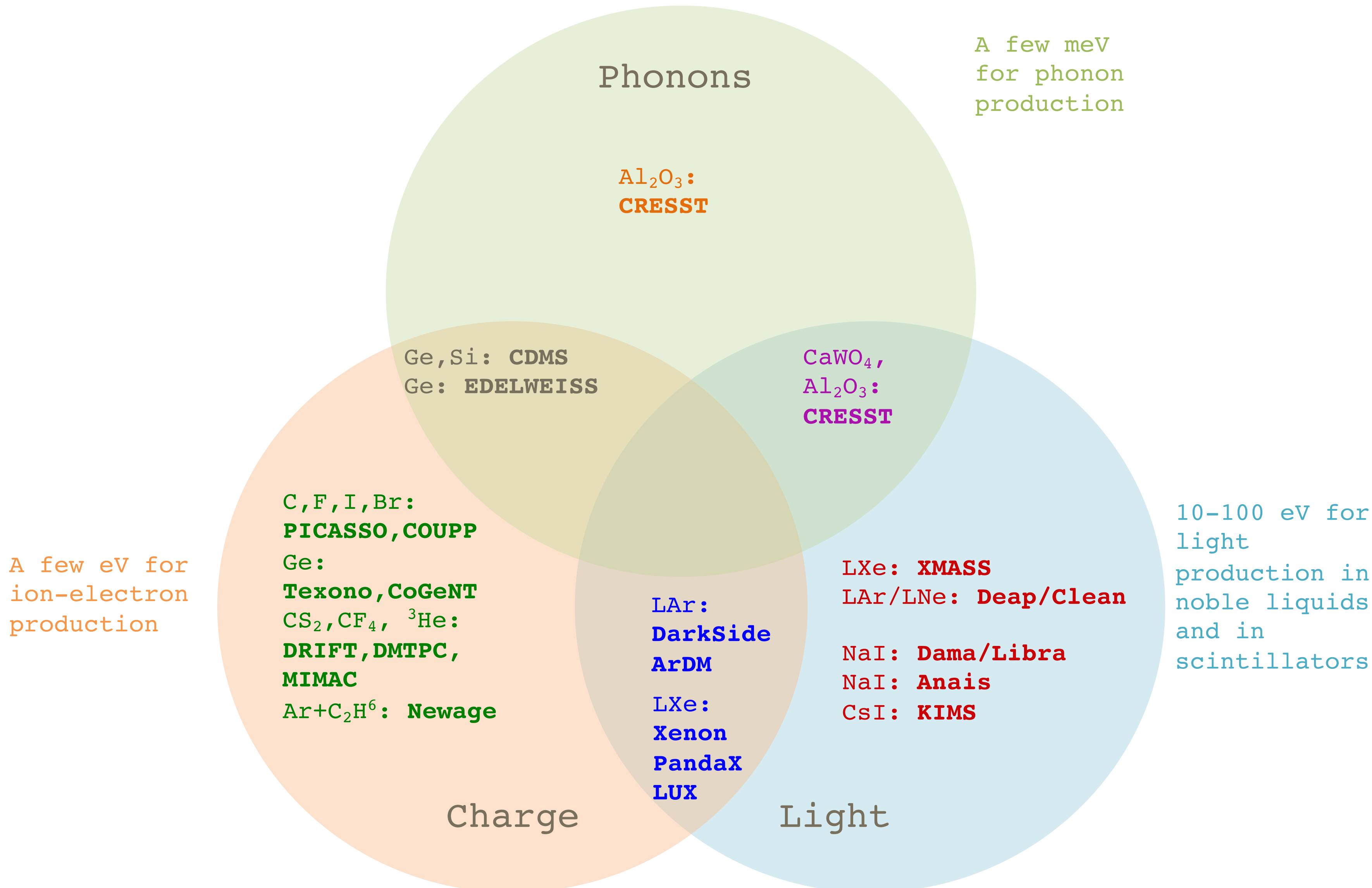
WIMP detector requirement:

- Large mass
- Low energy threshold
- Ultra-low background
- Signal/background discrimination

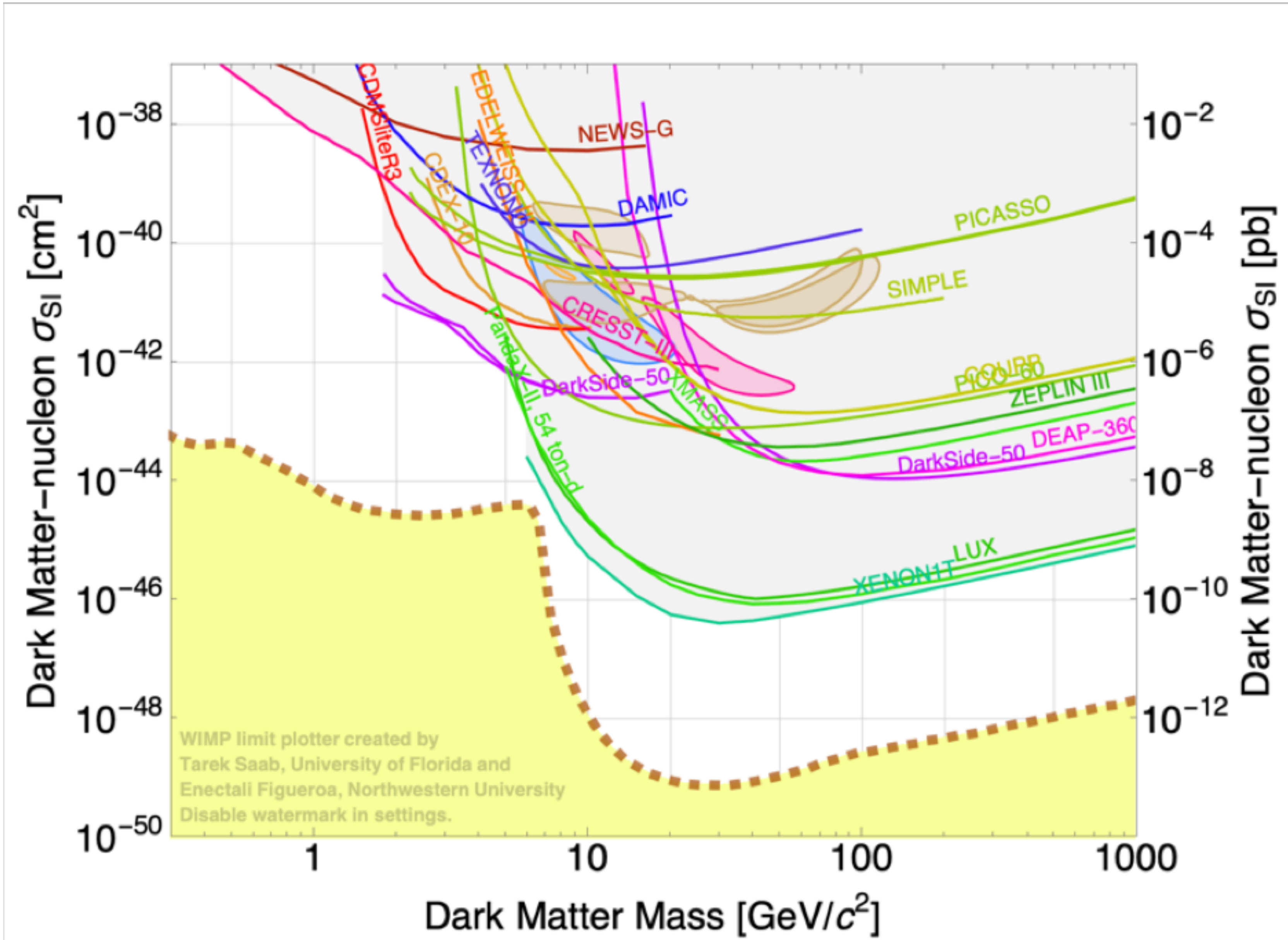
Either **background free** or perfectly constrained background

Or **clear signature** (annual modulation, directionality)

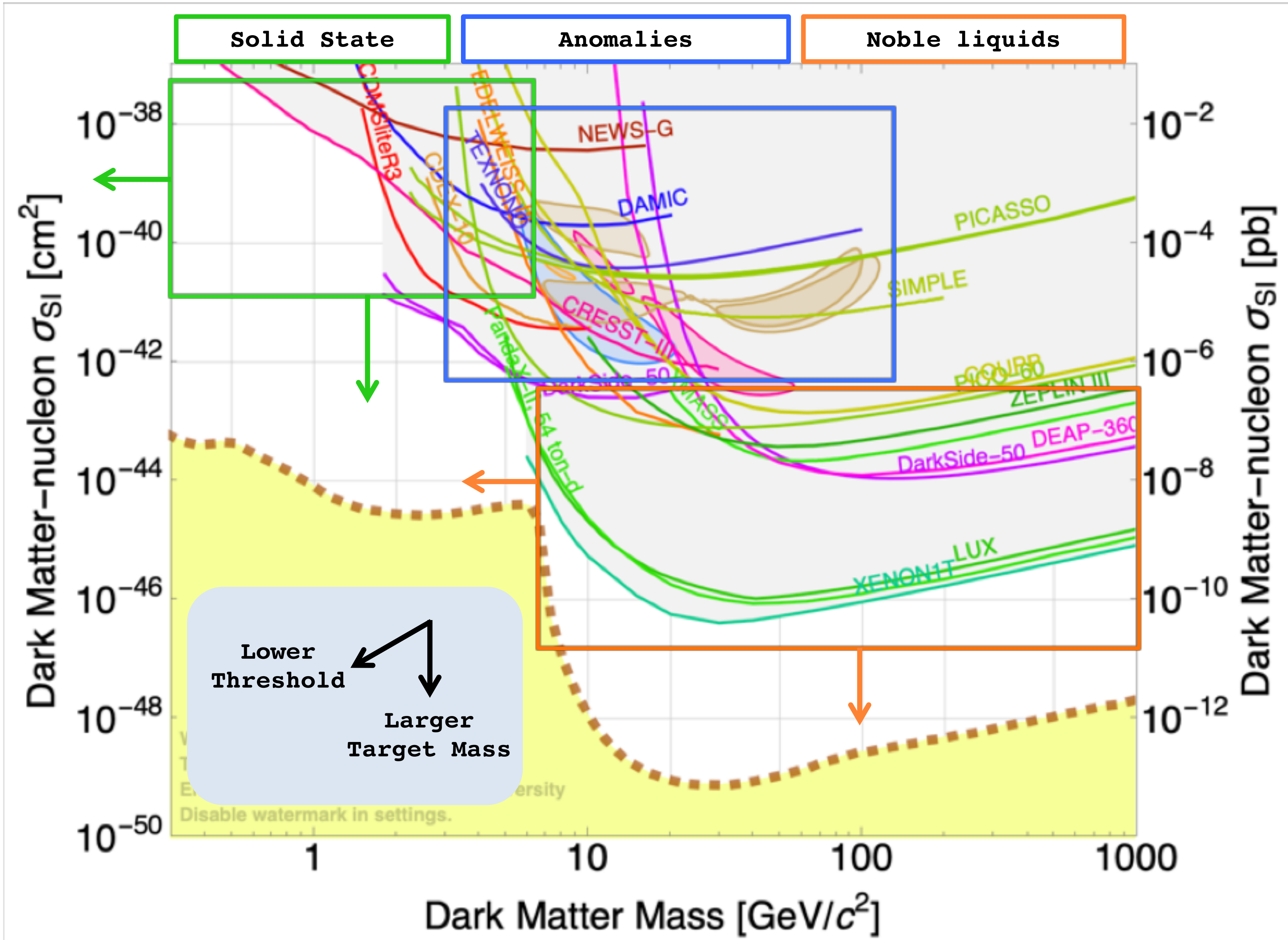
Direct Detection Techniques



Search Status



Search Status

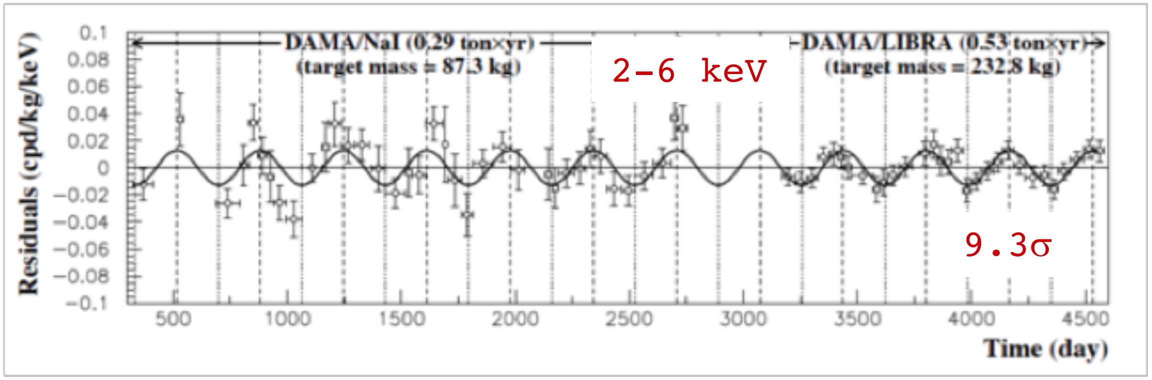


Inorganic Scintillators

Characteristics
- Operating at room temperature
- High density (3-5 g/cm^3): **large stopping power**
- High light yield: **low thresholds** ~O(keV)
- **Limited crystal size** (several cm^3): several detectors for large masses
- **Limited background rejection** (only multiple crystal cut)

DAMA/Libra

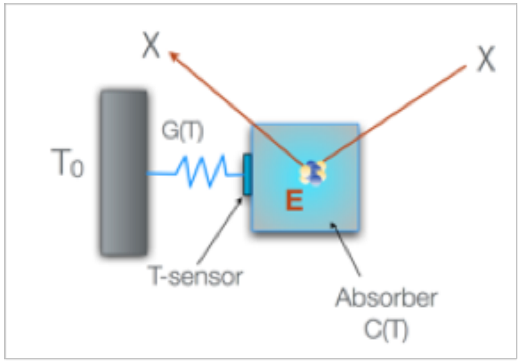
Annual modulations with high radio-purity NaI crystals
Exposure: 1.33 ton/year
Phase: compatible with June 2nd within 2σ
Evidence at more than 9σ



Several experiments in the next years with same techniques (NaI, CsI) will probe the modulation signal:
DM-Ice, Anais, KIMs, SABRE

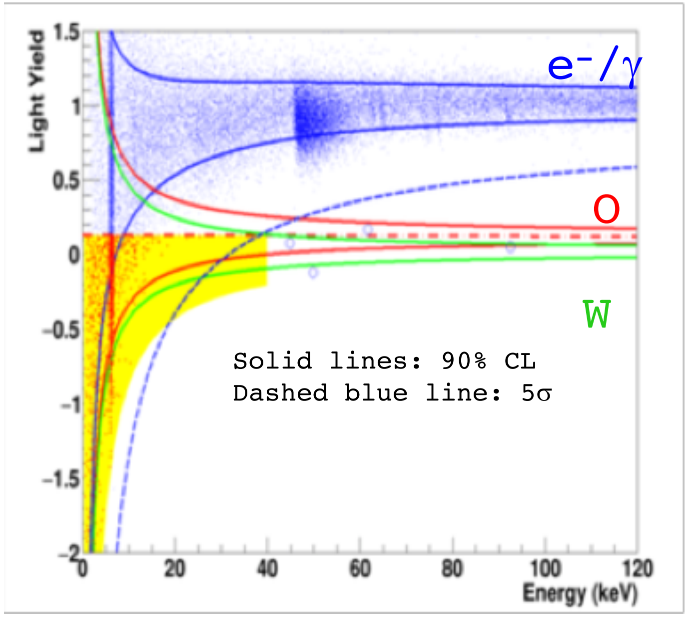
Cryogenic Bolometers

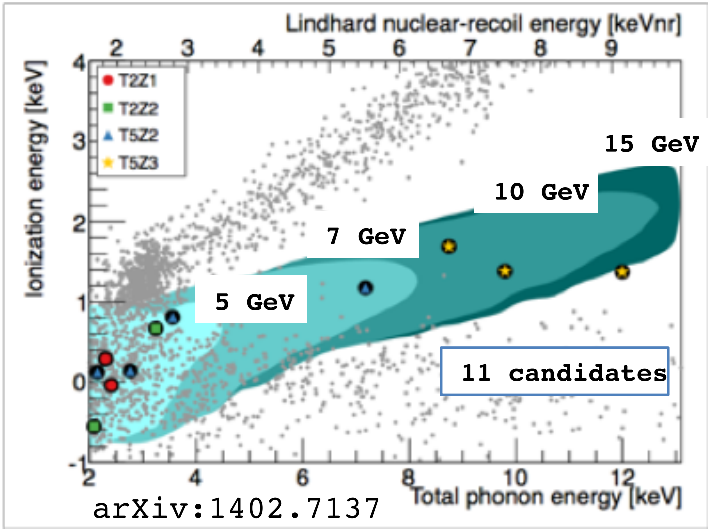
Characteristics
- Operating at **mK temperature**
- Excellent **energy resolution**
- Very low thresholds **<100 eV**
- **Limited crystal sizes** (100 g – 1.4 Kg)
- **Good discrimination with phonon vs light/charge**



Phonon vs **Light**

Phonon vs **Charge**





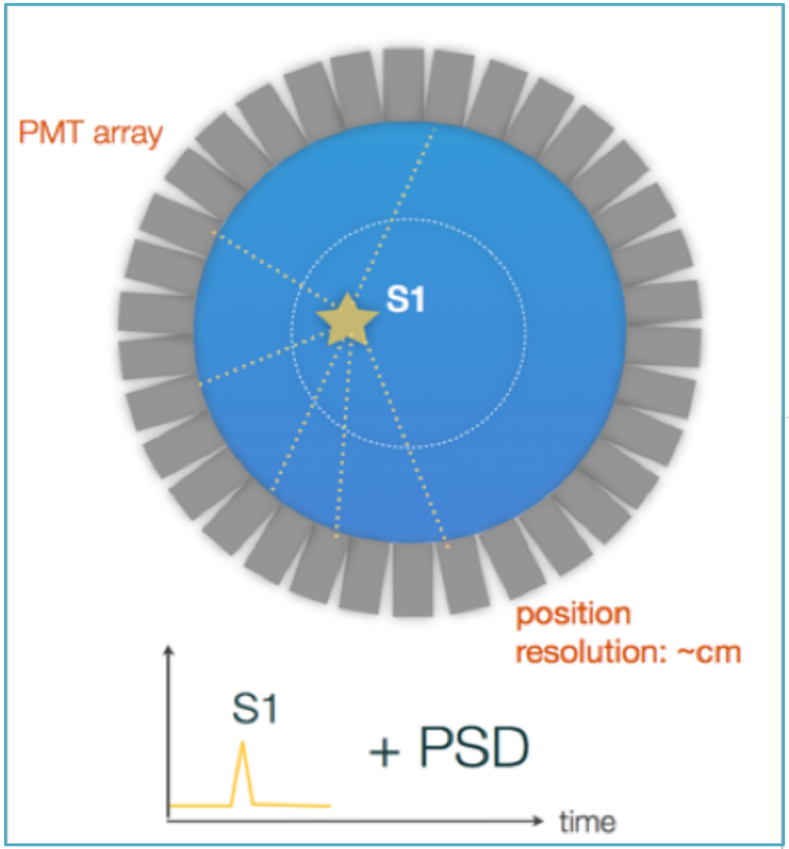
CRESST-II

SuperCDMS
EDELWEISS

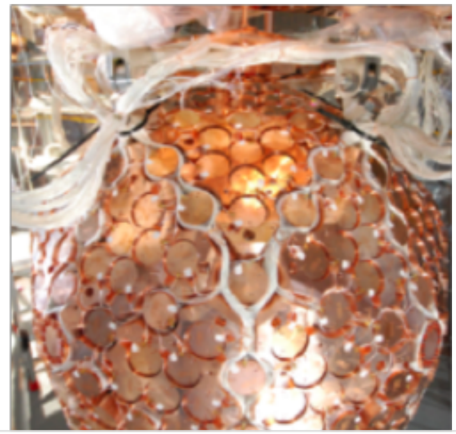
Noble Liquids: Xenon vs Argon

	LAr	LXe
WIMP SI cross section	**Limited to large masses ($M\chi$ > 10 GeV)**	**Sensitive also to low masses**
WIMP SD cross section	**Not accessible**	**Accessible**
Radio-purity	^{39}Ar contamination (fixed: see next slides)	**Intrinsically pure**
Density	1.4 g/cm^3	**3.1 g/cm^3**
Temperature	**87.2 K** (close to nitrogen)	166.4 K
S1 Pulse Shape Discrimination	**Yes (singlet ~7 ns; triplet ~1600 ns)**	Very limited (singlet: ~2 ns; triplet: ~27 ns)
Cost and availability	**Generically cheap** (~$/kg) + **extra costs** for underground extraction **Abundant**	**Expensive** (~kDollar/kg) **Limited** world production

Single-Phase Noble Liquids

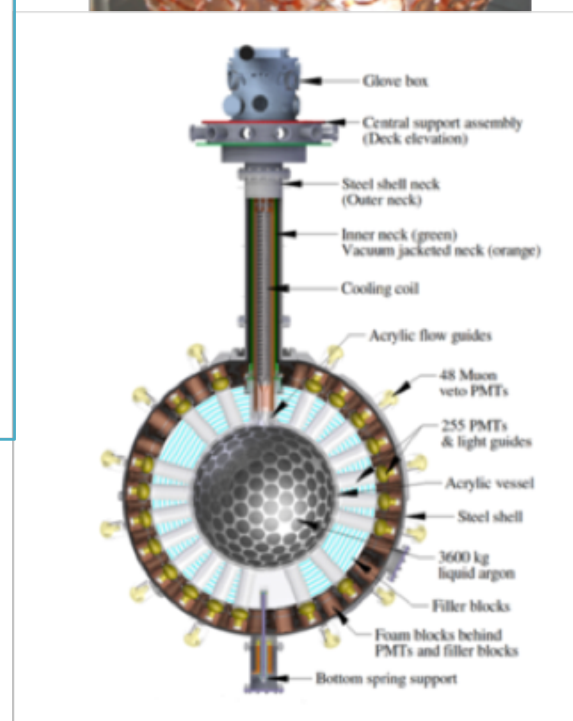


from L. Baudis@Solvey-Francqui Workshop 2015



XMASS at Kamioka

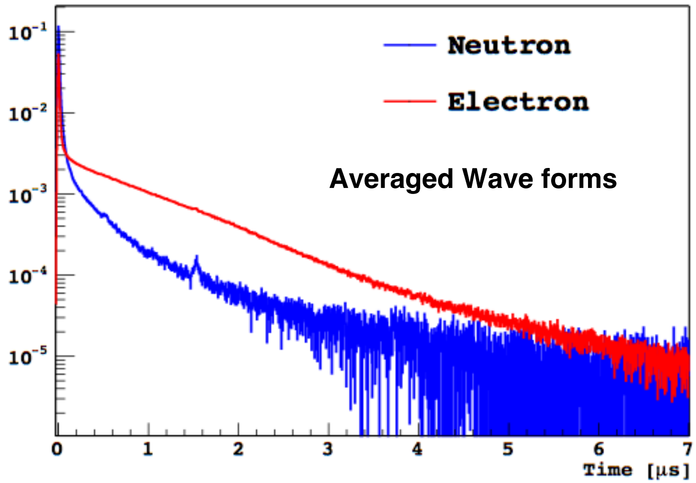
- **832 kg of LXe**
- Data taking ~1 year
- 642 2'' PMTs (62% optical coverage)
- **Light Yield: 14.7 pe/keV**
- Looking for annual modulation



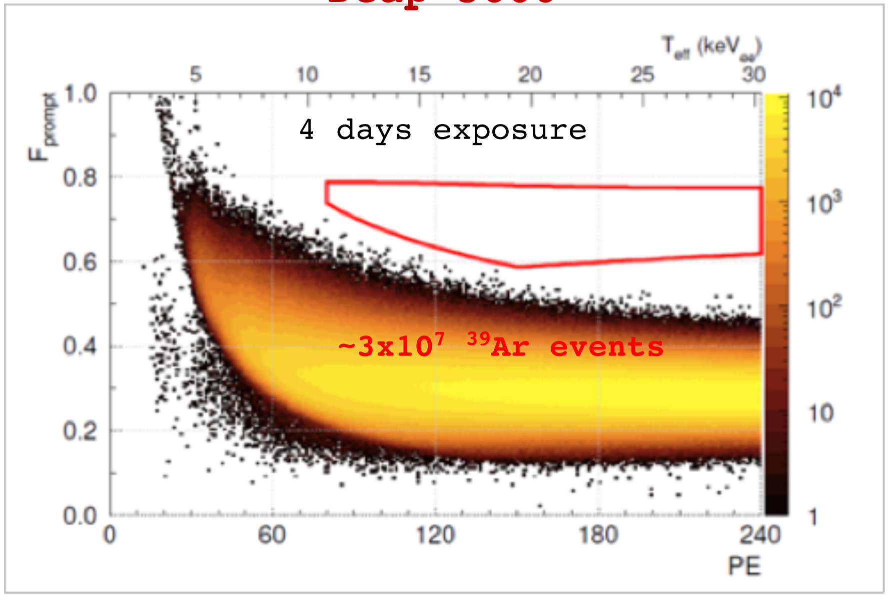
Deap-3600 at SNOLab

- **3600 kg of LAr**
- 255 PMTs
- Light Yield: ~8 pe/keV
- **Exceptional PSD**
- Ready for beginning 2016

LAr Pulse Shape Discrimination



Deap-3600



De-excitation times

LAr:

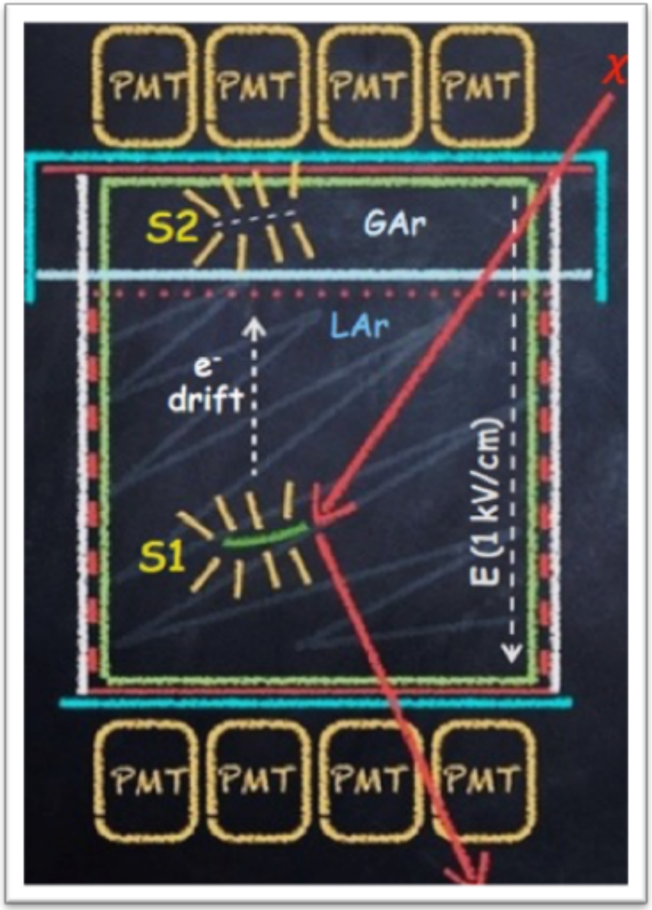
$\tau_{singlet}$ ~ 6 ns
$\tau_{triplet}$ ~ 1600 ns

LXe:

$\tau_{singlet}$ ~ 4 ns
$\tau_{triplet}$ ~ 22 ns

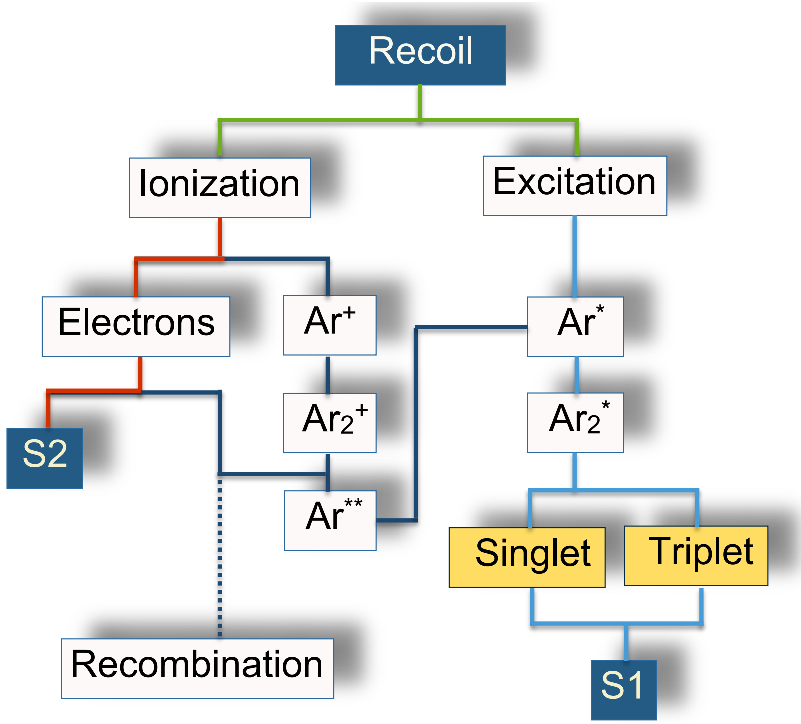
Projected rejection power: $>10^9$

Dual-Phase Noble Liquids



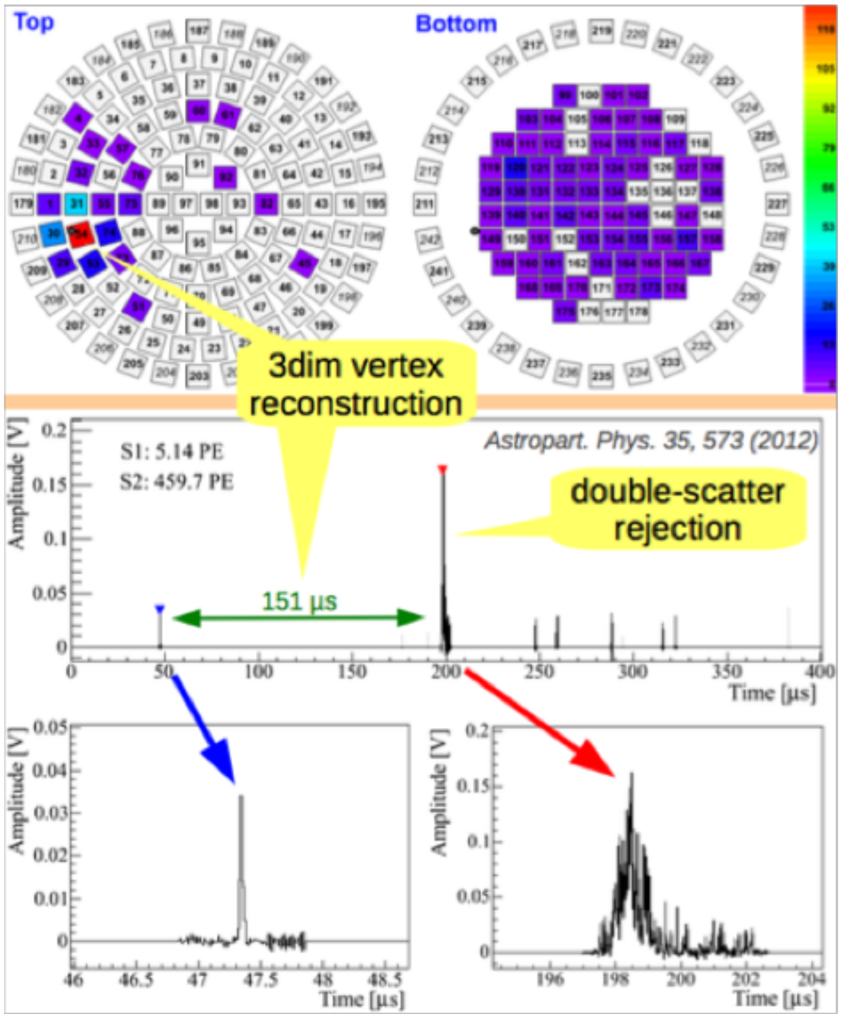
Particle discrimination through:

- Accurate 3D **position** identification
- **Multiple-scattering** rejection
- **S2/S1** ratio
- S1 **PSD** (if available)

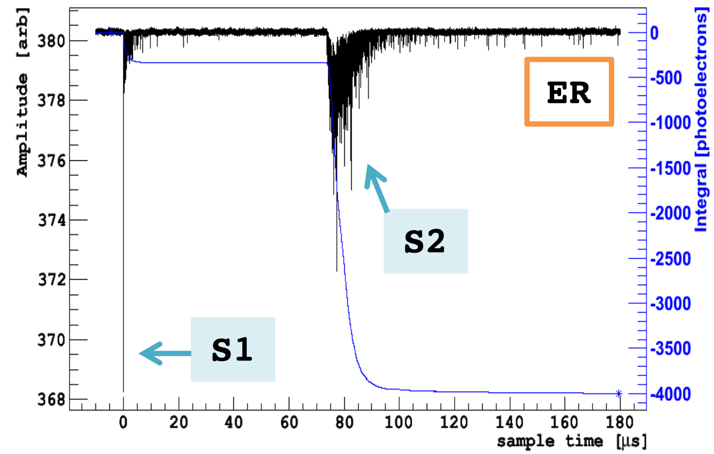


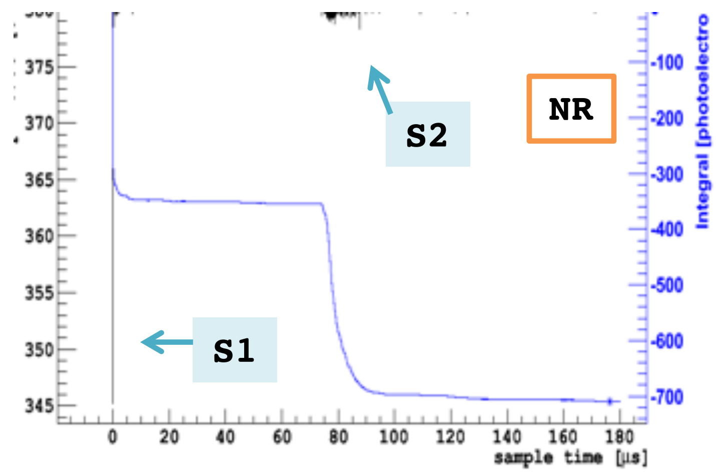
Dual-Phase TPC

Position reconstruction and multiple scatter



S2/S1 Particle Discrimination



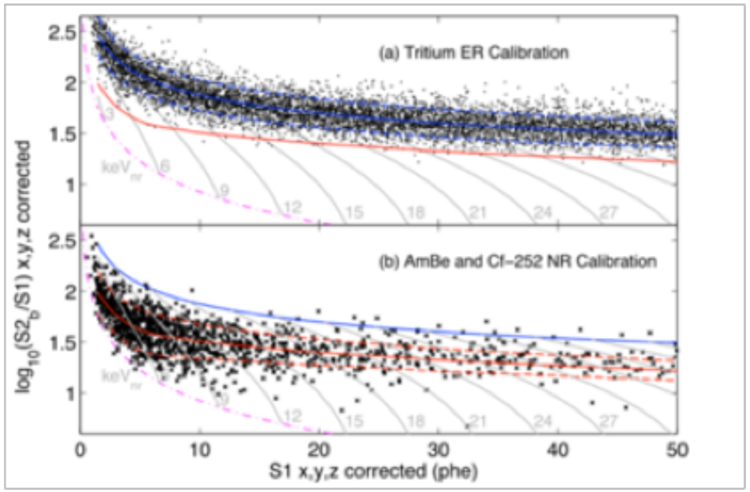


Rejection factor ~ 10^2 – 10^3

Dual-Phase Liquid Xenon

Xenon1T – LUX - PandaX

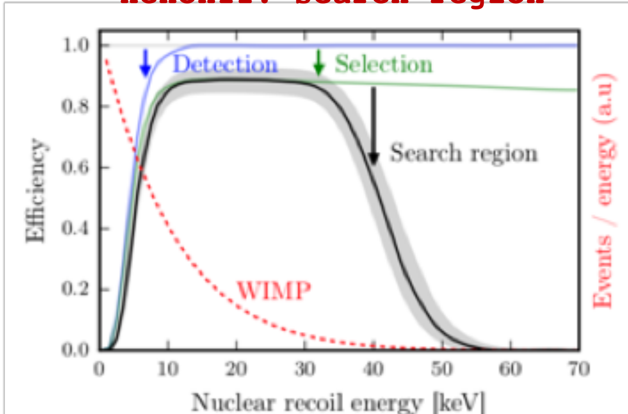
LUX: calibration

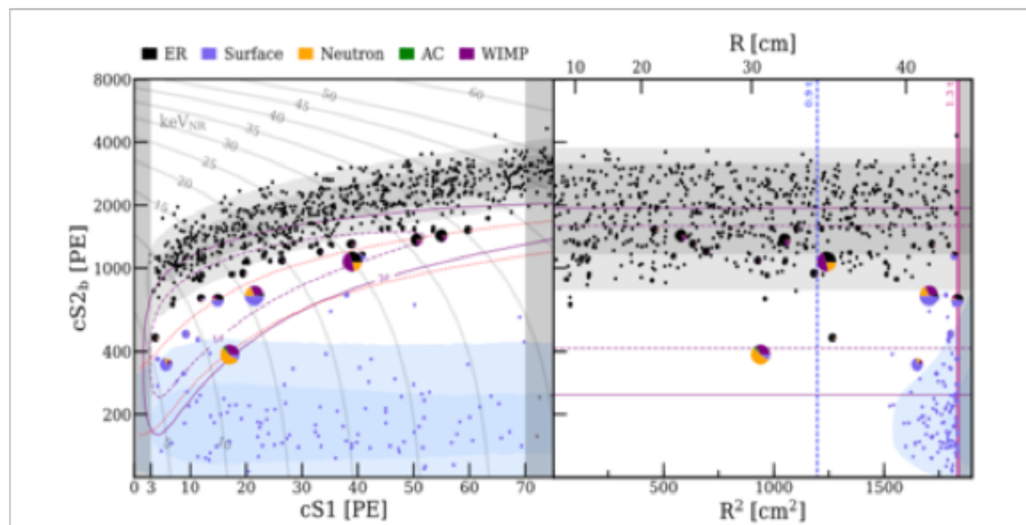


Xenon1T: ~1 year exposure

Mass	1.3 t	1.3 t	0.9 t	0.65 t
($cS1$, $cS2_b$)	Full	Reference	Reference	Reference
ER	627±18	1.62±0.30	1.12±0.21	0.60±0.13
neutron	1.43±0.66	0.77±0.35	0.41±0.19	0.14±0.07
CEνNS	0.05±0.01	0.03±0.01	0.02	0.01
AC	$0.47^{+0.27}_{-0.00}$	$0.10^{+0.06}_{-0.00}$	$0.06^{+0.03}_{-0.00}$	$0.04^{+0.02}_{-0.00}$
Surface	106±8	4.84±0.40	0.02	0.01
Total BG	735±20	7.36±0.61	1.62±0.28	0.80±0.14
$\mathrm{WIMP}_{\text{best-fit}}$	3.56	1.70	1.16	0.83
Data	739	14	2	2

Xenon1T: search region





Detector

- a **50 kg** dual-phase Liquid Argon TPC
- Using **Underground Argon**: depleted in ^{39}Ar
- In a **30 ton** borated liquid scintillator **neutron veto**
- In a **1000 ton Water** Cherenkov Veto
- Underground at Gran Sasso National Lab, Italy

Performance

S1 and S2 Yields:

- S1 Yield ~7.9 pe/keV at null field
- S1 Yield **~7.0 pe/keV** at 200 V/cm
- S2 yield **~23 pe / e⁻**

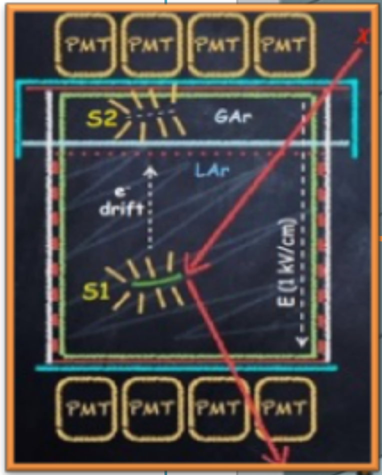
Electron lifetime > 10 ms

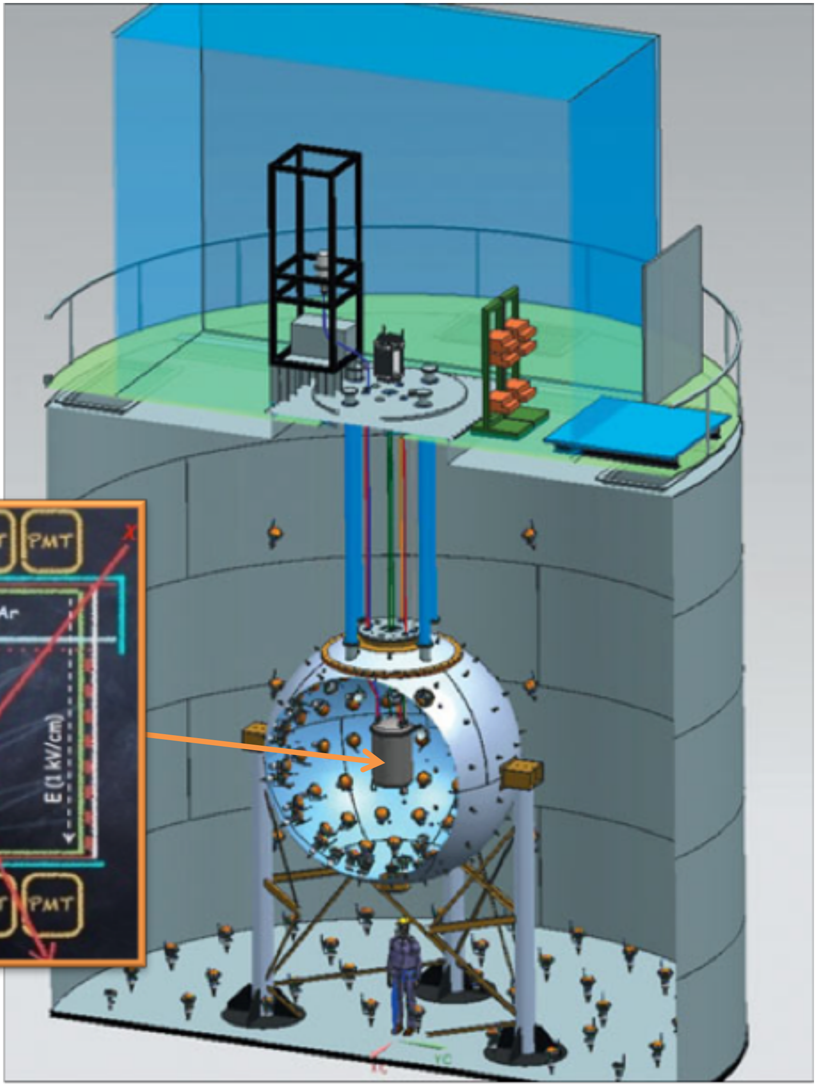
Maximum drift time: 376 μs

Position reconstruction:

- Resolution in Z **~1 mm**
- Resolution in XY **<1 cm**

Neutron Veto Rejection Efficiency: 99.6%





^{39}Ar issue: fixed!

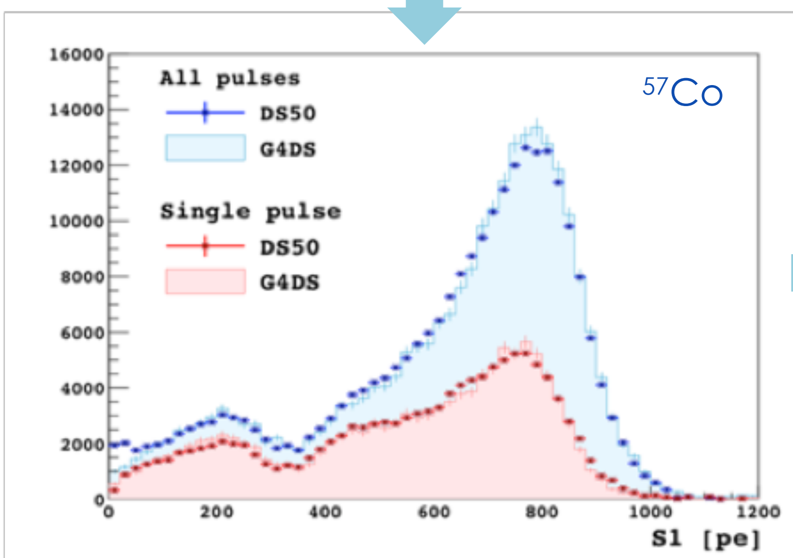
G4DS

the DarkSide Monte Carlo package

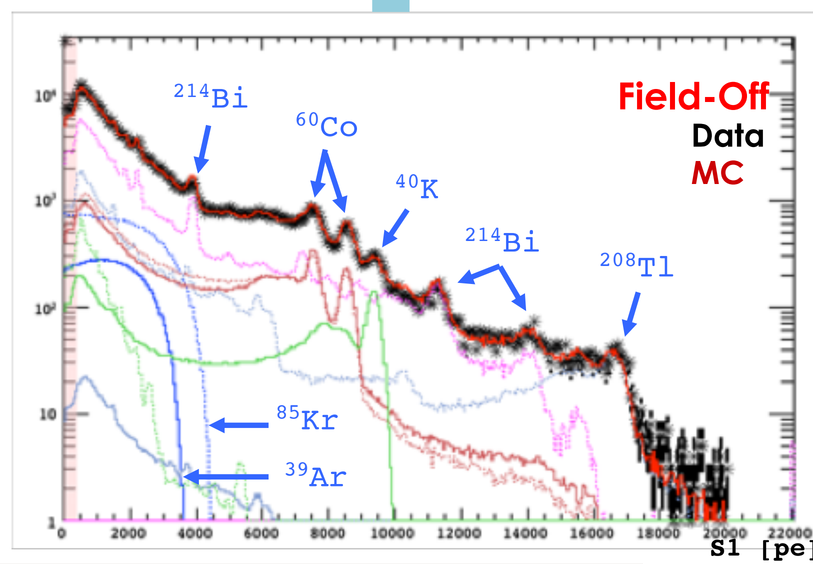
☑ PARIS: custom made LAr scintillation-ionization response model

☑ Percent level accuracy in energy scale and resolution

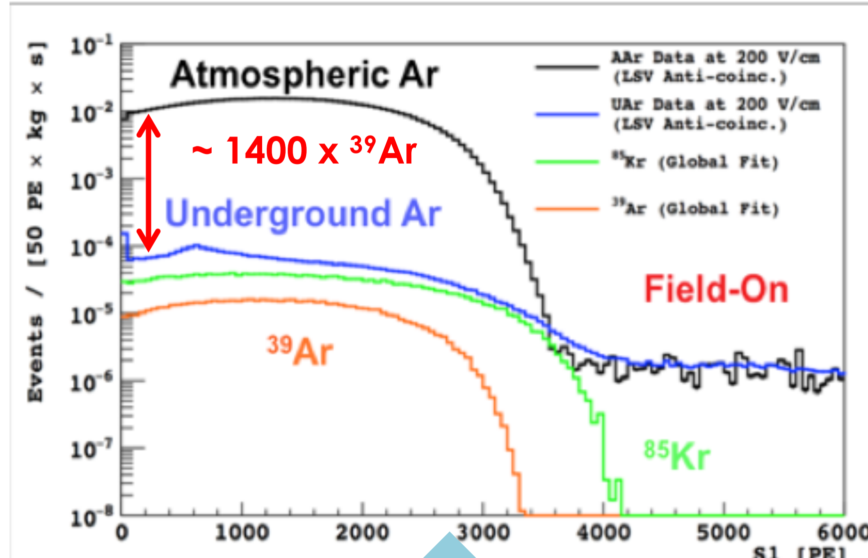
Calibration



Fit



Result



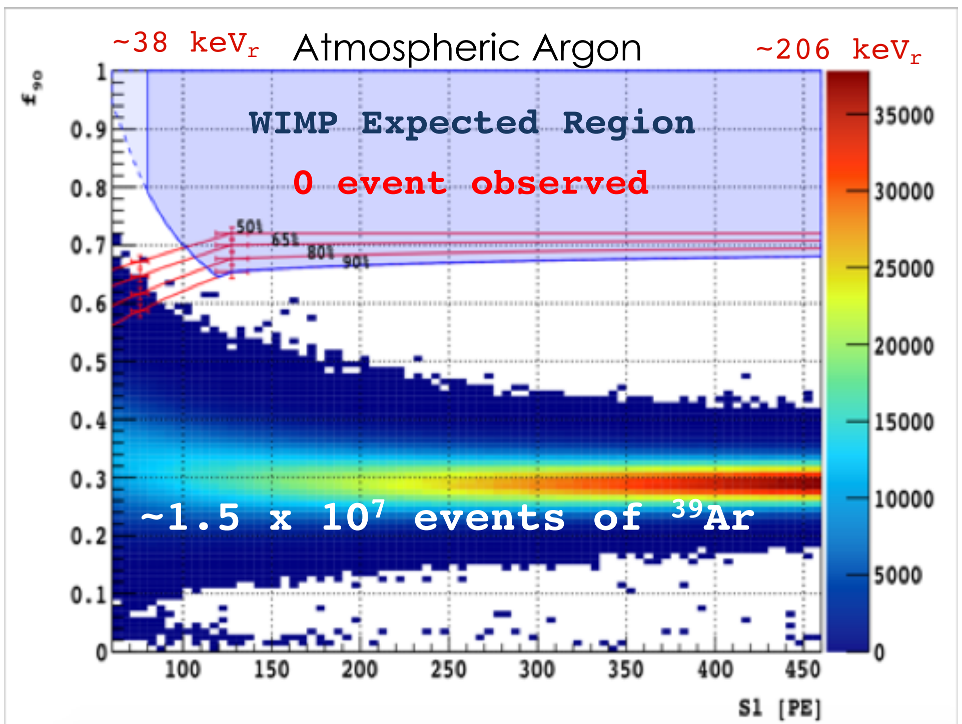
Advantages of Using Argon

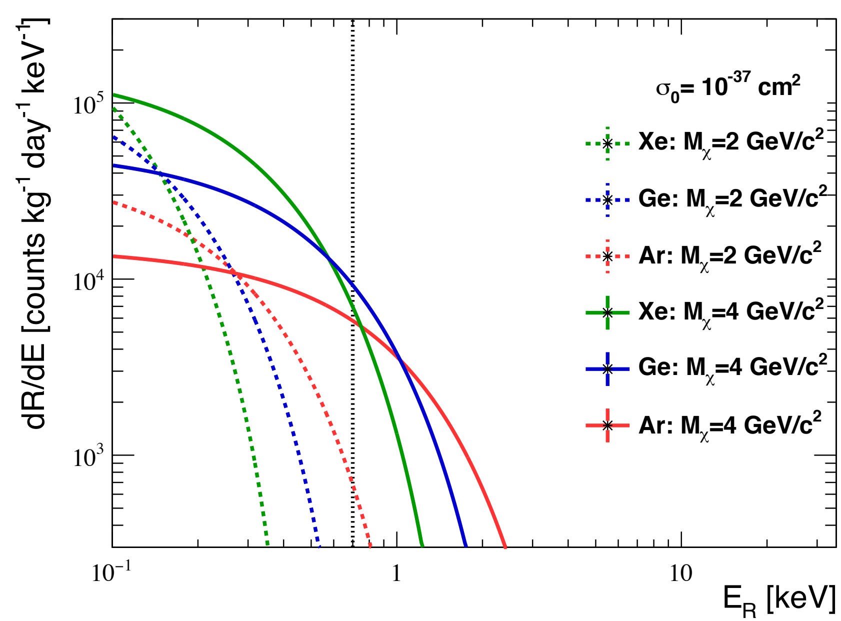
High Mass WIMPs: > 20 GeV/c²

- Range: **45-200 keV$_{nr}$**
- S1 and S2 signals
- Excellent Pulse Shape Discrimination
- **Background free (<0.1 events) analysis**

Low Mass WIMPs: < 20 GeV/c²

- Range: **0.7-15 keV$_{nr}$**
- Ionization signal only
- Profile Likelihood Analysis
- **Lighter nucleus, larger recoil energy**





Neutrons

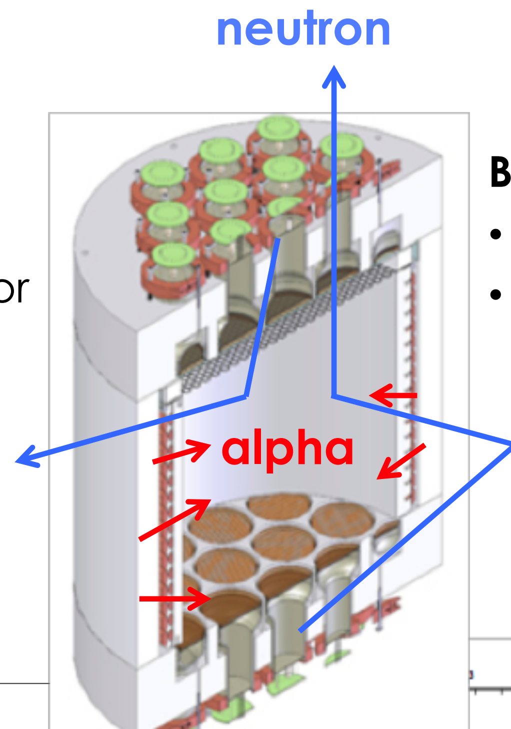
Background rejection:

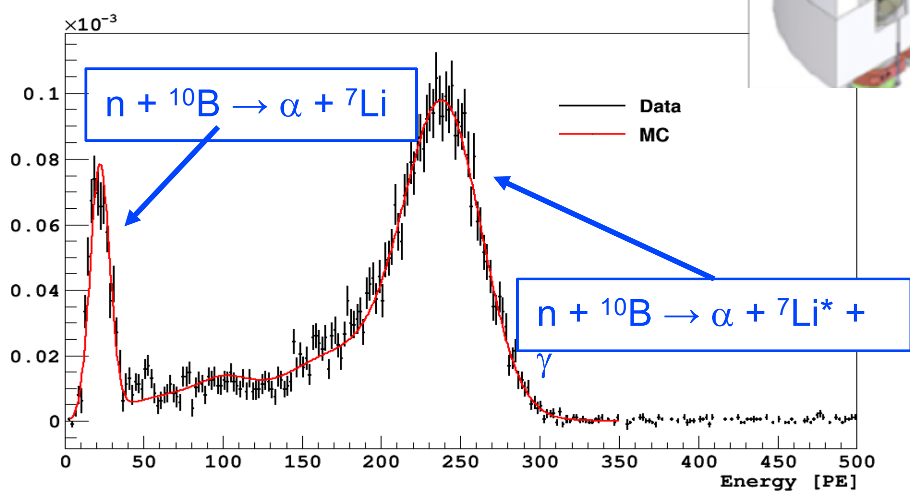
- TPC: multi-scatter
- LS Veto: efficiency from Am-C for TPC single-NR: **0.9964±0.0004**
- Water Cherenkov Veto
- Neutrons in data counted

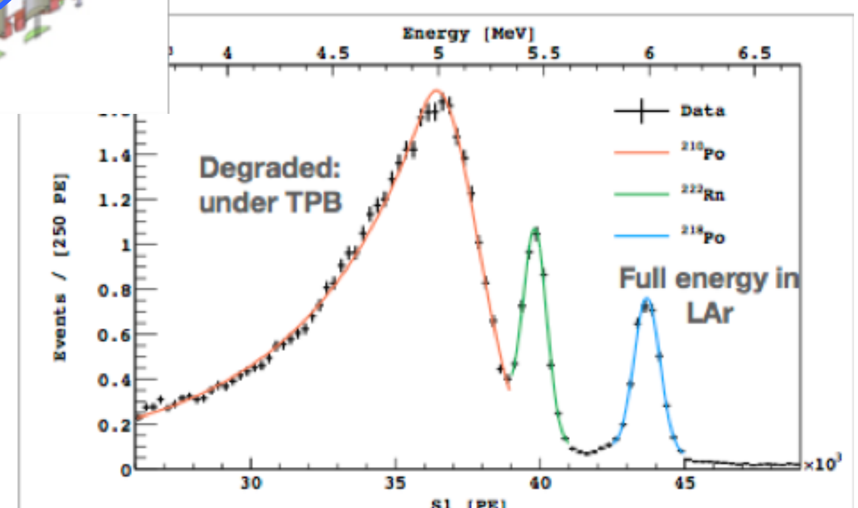
Alpha's

Background rejection:

- Small fraction at low energies
- Self-vetoing in DS-50!
    - Small or no S2
    - Long S2 tail from TPB fluorescence

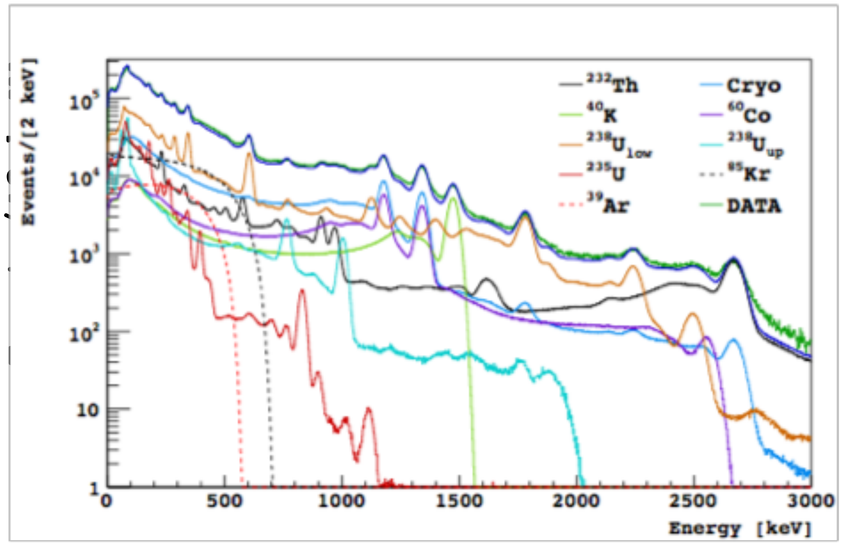






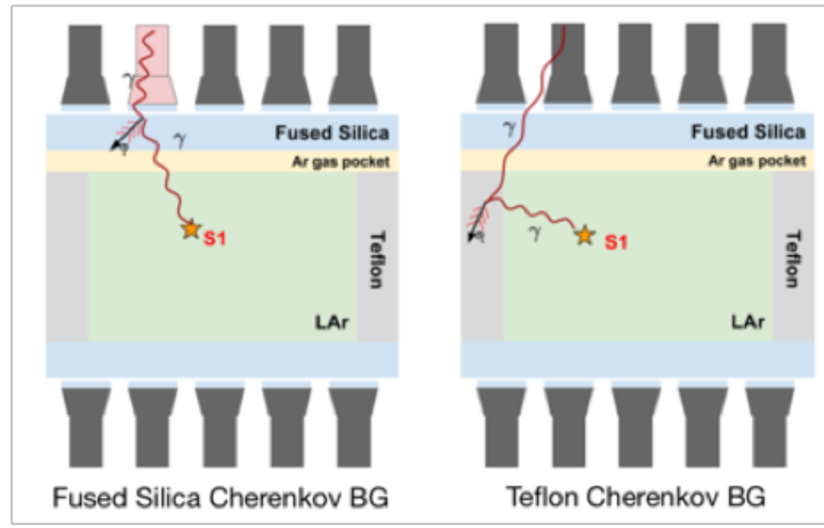
Electron Recoil Backgrounds

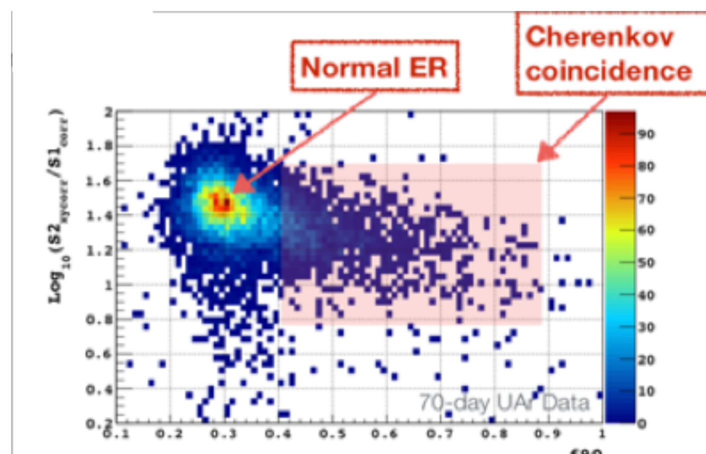
Internal ^{39}Ar and ^{85}Kr
External gammas



Energy [keV]

Cherenkov



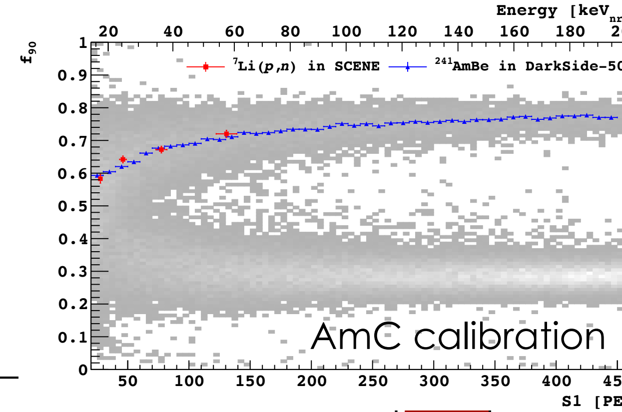


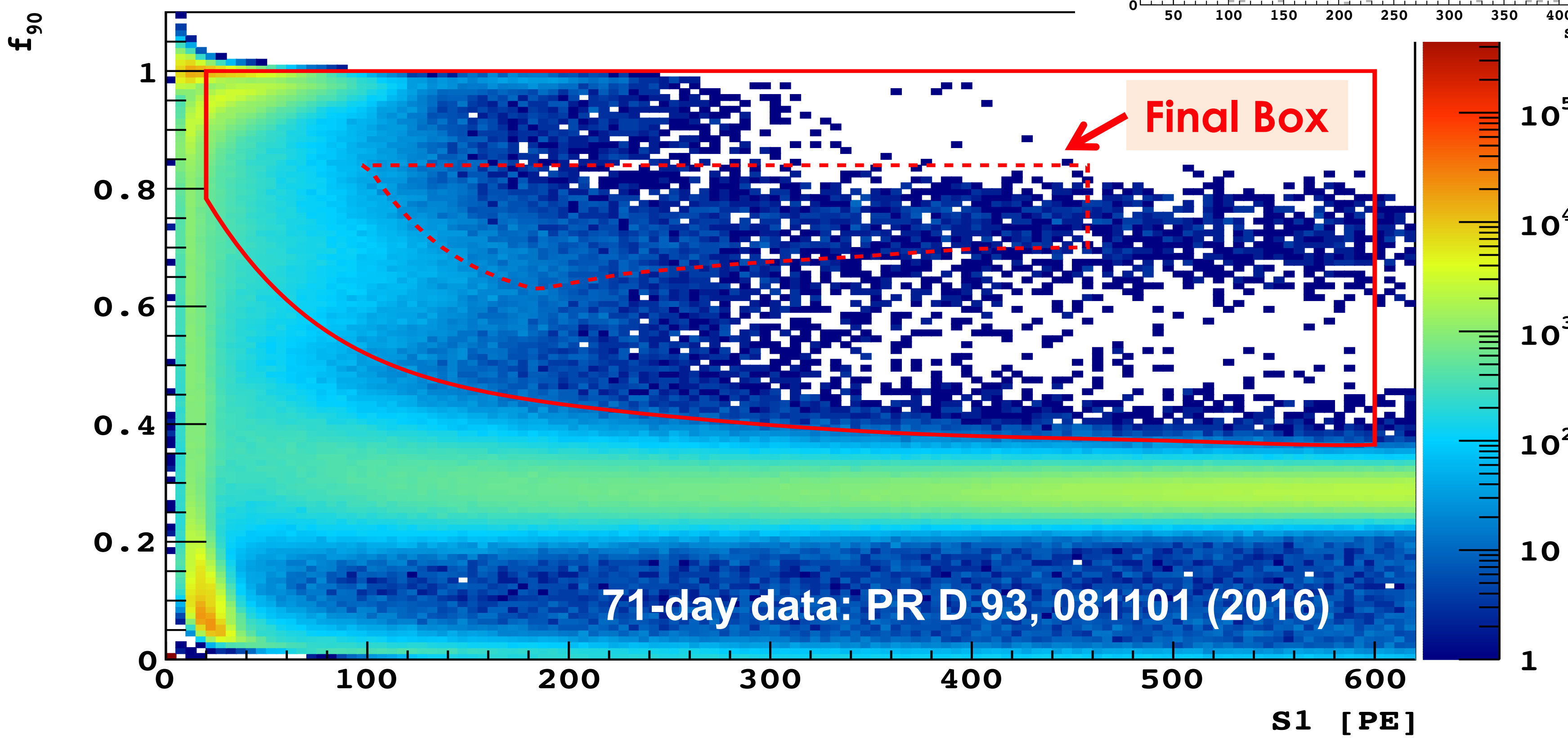
Background rejection:

- **Underground Ar**
- **S1 fraction in max PMT**
- PSD: f_{90} = S1 fraction in first 90 ns
  * Design cut to reduce ER to <0.08 event of background

High Mass: Blind Analysis

Goal: design an analysis that will have <0.1 event of background in 534 live-days





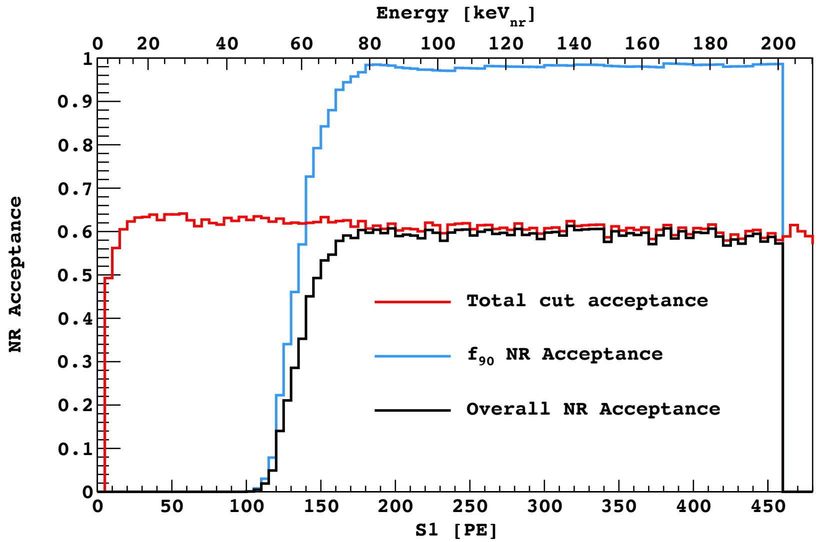
High Mass: Background and Acceptance

Expected background

Background	Events surviving all cuts
Surface Type 1	0.0006 ± 0.0001
Surface Type 2	0.00092 ± 0.00004
Radiogenic neutrons	< 0.005
Cosmogenic neutrons	< 0.00035
Electron recoil	0.08 ± 0.04
Total	0.09 ± 0.04

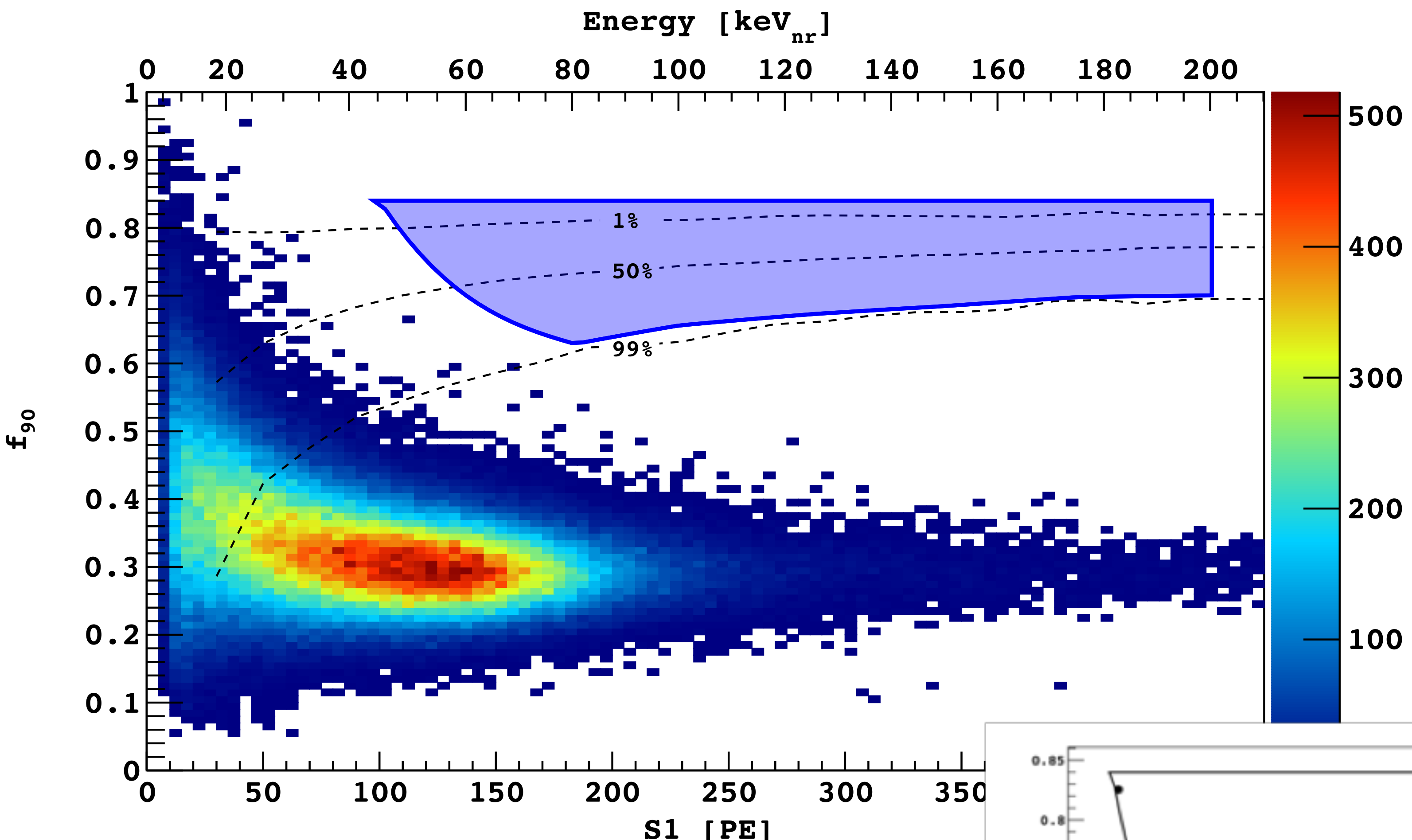
Goal < 0.1 events achieved: open the box!

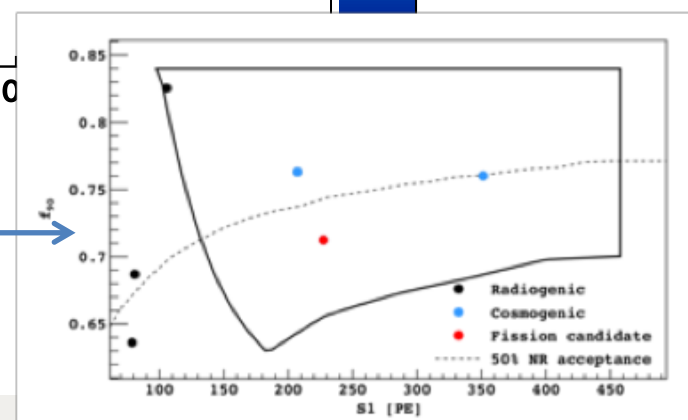
WIMP Acceptance



~0.6: dominated by PSD ER rejection

High Mass: 0 events

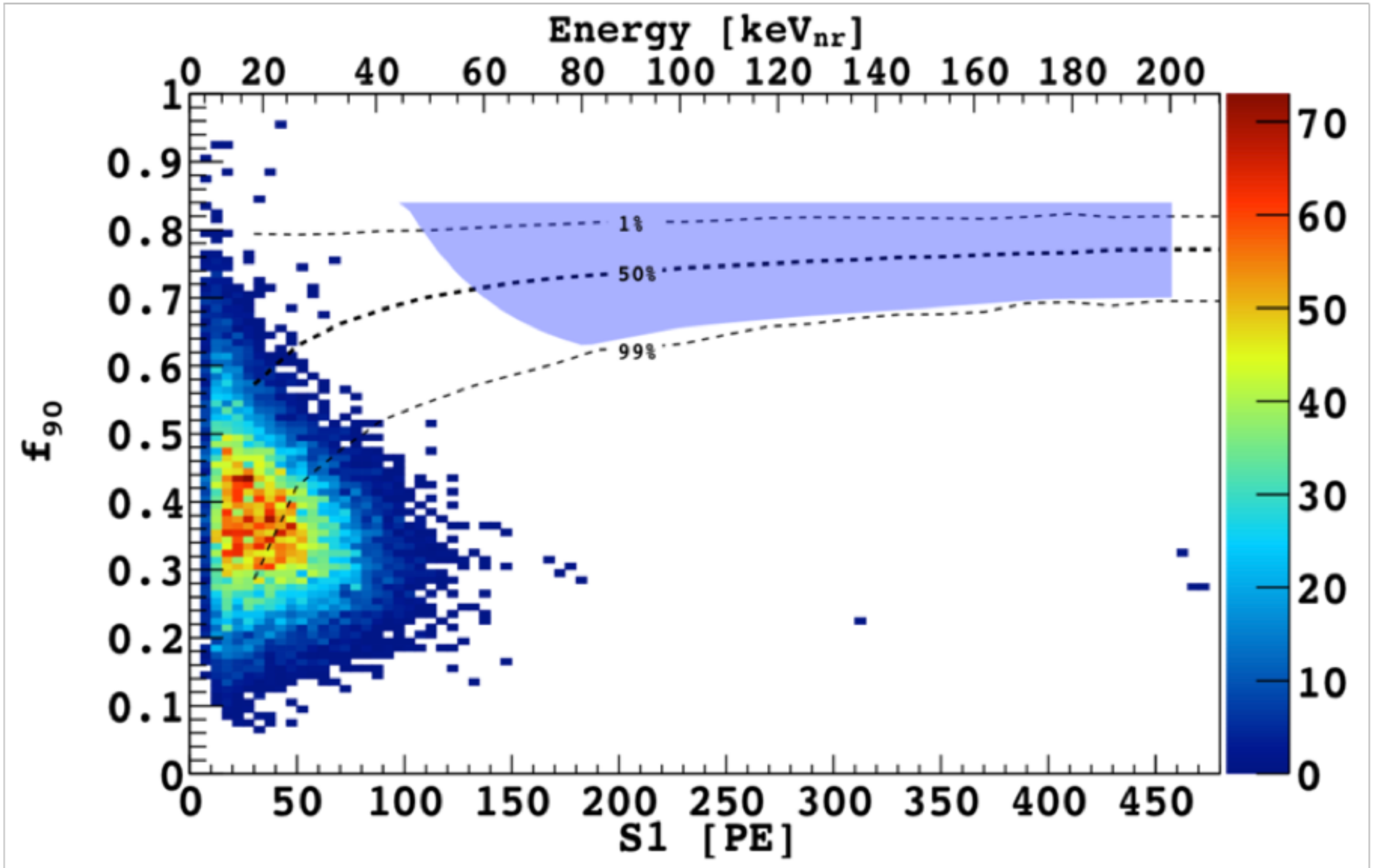




4 events identified as neutrons before the veto cuts
Consistent with expectations

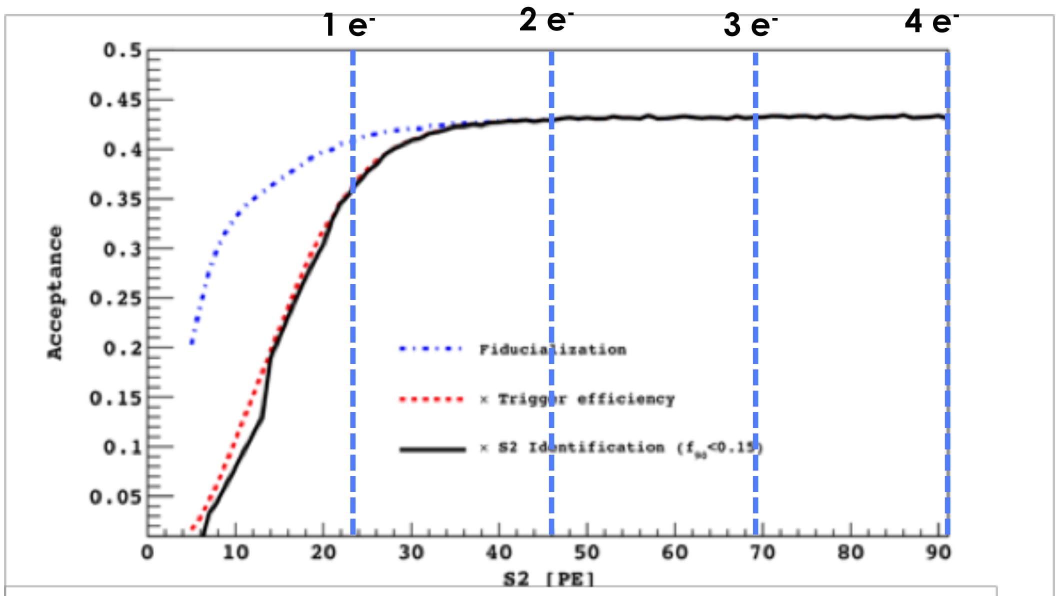
High Mass: 0 events

Adding the S2/S1 cut

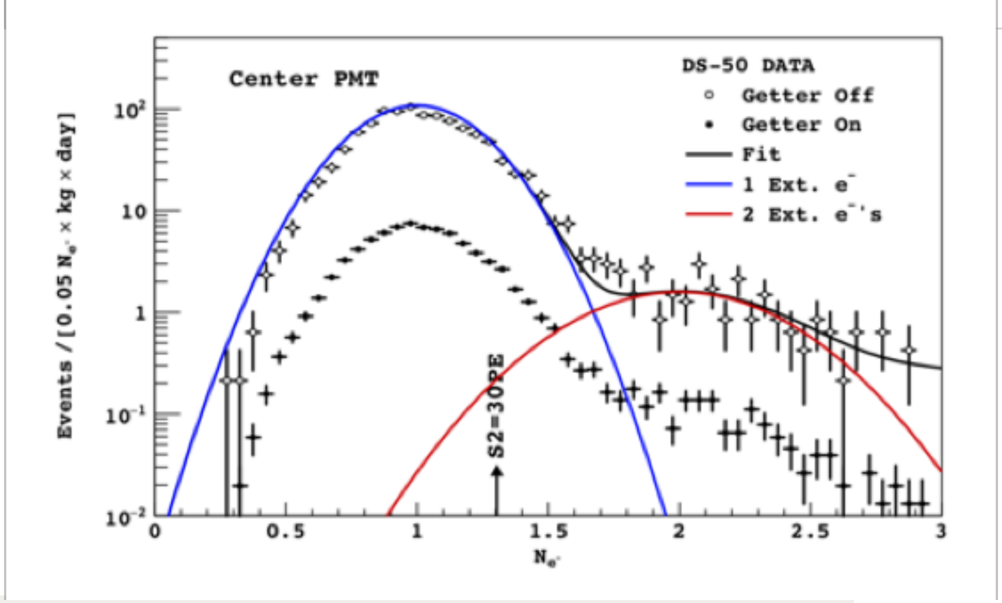


Low Mass: Ionization Signal Only

Threshold at 4 e⁻: 100% efficiency

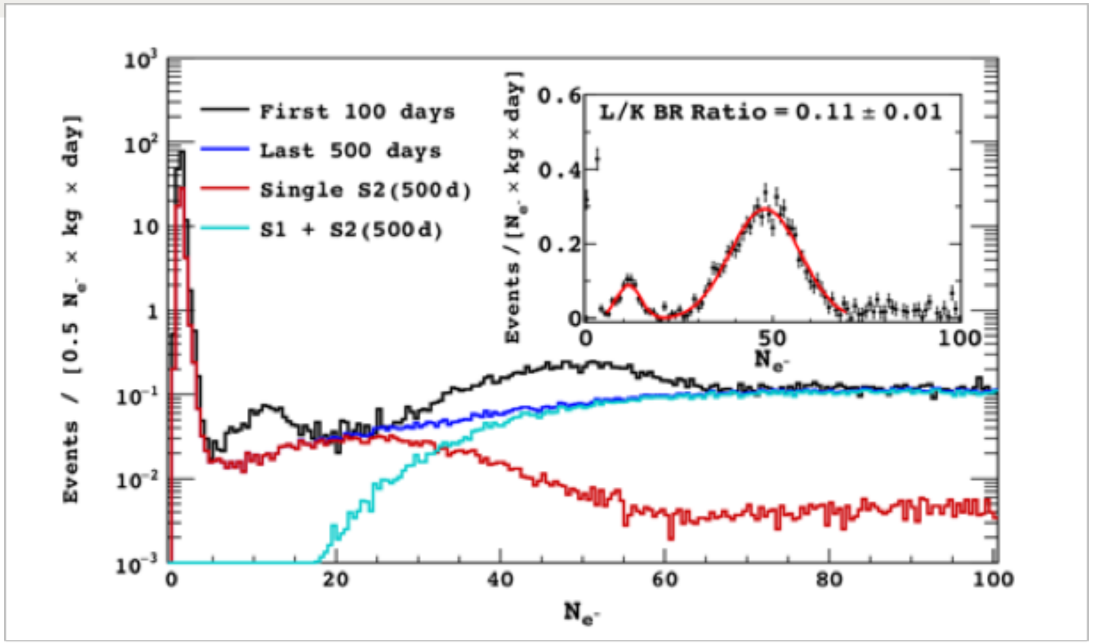


Single and double electrons events



Low Mass: Electron Recoil Scale

Excellent low-energy ER calibration peak from ^{37}Ar ($t_{1/2}$ = 37d).



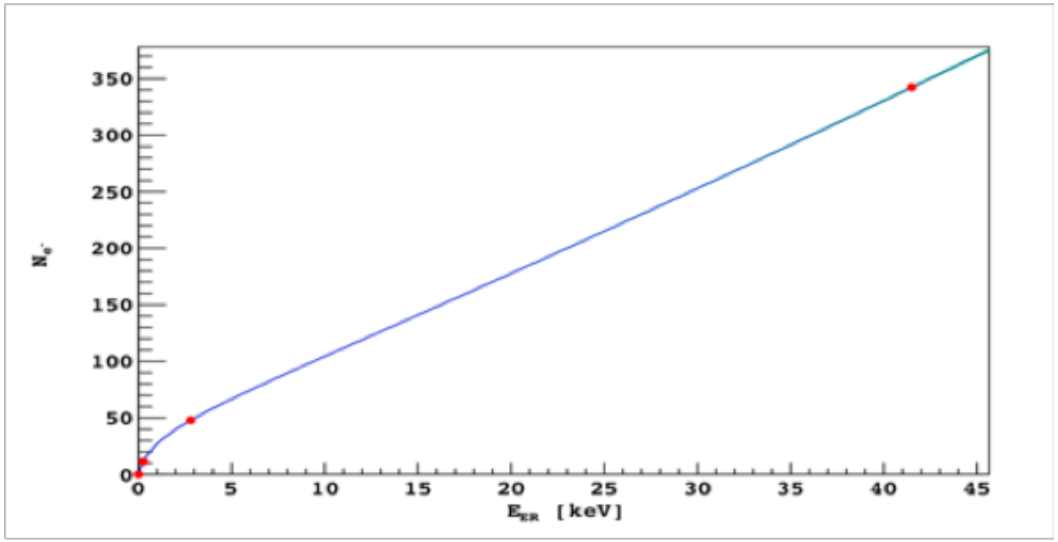
^{37}Ar lines

E = 0.27 keV → Ne = 11

E = 2.8 keV → Ne = 47.9

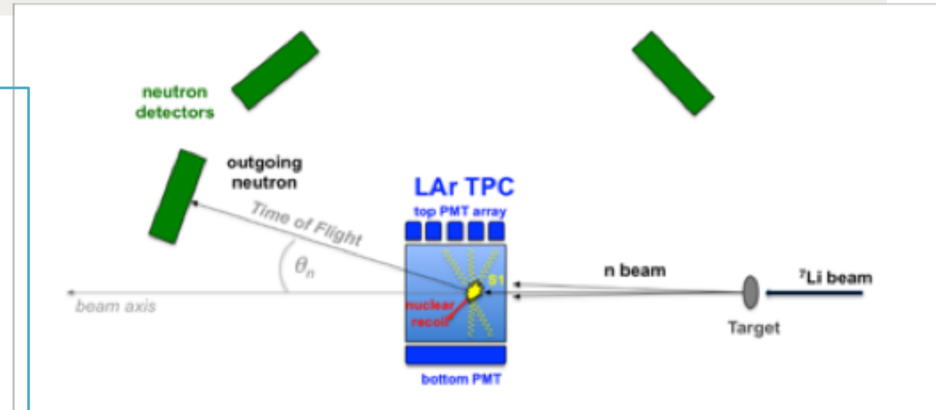
^{83m}Kr line

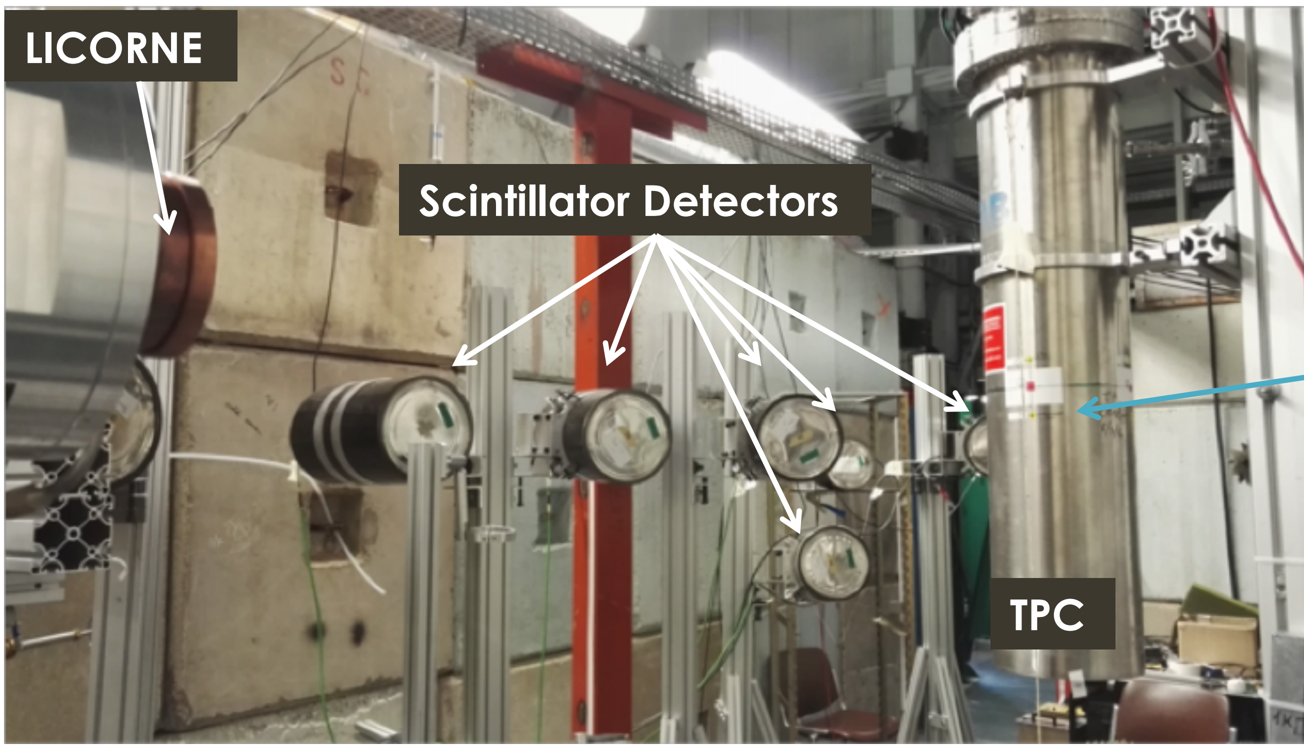
E = 41.5 keV → Ne ~ 350

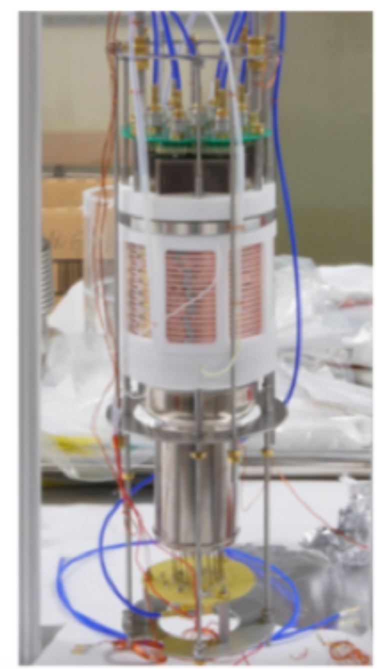


ARIS @ IPNO

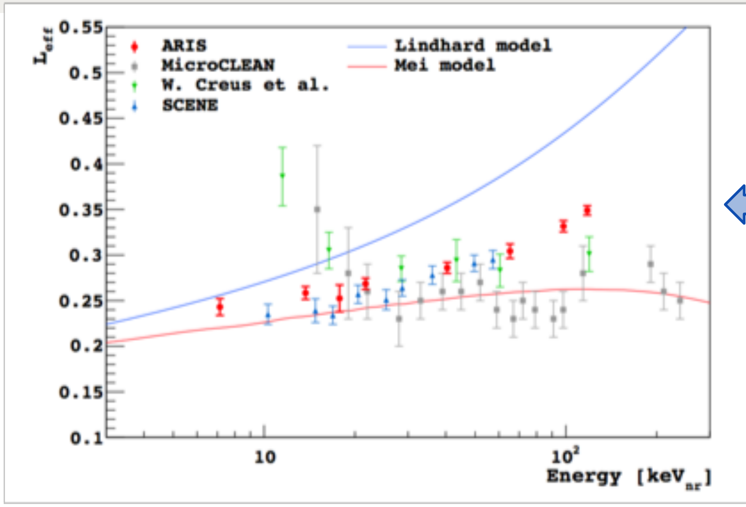
LICORNE source: **inverted $^7Li(p,n)^7Be$** reaction
- ☑ Pulsed (1.5 ns width)
- ☑ Monochromatic: <6% (μ~1450 keV σ~85 keV)
- ☑ Collimated: < 2 degrees
- ☑ Correlated 478 keV gammas: ER calibration





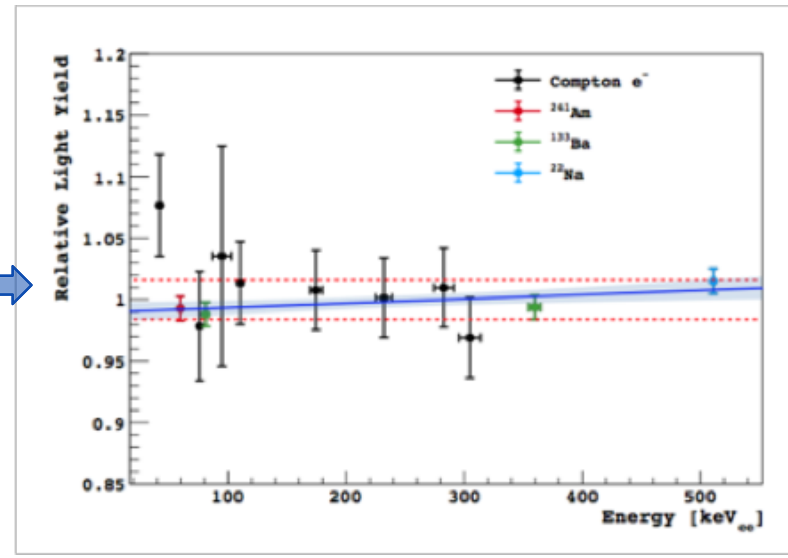


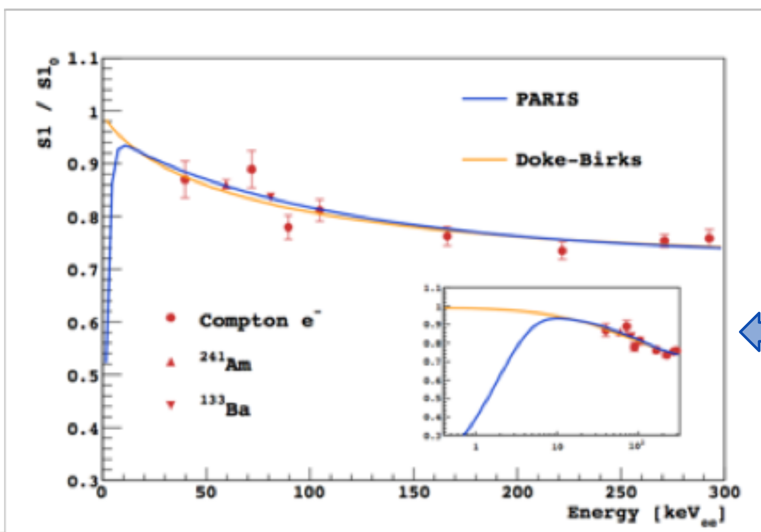
ARIS Results



Most accurate measurement of the **quenching** effect: **crucial for the low-mass analysis**

Best constraint on **linearity** of LAr response to ER at field-off

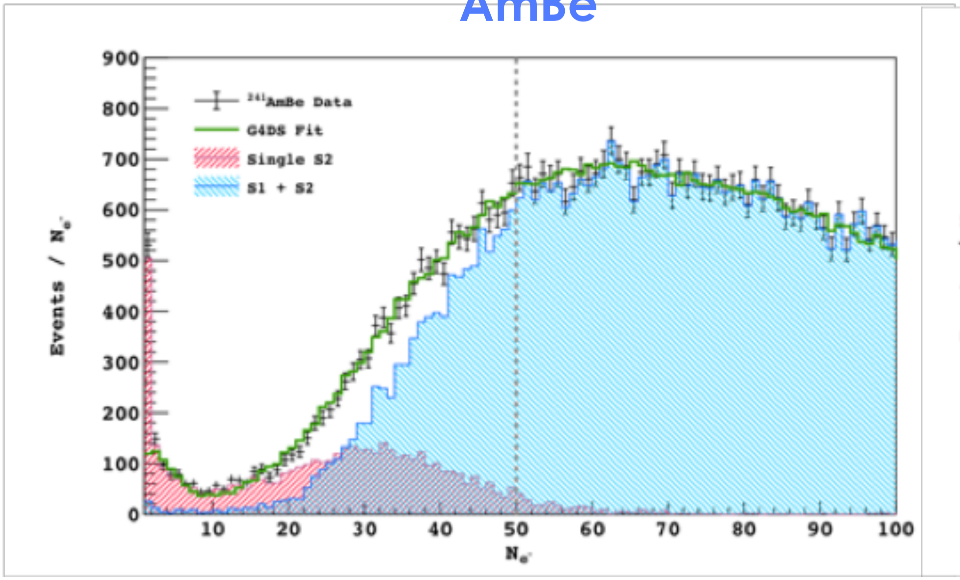




Excellent agreement with the **PARIS** model

Low Mass: Nuclear Recoil Scale

AmBe

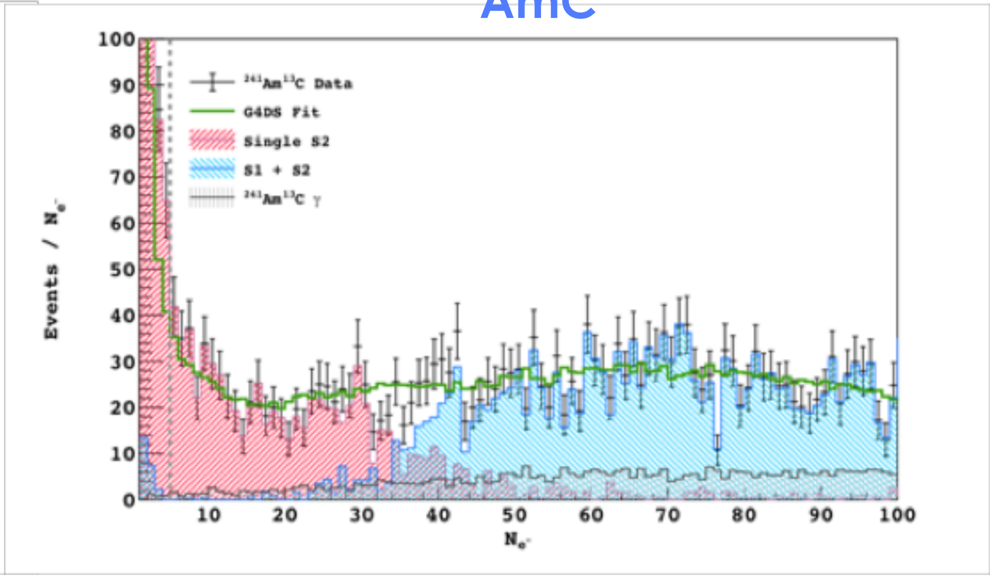


AmBe neutrons selected in coincidence with 4.4 MeV gamma in the veto

Random/correlated background strongly suppressed

Strong inefficiency for S2 only events

AmC



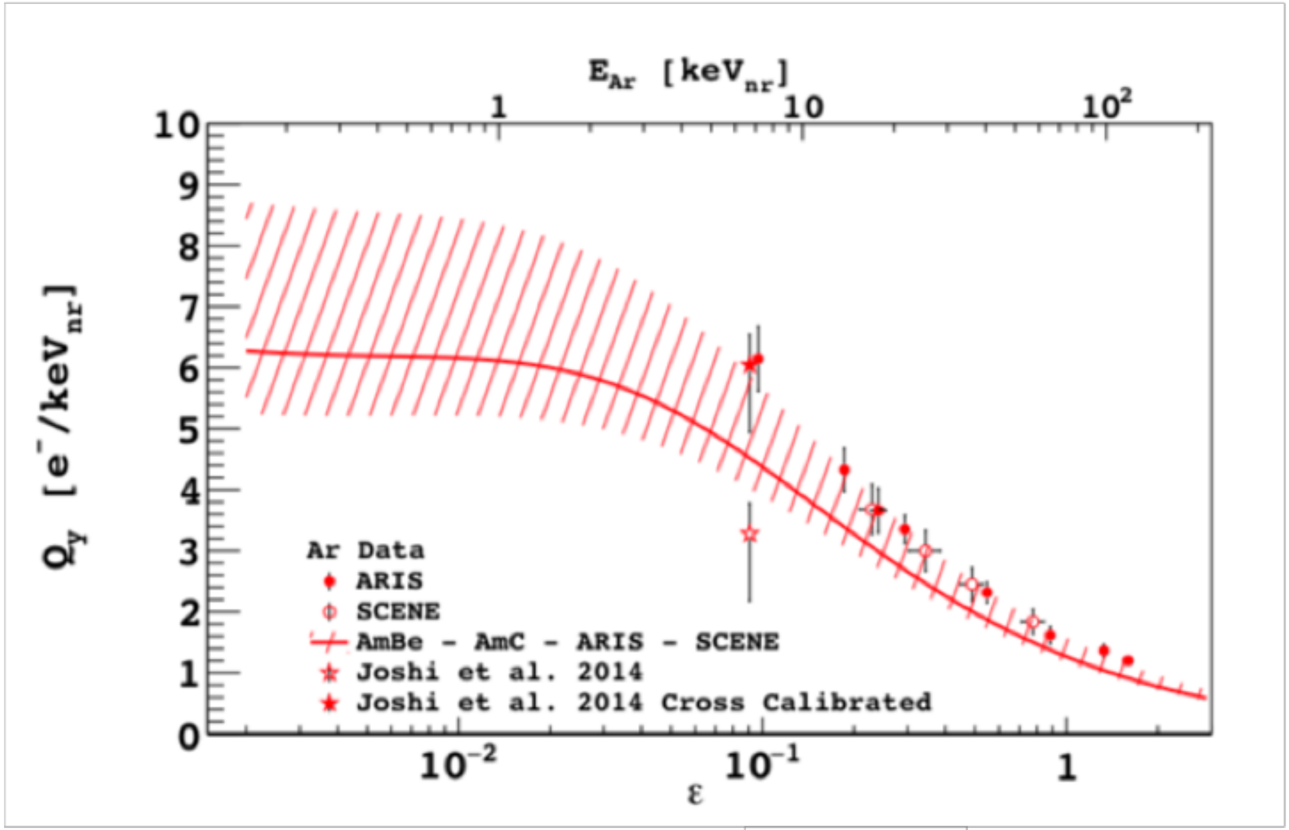
No gamma emission correlated with AmC (alpha,n) reaction

Gammas from ^{241}Am decay accounted with MC

Accidentals subtracted using UAr normalized by the exposure

No inefficiency

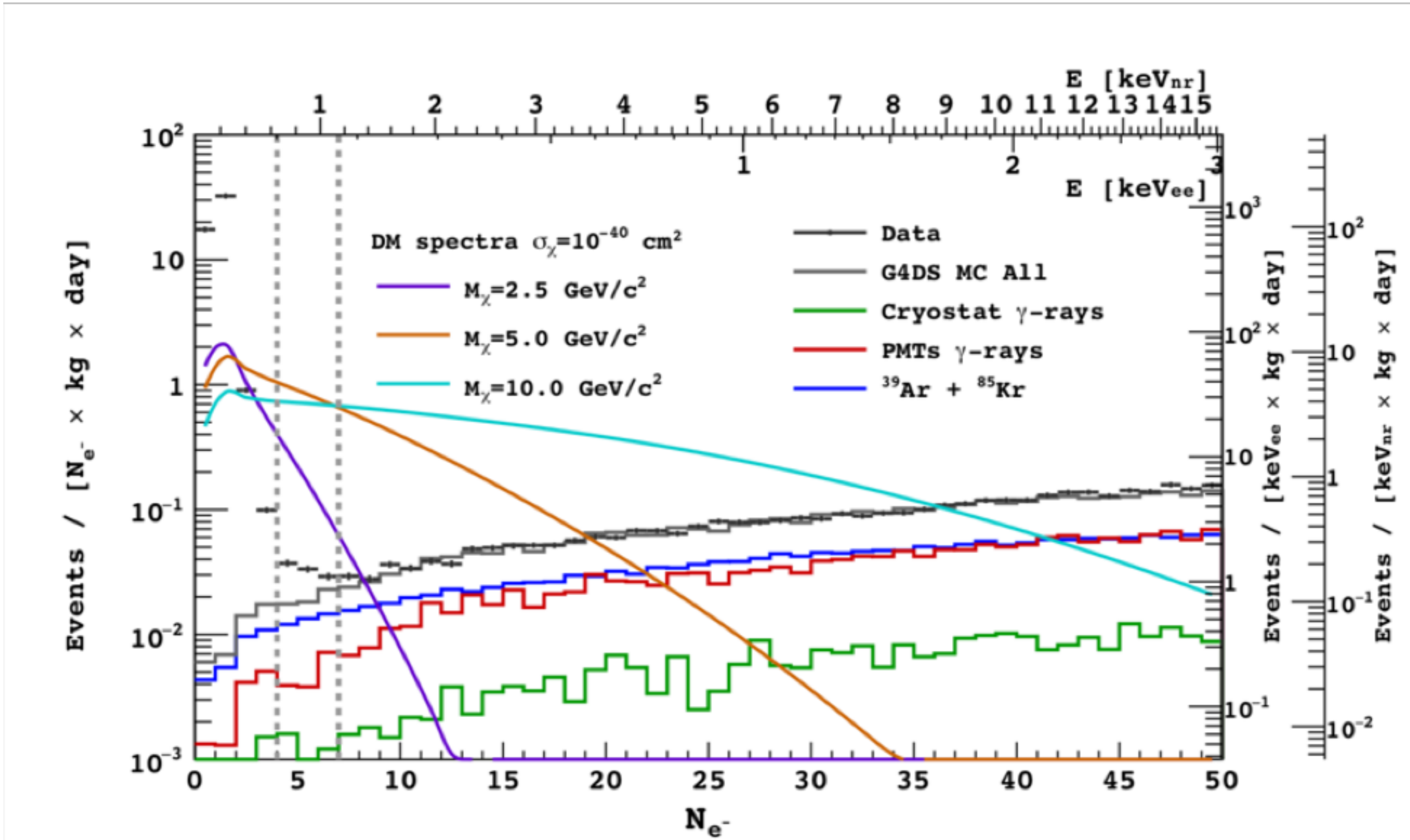
Low Mass: Nuclear Recoil Scale



Reduced Energy $\epsilon = \frac{a}{2e^2Z^2}E$

$a = 0.626 a_0 Z^{-1/3}$ Is the Thomas–Fermi screening length

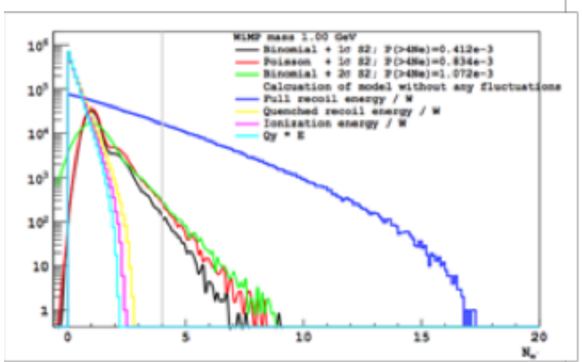
Low Mass: Background

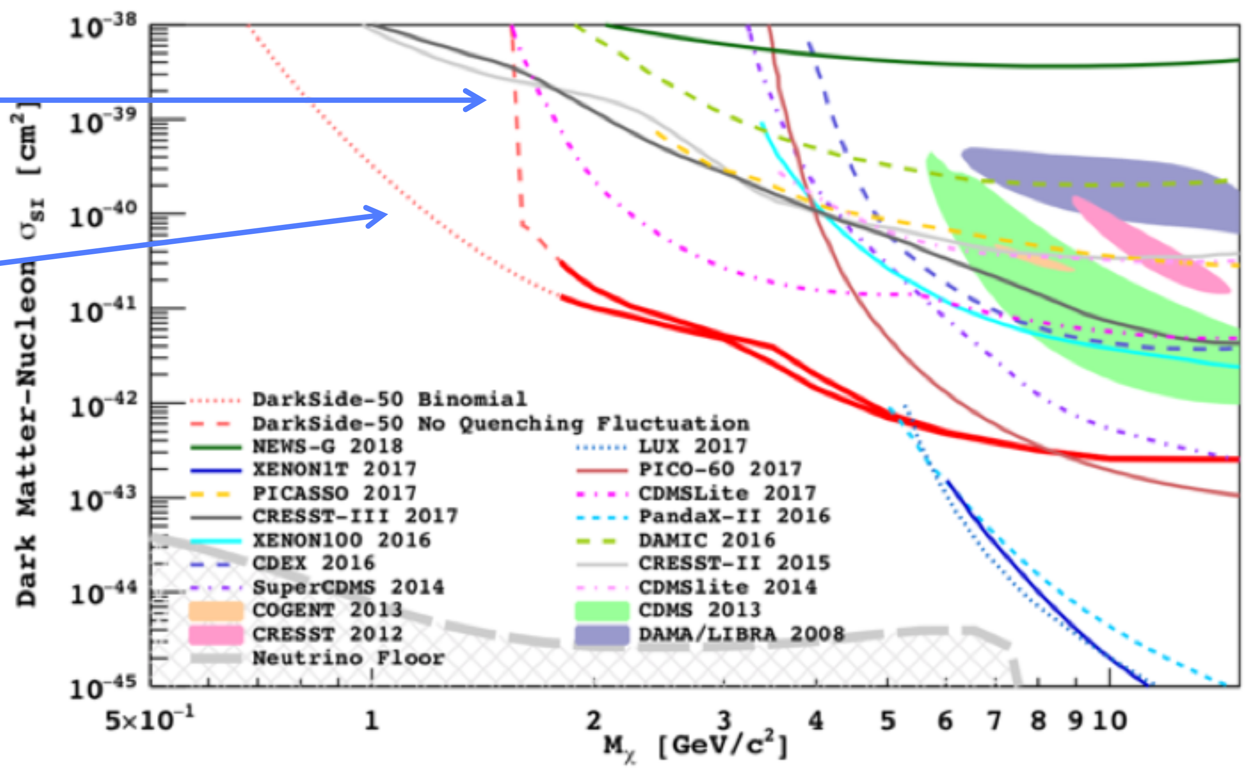


Low-Mass

Assuming quenching a non-stochastic process

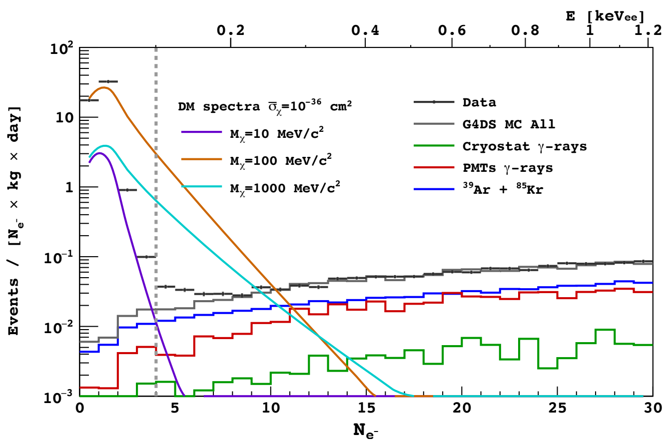
Assuming binomial quenching fluctuations

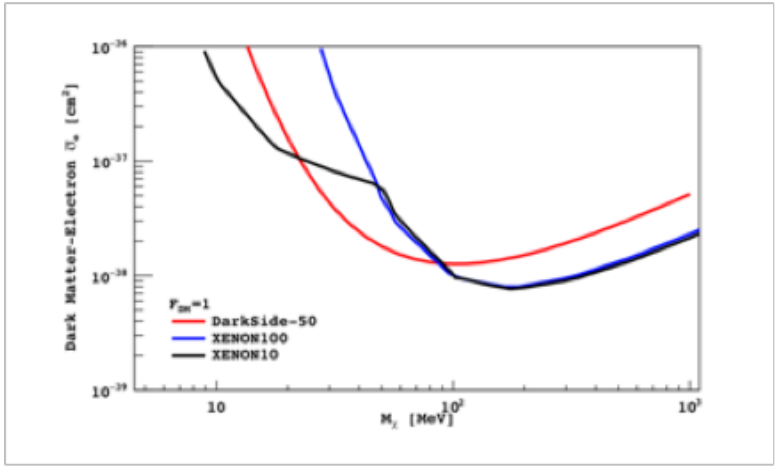




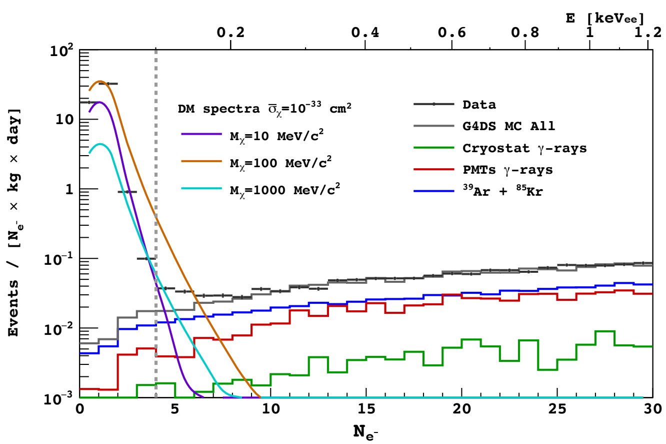
WIMP-Electron Scattering

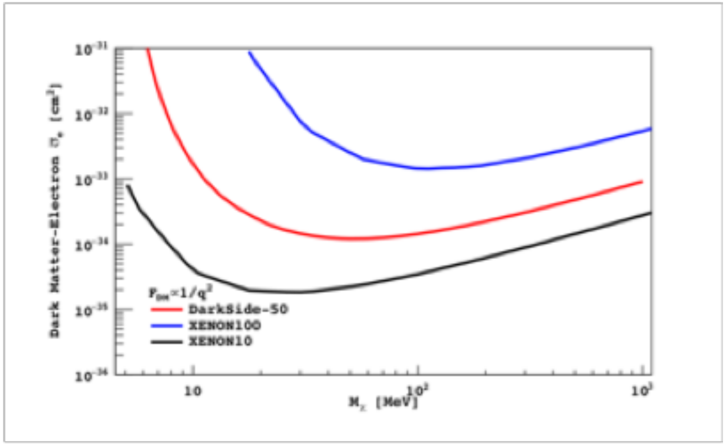
$F_{DM} \sim 1 \rightarrow$ heavy mediator





$F_{DM} \propto 1/q2 \rightarrow$ light mediator



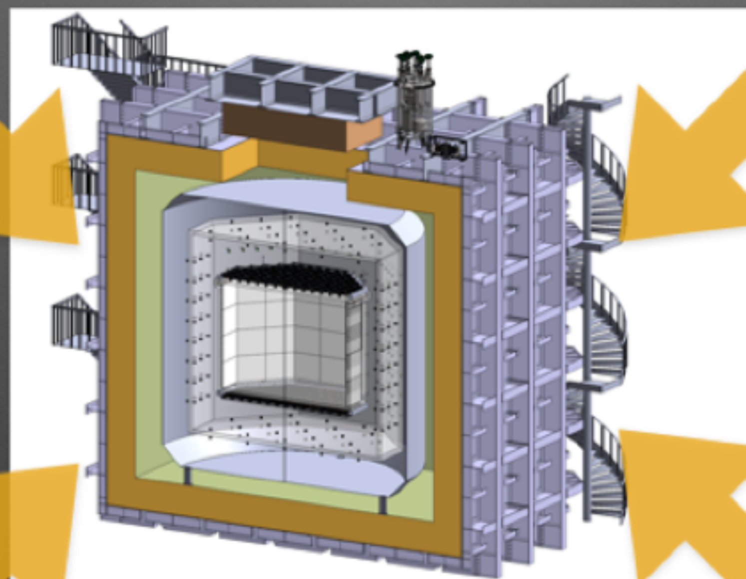


The Global Argon Dark Matter Collaboration

DarkSide-50

ArDM

DarkSide-20k



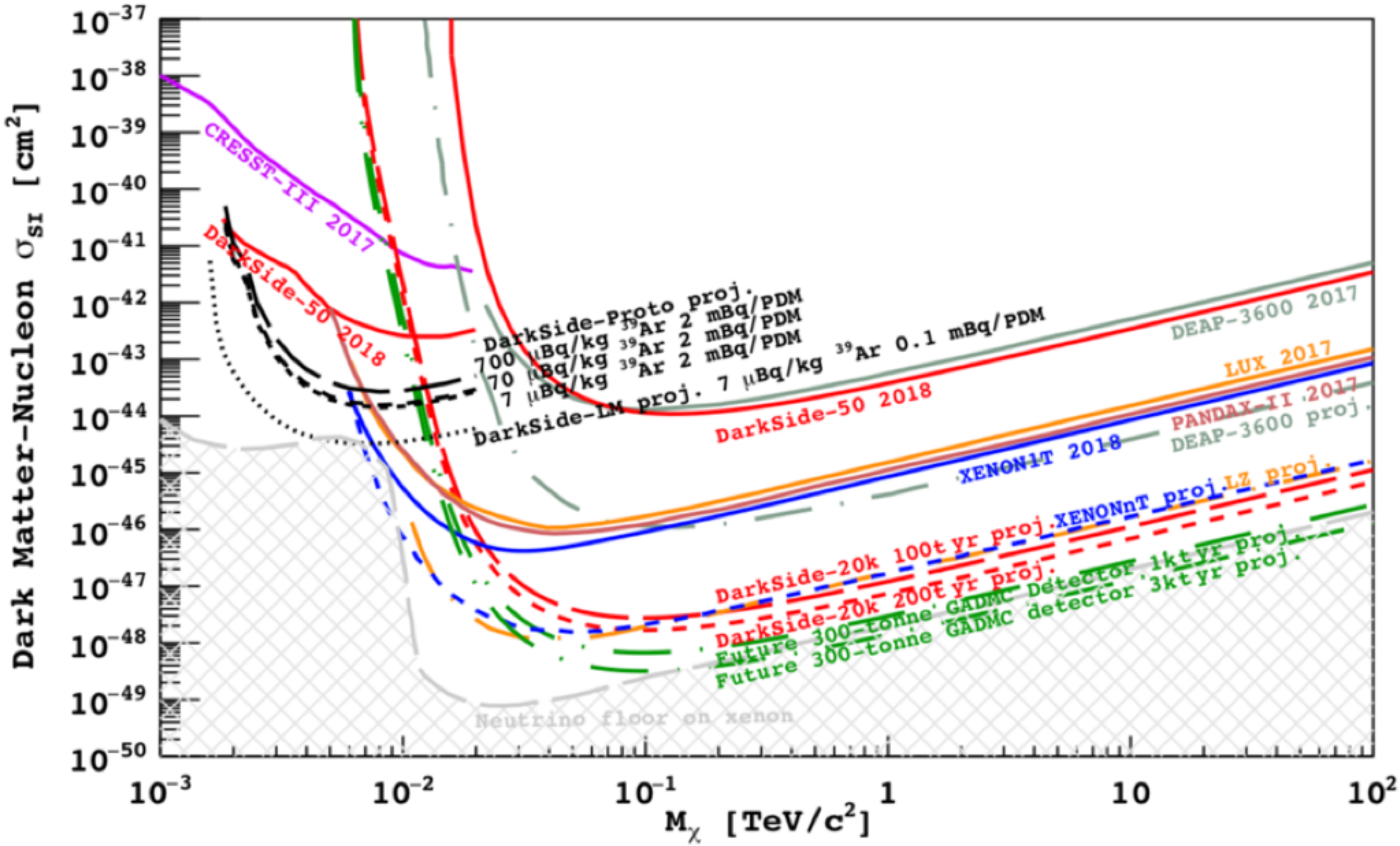
CERN Neutrino Platform joined DarkSide-20k → many synergies with DUNE (DS-20k cryostat will be the same of protoDUNE)

DEAP-3600

Access to DEAP-3600 data

MiniCLEAN

DS-20k collaboration
350 scientists
13 countries



Dark Matter-Nucleon σ_SI [cm²]
M_χ [TeV/c²]
10⁻³⁷
10⁻³⁸
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
10⁻⁴⁹
10⁻⁵⁰
10⁻³
10⁻²
10⁻¹
1
10
10²
CRESST-III 2017
DarkSide-50 2018
DarkSide-Proto proj.
700 μBq/kg ³⁹Ar 2 mBq/PDM
70 μBq/kg ³⁹Ar 2 mBq/PDM
7 μBq/kg ³⁹Ar 2 mBq/PDM
DarkSide-LM proj. 7 μBq/kg ³⁹Ar 0.1 mBq/PDM
DarkSide-50 2018
DEAP-3600 2017
LUX 2017
PANDAX-II 2017
DEAP-3600 proj.
XENON1T 2018
XENONnT proj.
LZ proj.
DarkSide-20k 100t yr proj.
DarkSide-20k 200t yr proj.
Future 300-tonne GADMC Detector 1kt yr proj.
Future 300-tonne GADMC detector 3kt yr proj.
Neutrino floor on xenon

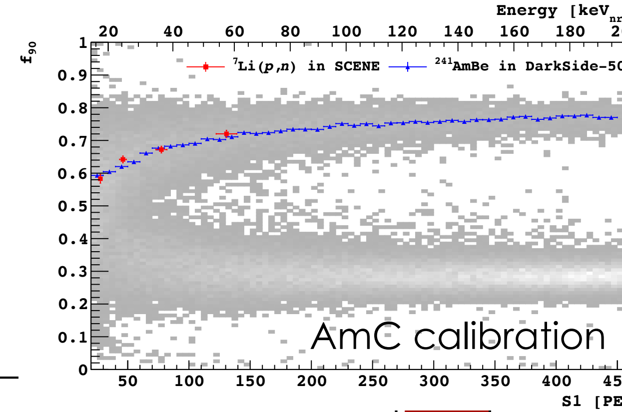
DarkSide

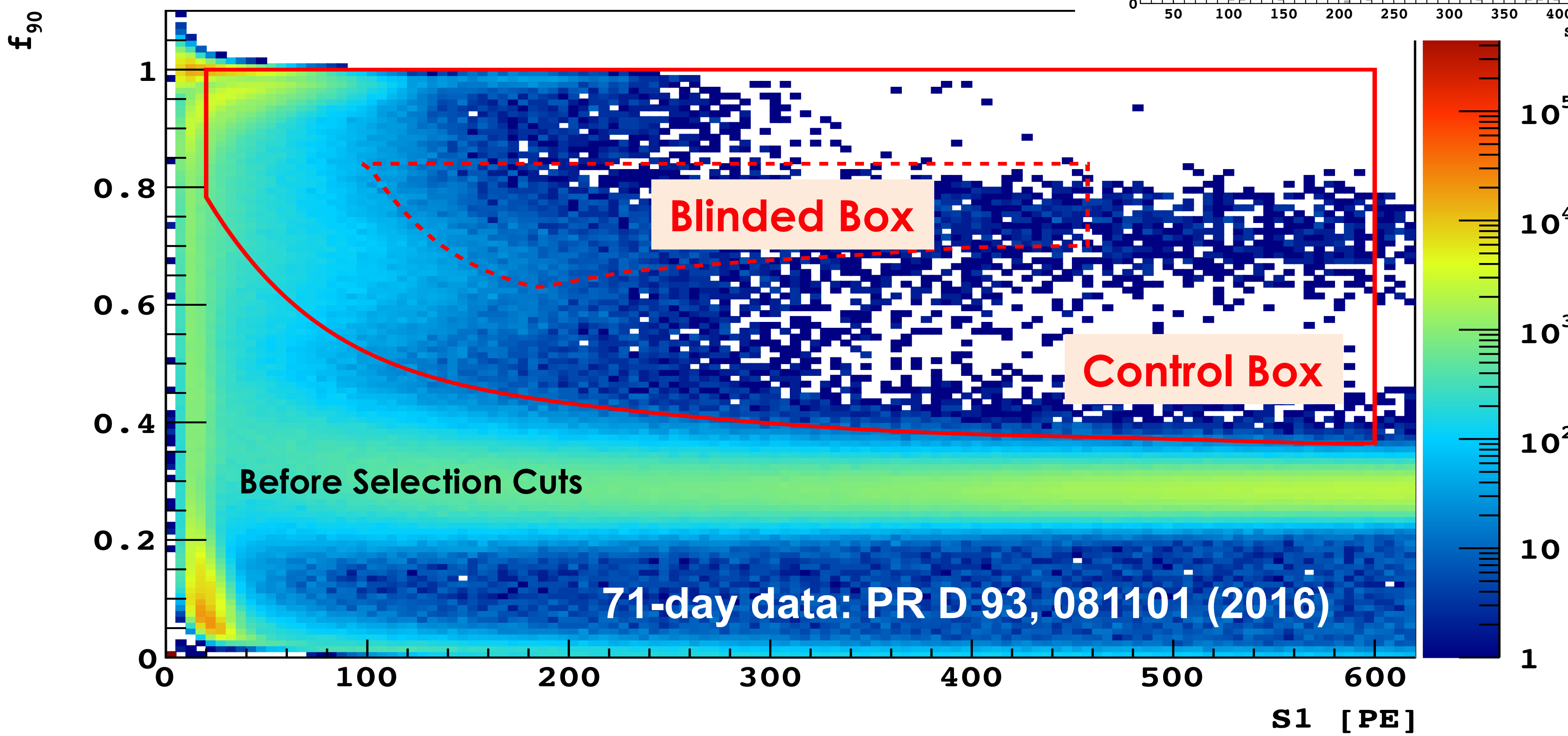
- ☑ **Background-free** experiment for high mass WIMP thanks to pulse shape discrimination in S1 (unique to LAr)
- ☑ **Best limit** in the low mass 1.8-6 GeV window
- ☑ Strong WIMP **discovery potential** in the next decade (from 1 GeV to 10 TeV)
- ☑ New opportunities also in looking for **WIMP directional signature** and **medical applications** (backup slides)
- ☑ Potential **synergies with DUNE**: astroparticle physics, cryostat and cryogenics, optical simulations, photo-collection efficiency, calibrations

Back Up

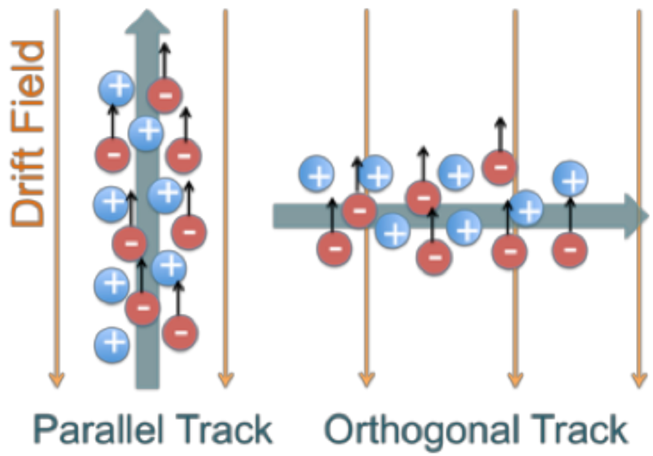
High Mass: Blind Analysis

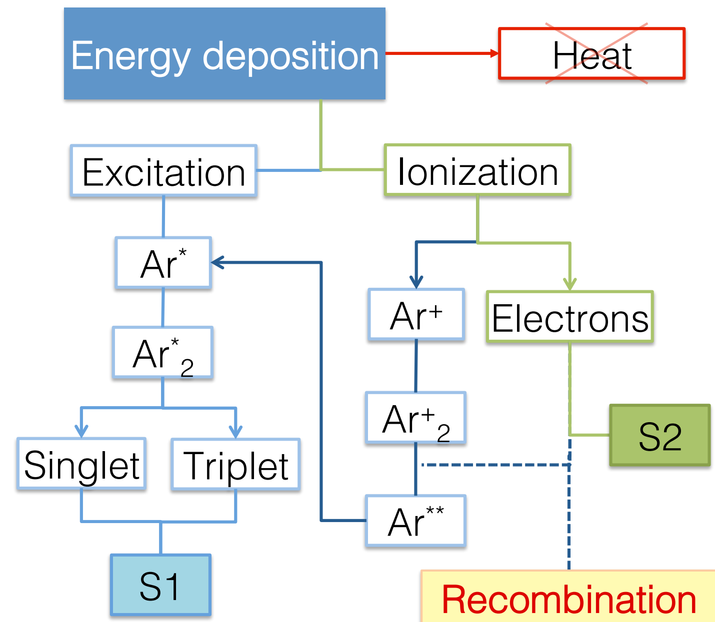
Goal: design an analysis that will have <0.1 event of background in 534 live-days





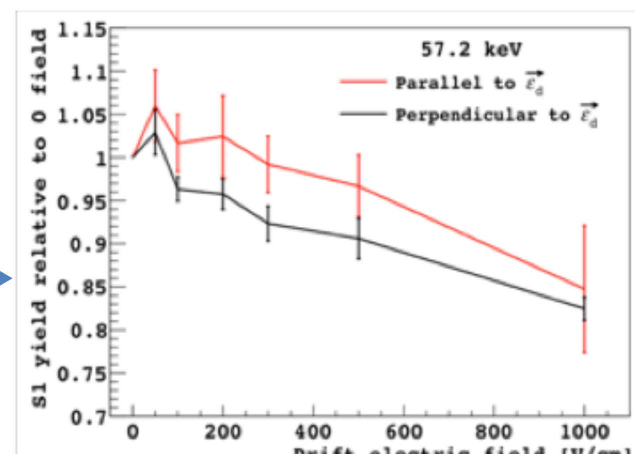
Below the neutrino floor? Directionality!



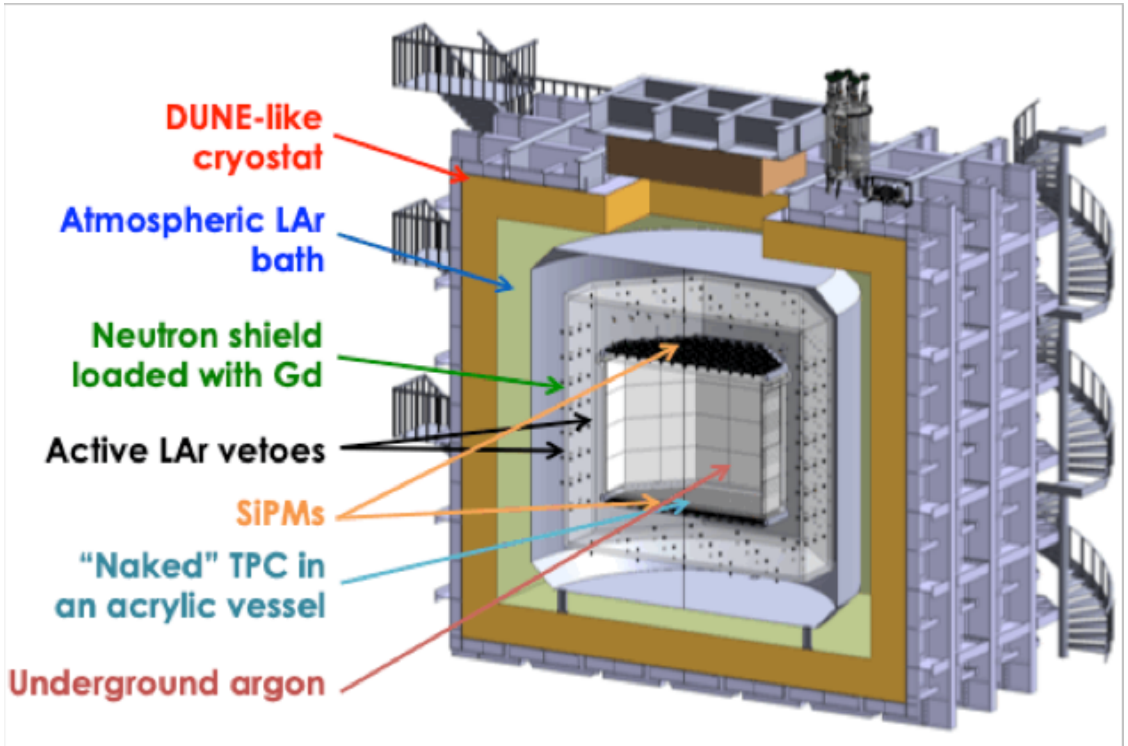


Directional signature by looking at recombination effect variation as function of the track orientation with respect to the direction of the field

An hint from SCENE



Design for a large mass bg-free LAr TPC



TPC: cryostat + teflon vessel => **only acrylic vessel**

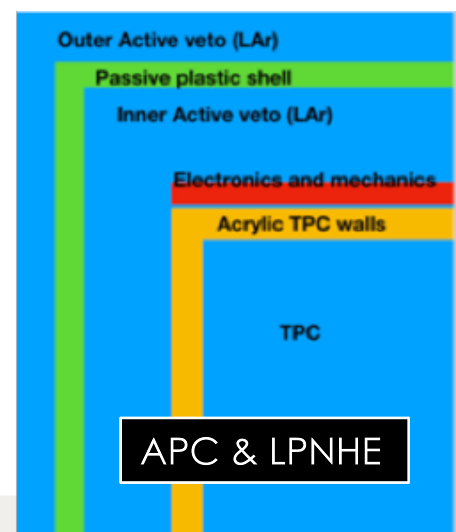
- ☑ Almost doubled the target mass (no UAr buffer): ~35 tonnes
- ☑ Removed cryostat, among the main sources of radiogenic neutrons

Photo-sensors: **~15 m² of SiPMs**

- ☑ **Radiopure** and limited amount of material
- ☑ High photodetection **efficiency**

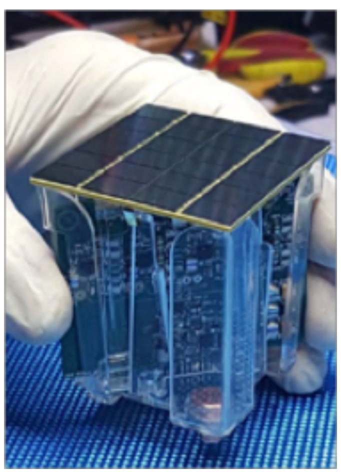
Vetoes: **LAr bath + moderator in acrylic loaded with Gd**

- ☑ **Neutron veto conceptual design by APC&LPNHE**
- ☑ **DUNE-like cryostat** (GTT patent)
- ☑ CERN Neutrino Platform technical support
- ☑ No organic scintillators

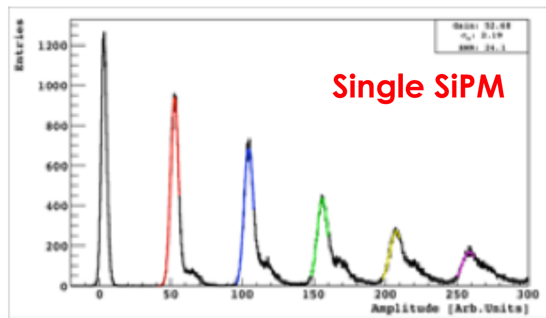


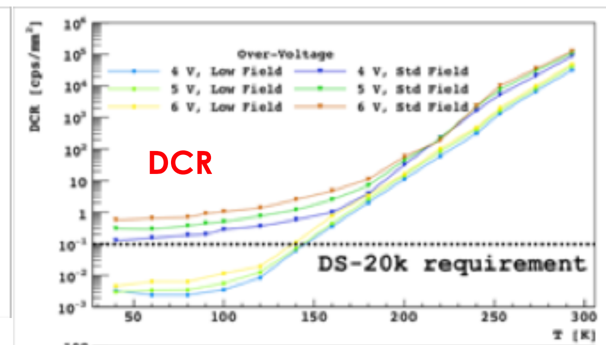
FBK NUV-HD SiPM

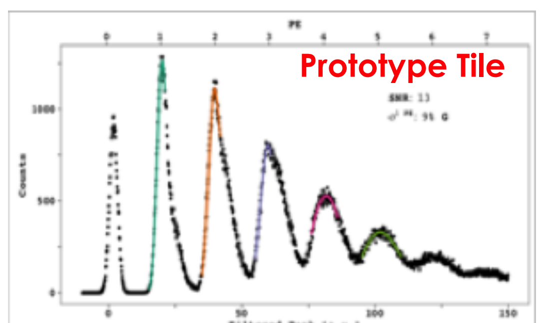
- ☑ Strict collaboration with Fondazione Bruno Kessler (**FBK**): development of specific SiPM for LAr (50 PDM under way)
- ☑ The FBK technology on transfer to **LFoundry** for mass production (starting April 2019)
- ☑ Packaging of 240,000 SiPMs at **NOA**, a facility funded at LNGS

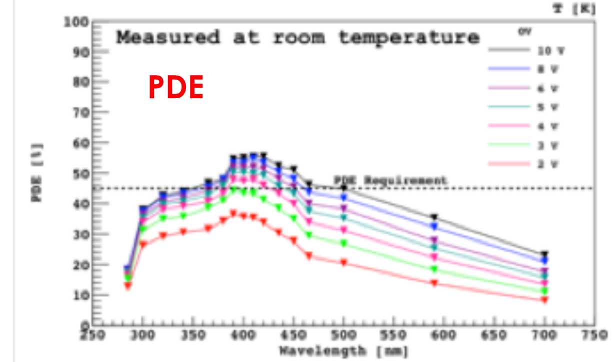


	DS-20k requirement	SiPM tile (PDM)	
Surface	5x5cm²	24cm² prototype 25cm² final PDM	✓
Power dissipation	<250mW	~170mW	✓
PDE	>40%	$50\% \cdot \varepsilon_{geom} = 45\%$	✓
Noise Rate	<0.1cps/mm²	0.004cps/mm²	✓
Time Resolution	O(10ns)	16ns	✓
Dynamic Range	>50	~100	✓

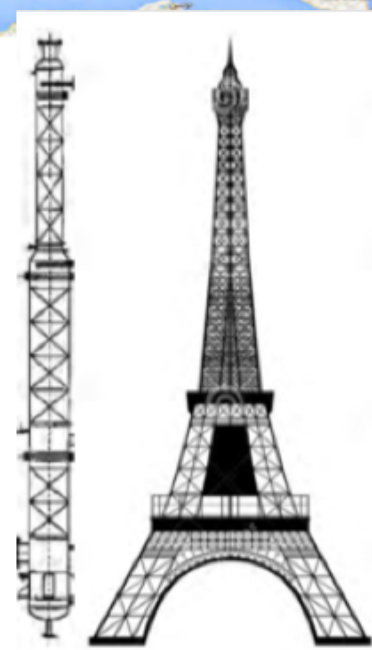








Underground/Depleted Argon



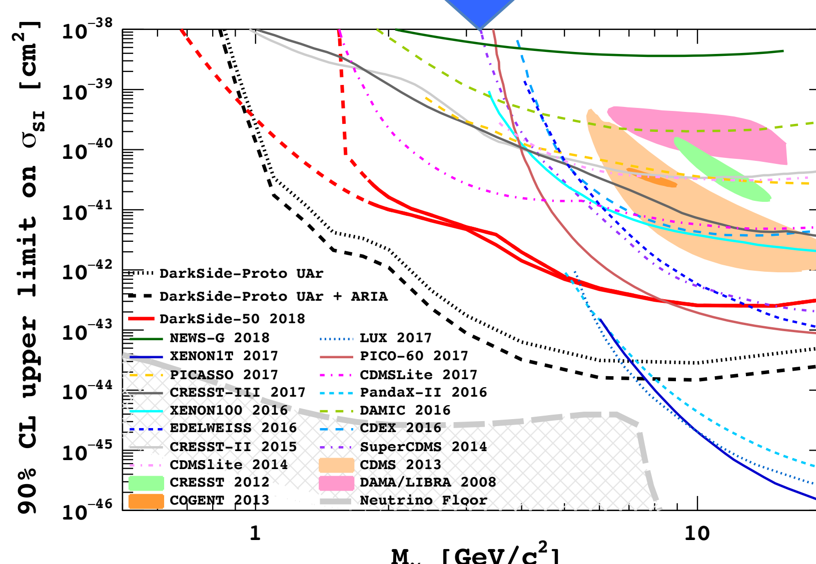
DS-Proto: 1-ton prototype

DS-Proto

Test of the DS-20k technology
(SiPM, electronics, cryogenics) and calibration/tuning of S2 amplification factor

(?)

DS-LowMass



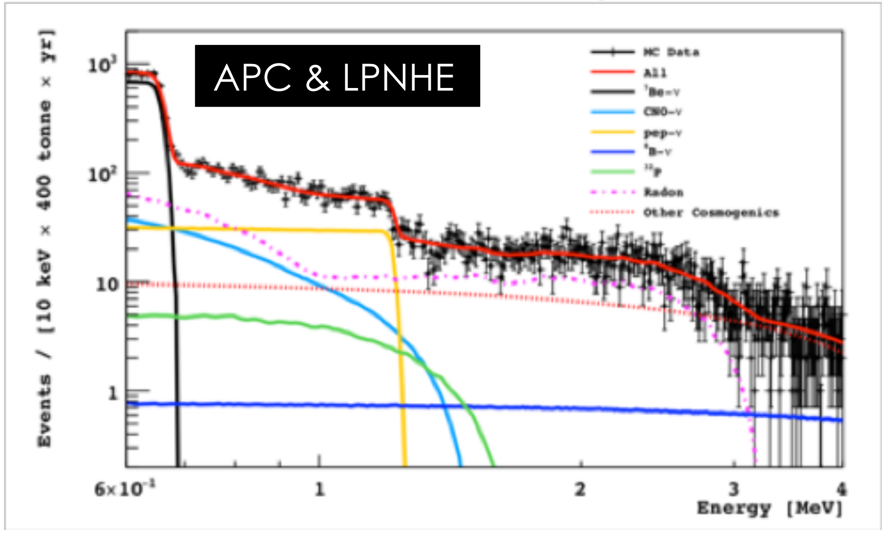
DarkSide Program

20-	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
DS-50																	
DS-Proto			DS-LM														
DEAP-3600																	
DS-20k																	
GADMC																	

GADMC

- ☑ **300 tonnes** detector
- ☑ **Background-free** (<0.1 background events) in the high-mass WIMP range
- ☑ Possible location at **SNOLAB**: letter of intent for collecting and stocking UAr underground
- ☑ Additional strong physics case with **CNO solar neutrinos**

First observation of CNO Solar neutrinos and solution to the Solar Metallicity Problem

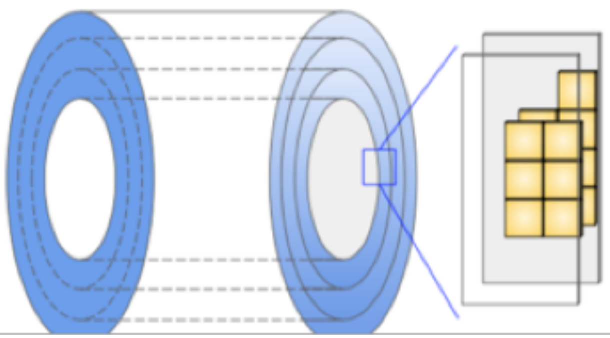


Simulation Package Information

- Based on Geant4 package built for the DarkSide experiments
  - Optical properties of LAr scintillation and light propagation tuned with real data from DarkSide detectors
  - Response to electron recoils from gamma rays has been well studied and compared with real detector data

http://arxiv.org/abs/arXiv:1801.06653

- Current simulations assume 9 layers of SiPM panels
  - Provide ~20 cm of LAr thickness → >70% of gammas scatter inside detector
  - Assumes minimal thickness of Ti cryostat (6 mm)
  - SiPMs assumed to have 40 ps intrinsic timing resolution
  - SiPM detection efficiency = 70% at 420 nm, 30% at 172 nm

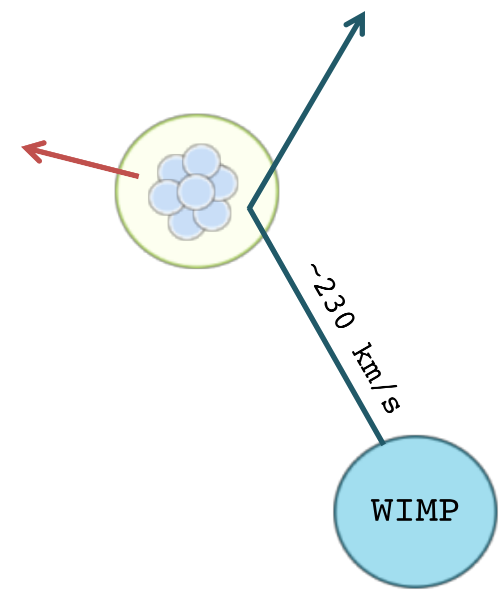


Observables: the Energy Spectrum

Differential Recoil Spectrum

$$\frac{dR}{dE}(E,t) = \frac{\rho_0}{m_\chi \cdot m_A} \cdot \int v \cdot f(\mathbf{v},t) \cdot \frac{d\sigma}{dE}(E,v)\, \mathrm{d}^3 v$$

ρ$_0$: local dark matter density
m$_a$: nucleus mass
m$_\chi$: WIMP mass
dσ/dE: differential cross section
***v*:** dark matter velocity wrt detector rest frame



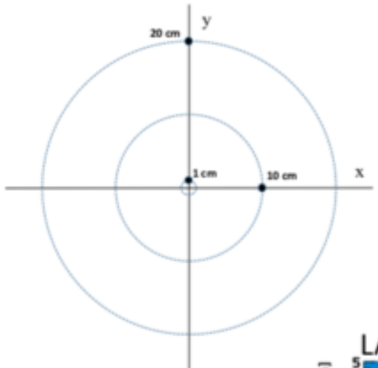
$$\frac{d\sigma}{dE} = \frac{m_A}{2\mu_A^2 v^2} \cdot \left(\boxed{\sigma_0^{\mathrm{SI}} \cdot F_{\mathrm{SI}}^2(E)} + \boxed{\sigma_0^{\mathrm{SD}} \cdot F_{\mathrm{SD}}^2(E)} \right)$$

Spin-independent interactions: all targets

Spin-dependent interactions: nucleus with unpaired nucleons

PET based on Xe-doped LAr

NEMA NU 2-2012 Spatial Resolution Test

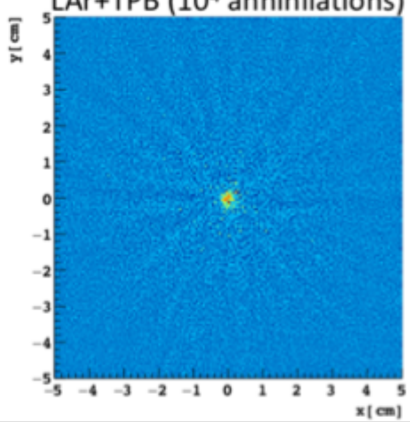


Source locations in the radial direction as shown

Two axial positions:
1) Center of FOV
2) 375 mm from center of FOV

Reconstruction done using simple filter back projection technique with no smoothing or apodization

LAr+TPB (10^4 annihilations)



LAr+Xe (10^4 annihilations)