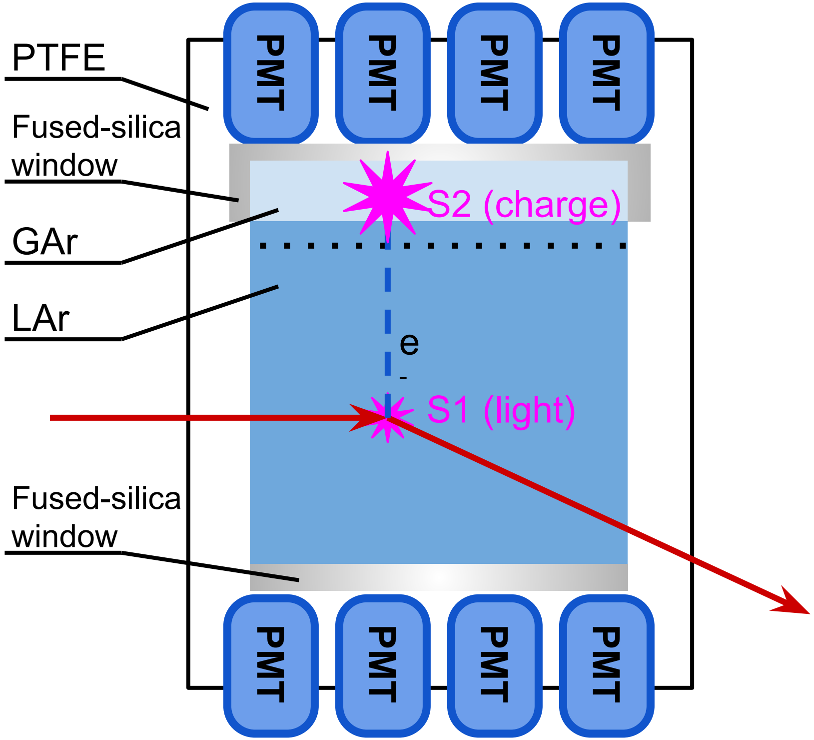
darkside
two-phase argon TPC for Dark Matter Direct Detection

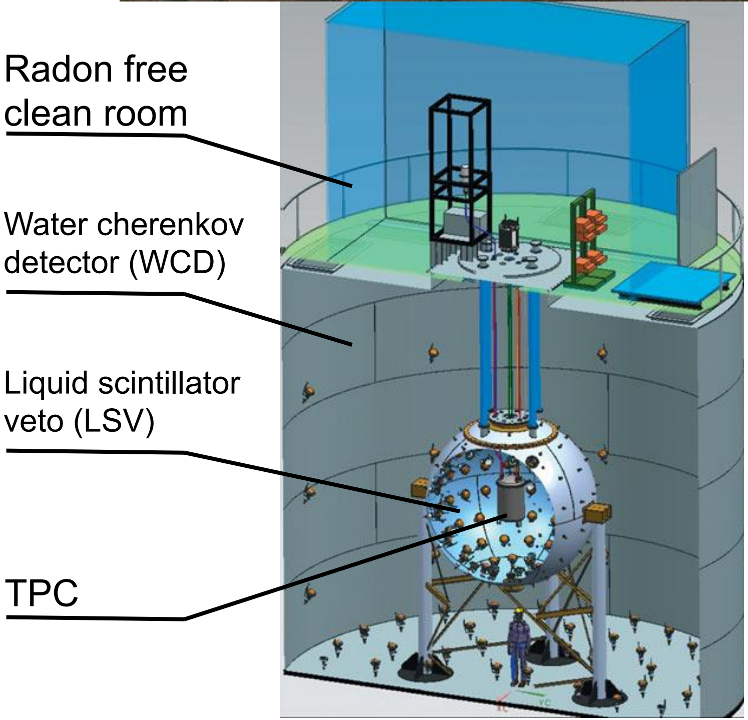
Results from the DarkSide-50 Search for Dark Matter

Dark matter (WIMPs) direct detection
Center for High Energy Physics, PKU
Xinran Li, Princeton University
10/14/2019

The DarkSide-50 Detector

Argon dual phase time projection chamber (TPC)



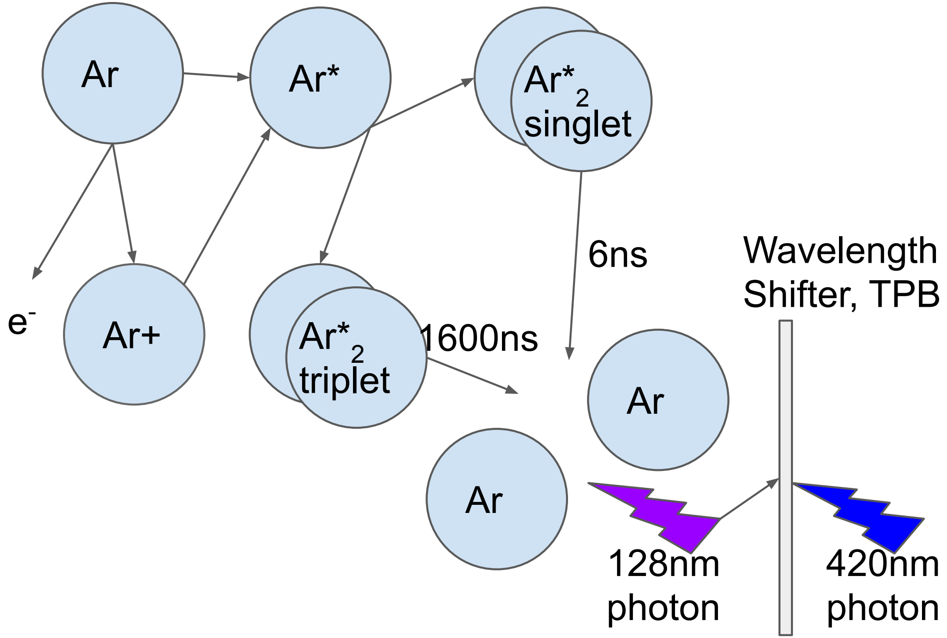


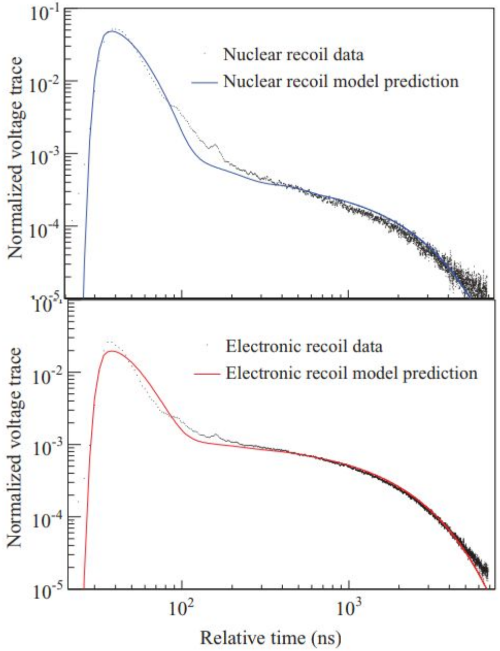
Schematic of DarkSide-50 detector

Liquid Argon Scintillation Light

LAr Scintillation light has 2 different decay time constants from the 2 types of dimer excitations, singlet and triplet state.

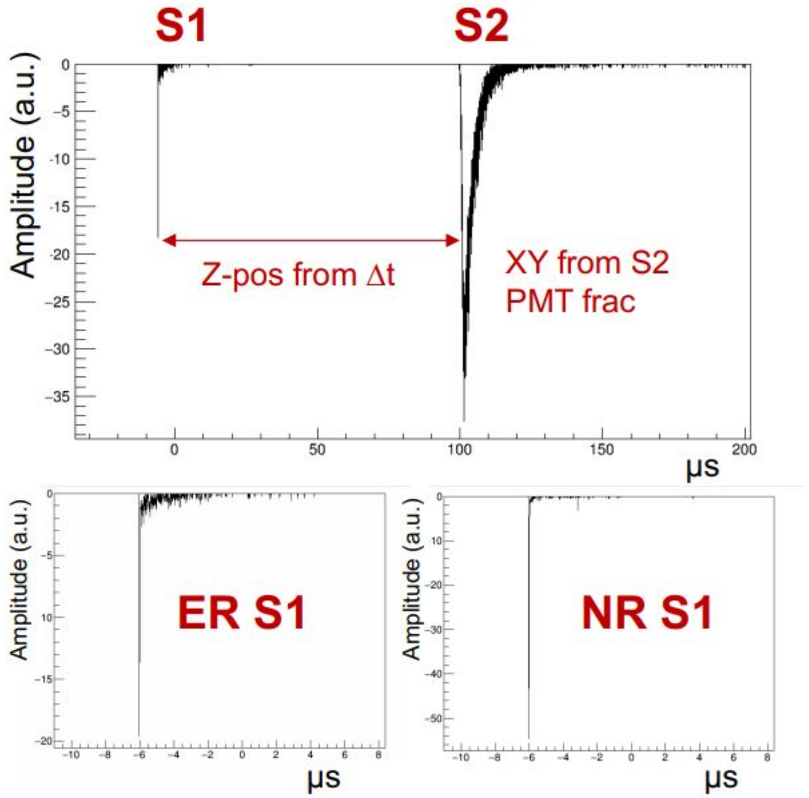
The relative abundance of the 2 types of excitations have strong dependence on ionization density, which is different for electronic recoil (ER) and nuclear recoil (NR) events.





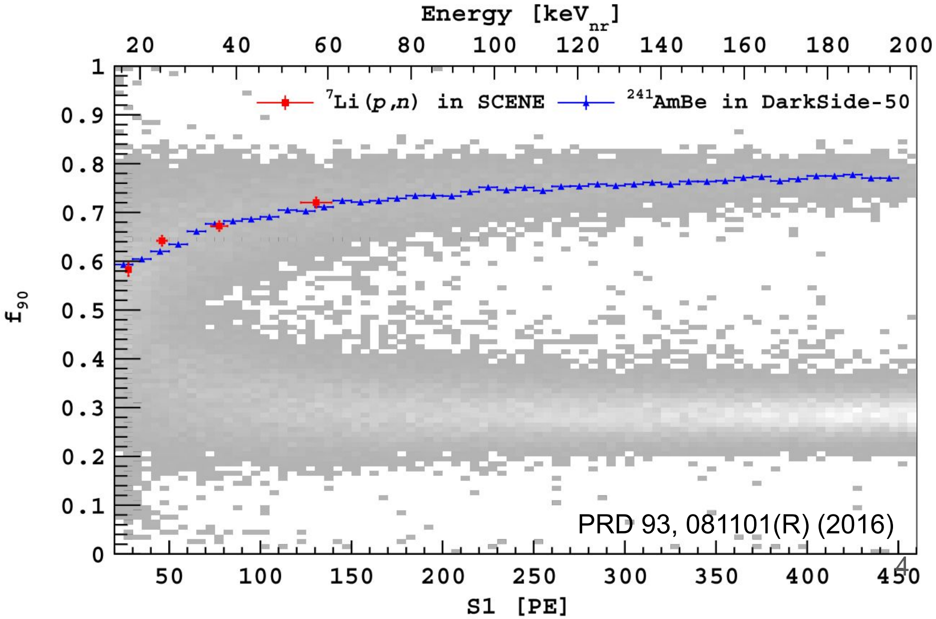
(10.1103/PhysRevC.78.035801)

Pulse Shape Discrimination (PSD)
Between Electronic Recoil (ER) and Nuclear Recoil (NR)



Pulse shape parameter:

$$f_{90} = \frac{\text{S1 light in first 90ns}}{\text{total S1 light}}$$



Recent Results

High-Mass Analysis

Physical Review D 98 (10), 102006 (2018)

Low-Mass Analysis

Physical Review Letters 121 (8), 081307 (2018)

Sub-GeV Dark-Matter-Electron Scattering

Physical Review Letters 121 (11), 111303 (2018)

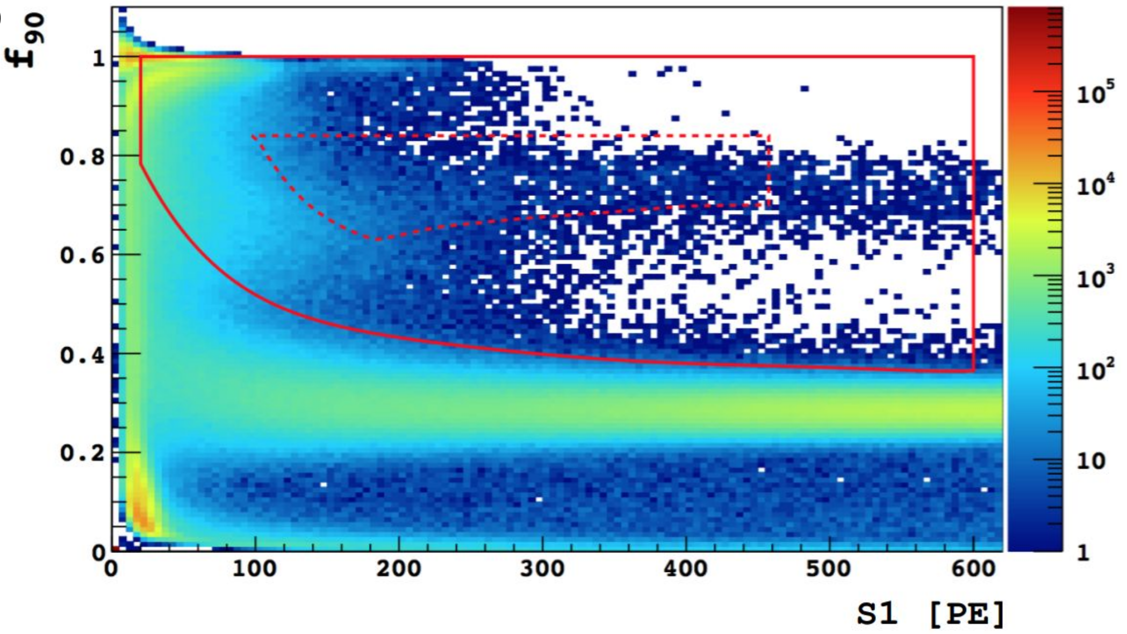
High-Mass Analysis

A blind analysis of 532 live-days (16.6 T d) exposure with low-radioactivity underground argon.

Blind box: solid red line. Shown on 70 live-days data (Phys. Rev. D 93, 081101 (2016))

Background free: <0.1 background in the region of interest indicated as the dashed red line.

- **Beta and gamma background**
- **Neutron background**
- **Surface alpha**
- **Cherenkov events**

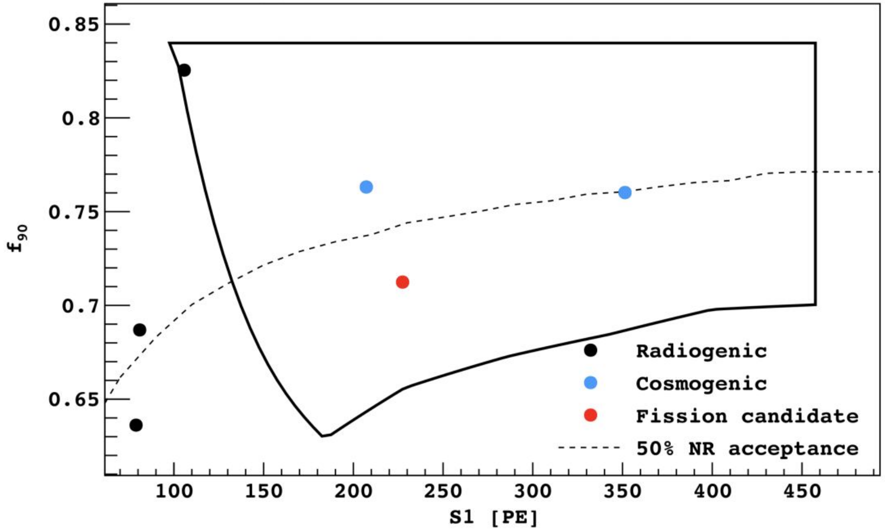


Neutron Backgrounds

Rejected by TPC multi-scatter.
LSV measured efficiency for TPC single-NR with AmC: 0.9964±0.0004

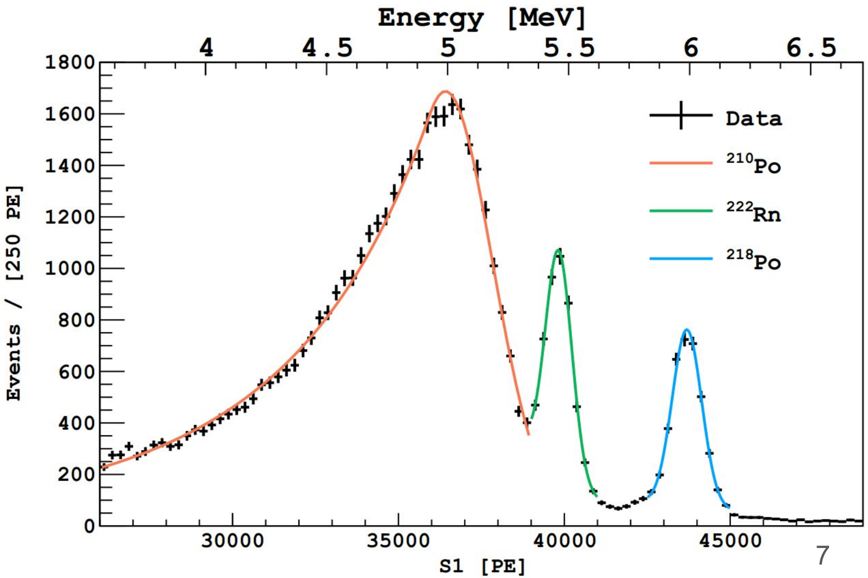
Cosmogenic neutrons vetoed by water tank.

Neutrons tagged by neutron veto:



Surface α Events

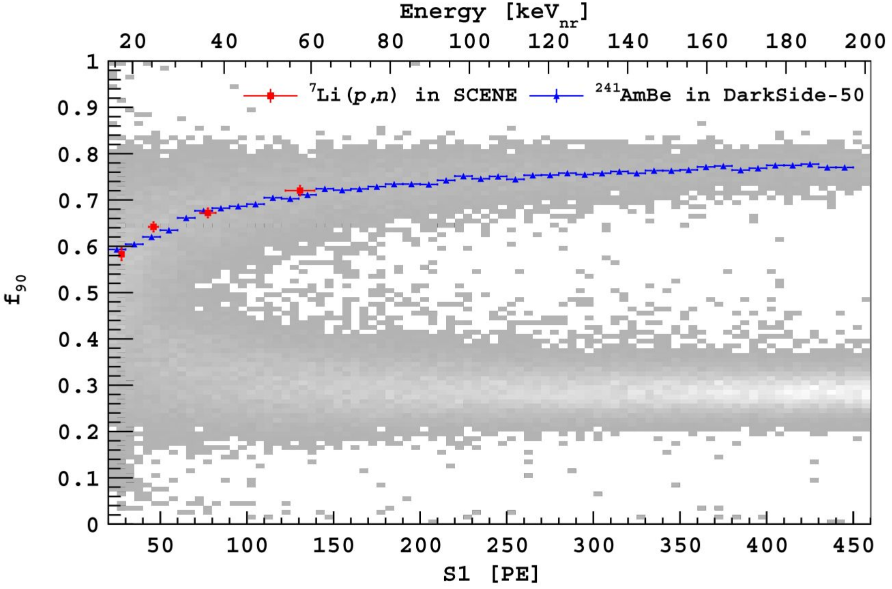
Much higher energy.
Further rejection based on S2 pulse shape, S2/S1, top-bottom asymmetry vs drift time.



γ and β Backgrounds

(0.73 ± 0.11) mBq/kg ^{39}Ar
(2.05 ± 0.13) mBq/kg ^{85}Kr
in underground argon (UAr)

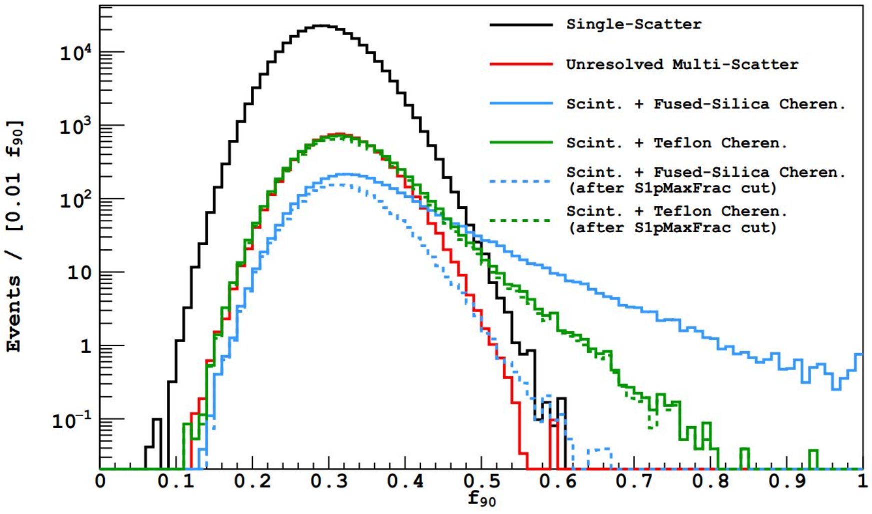
PSD rejection power in ROI:
Down to 6×10^{-8} for single-site ERs.



Cherenkov + Scintillation Events

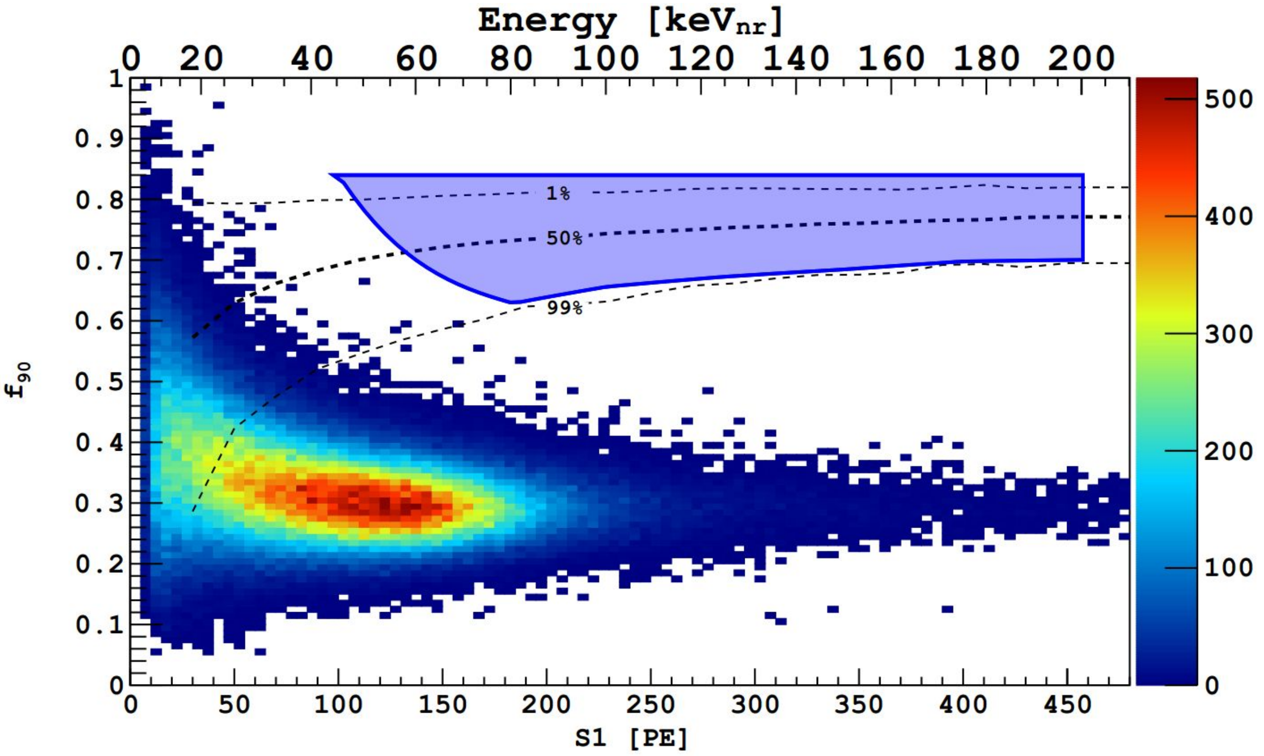
γ multiple scatters in LAr and PTFE or fused-silica. Cherenkov light will increase f90 of the events.

Rejected by light distribution in top PMTs, radial fiducialization, f90 accepted region.

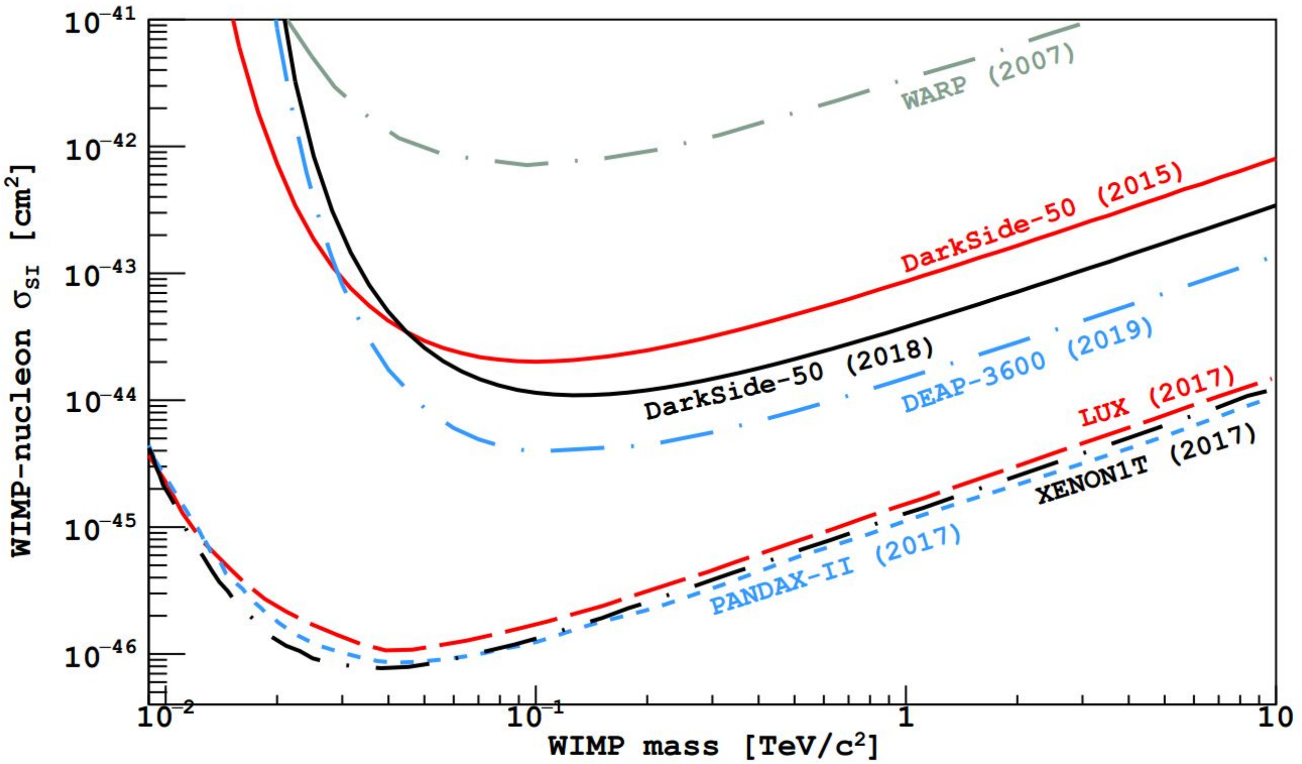


Prediction of <0.1 total background events. Open box!

Background	Estimated # surviving all cuts
Cosmogenic neutrons	$< 3 \times 10^{-4}$
Radiogenic neutrons	$< 5 \times 10^{-3}$
Surface α	1×10^{-3}
Cherenkov + scintillation	0.08
Total	0.09 ± 0.04

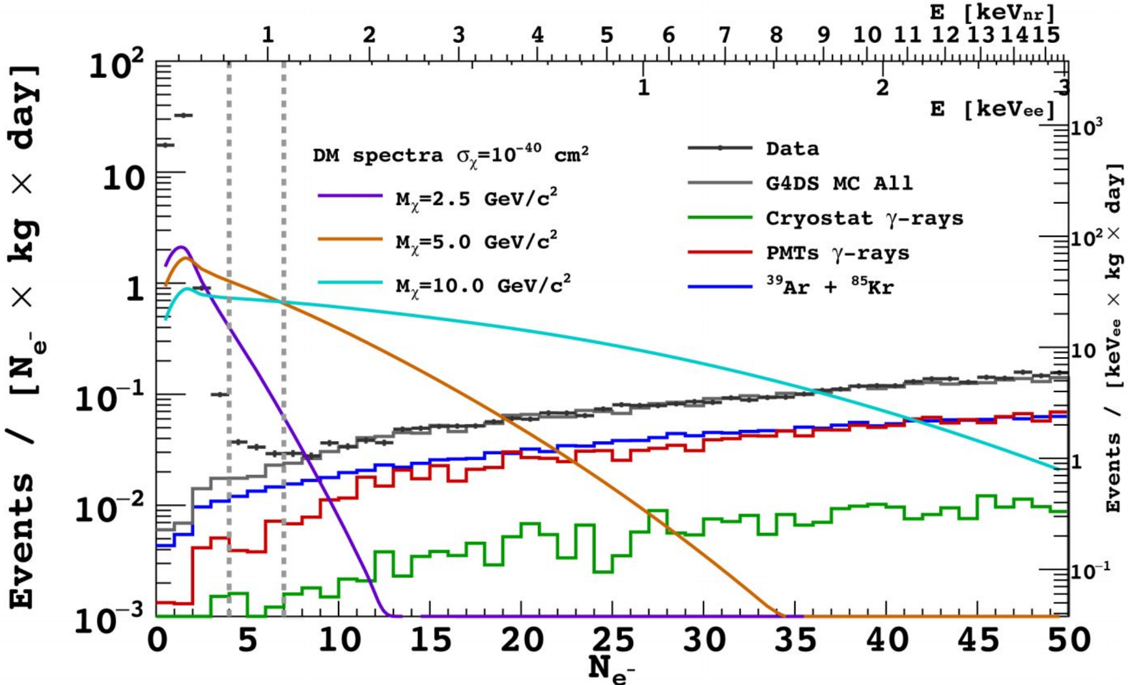


The Exclusion Curve for SI WIMP-nucleon Scattering



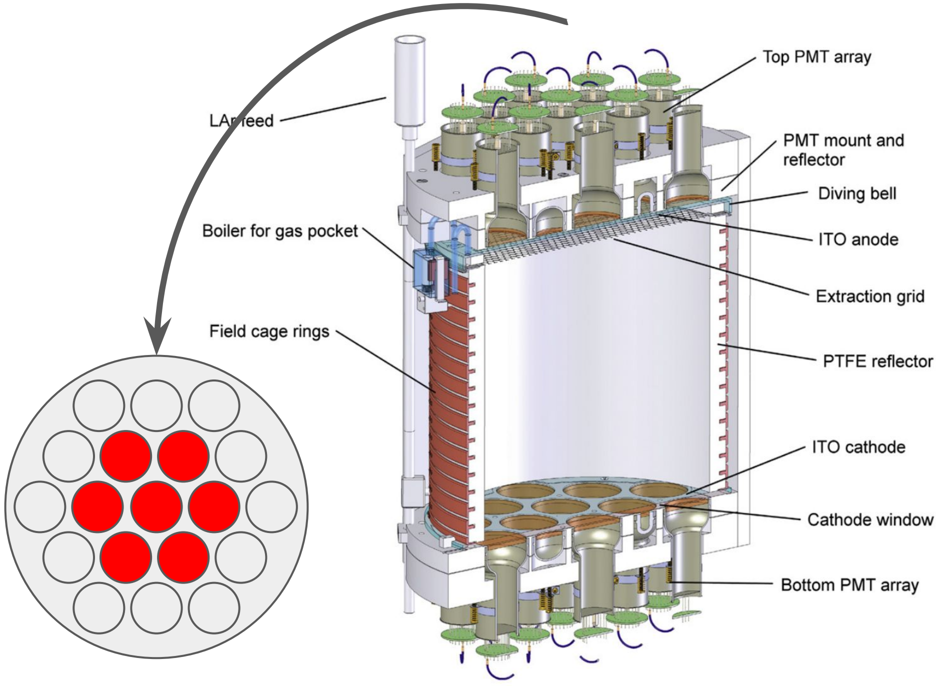
S2-Only Analysis

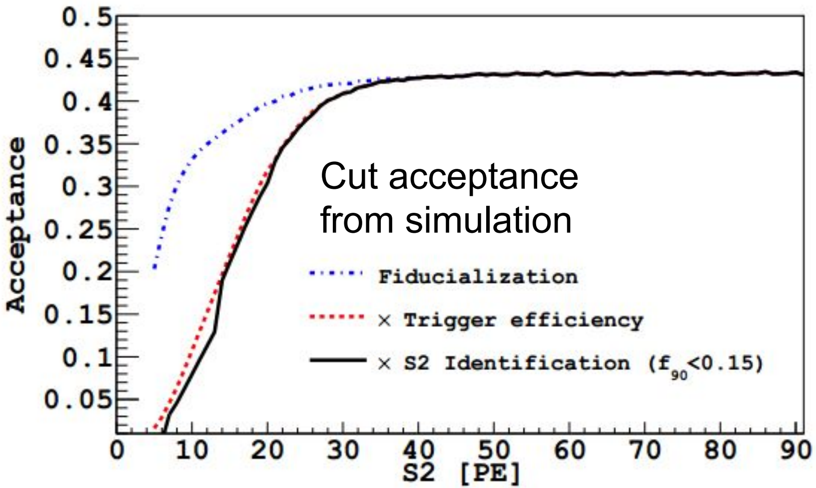
- Electron detection threshold and efficiency.
- Nuclear and electronic recoil energy scale calibration.
- Background estimation.
- Profile likelihood analysis.

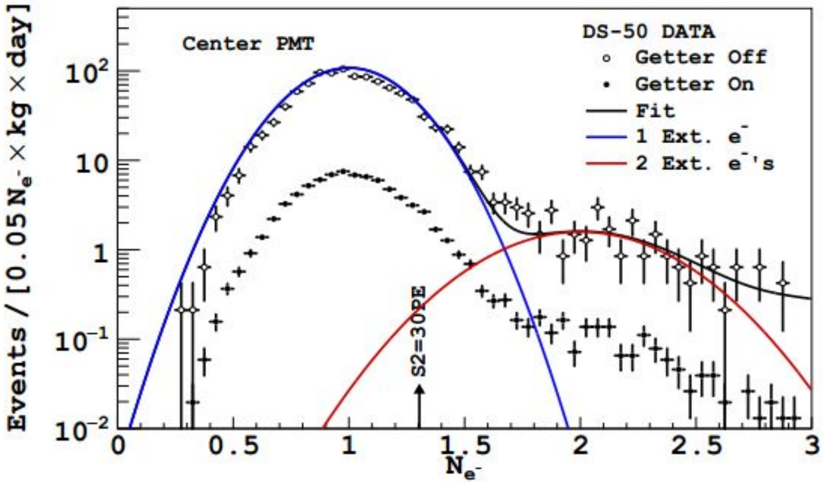


We achieved a detection threshold of 1 electrons (N_{e-}).

Select events with maximum S2 fraction under the 7 inner PMTs. No z direction fiducialization.

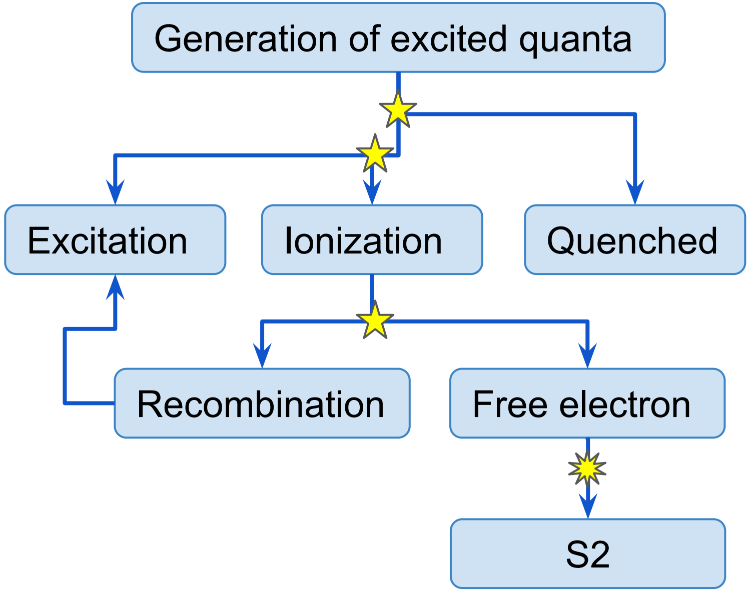






NR Energy Scale

The NR ionization process in DS-50:



The charge yield is calibrated by SCENE, ARIS and in situ $^{241}Am^{13}C$, $^{241}AmBe$ neutron sources. Energy quenching / ionization to excitation ratio / recombination rate of ionization pairs. (☆)

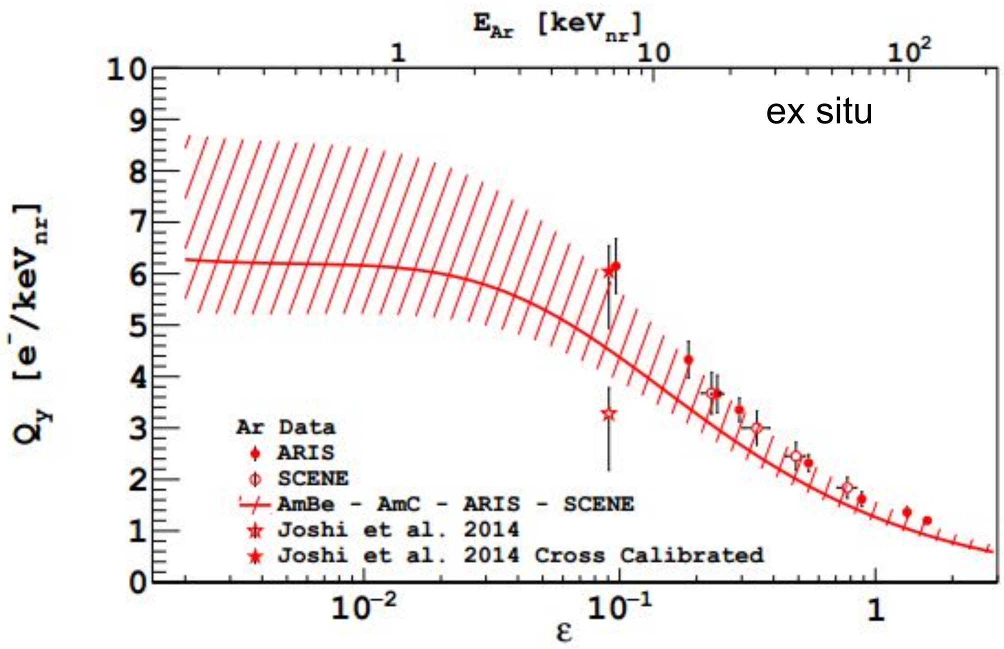
Model from F. Bezrukov et al (Astroparticle Physics 35 (2011) 119–127) is adopted, including 2 free parameters which are fitted to calibration data.

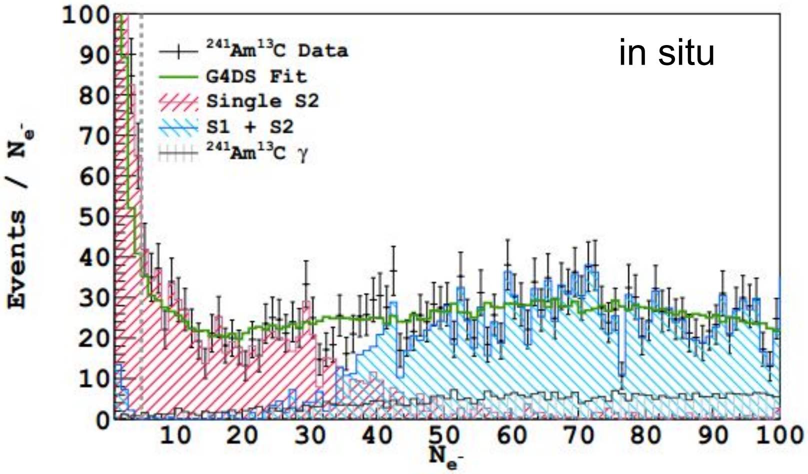
$$N_q(\epsilon) = \frac{4}{\gamma} \ln\left(1 + \frac{\gamma N_i(\epsilon)}{4}\right),$$

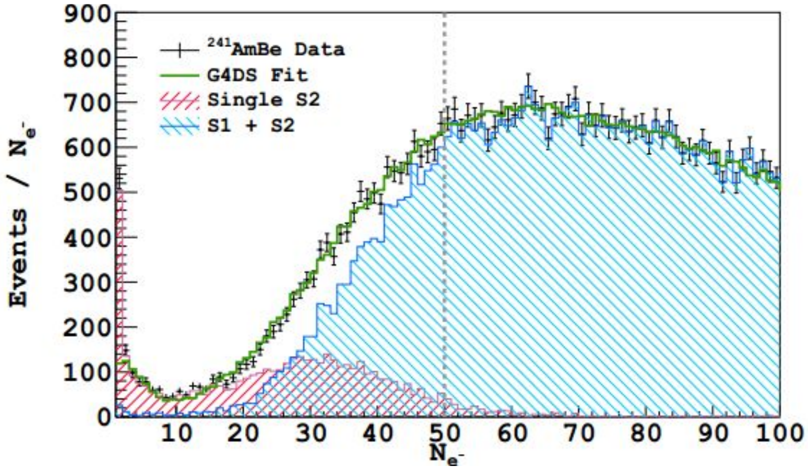
$$N_i(\epsilon) = \frac{\beta \epsilon \xi(\epsilon)}{1 + N_{ex}/N_i}.$$

Finally the S2 yield of electrons (✵) is determined by the mean value of the single electron peak in slide 12.

NR Charge Yield Fitting Result



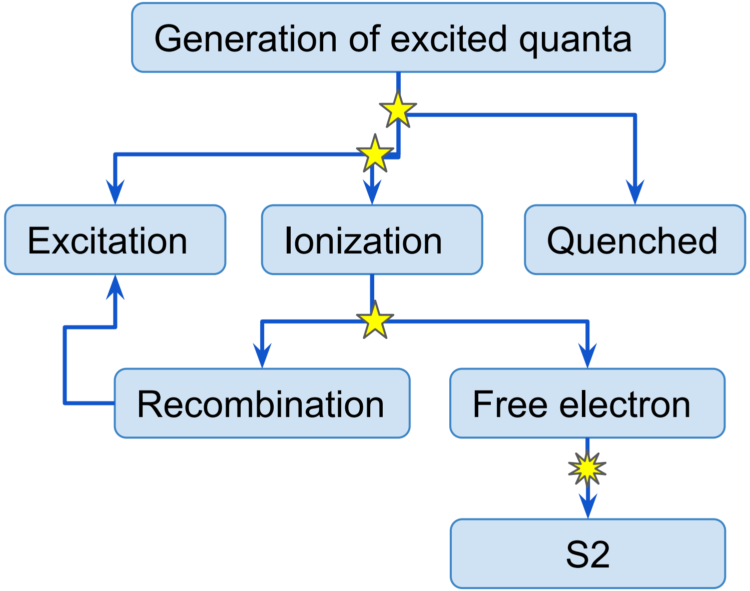




Epsilon is the reduced energy defined in Bezrukov.
Solid line and lower uncertainty from AmC AmBe fit.
Upper uncertainty from ARIS-SCENE fit.

NR Energy Scale - Fluctuations

The NR ionization process in DS-50:



All the energy partition processes (★) could introduce fluctuations in the charge yield.

We have no a priori knowledge of the width of the ionization distribution of nuclear recoils and are not aware of measurements in liquid argon in the energy range of interest. **Two extreme cases:**

1) **Binominal fluctuations in the 3 processes.**
2) **No fluctuations in the 3 processes.**

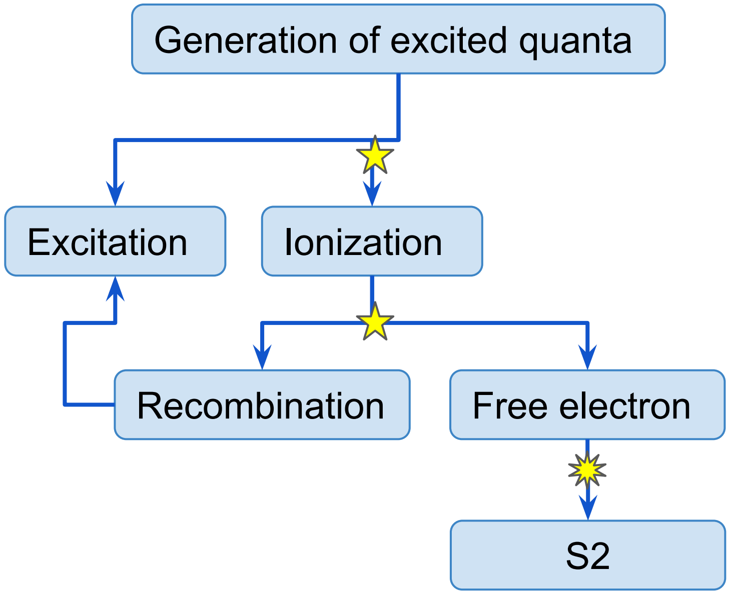
There is an additional fluctuation from the electron-luminescence process in the gas pocket that converts charge to S2. (✷)
Included in S2 light yield uncertainty and the single electron peak RMS.

ER Energy Scale

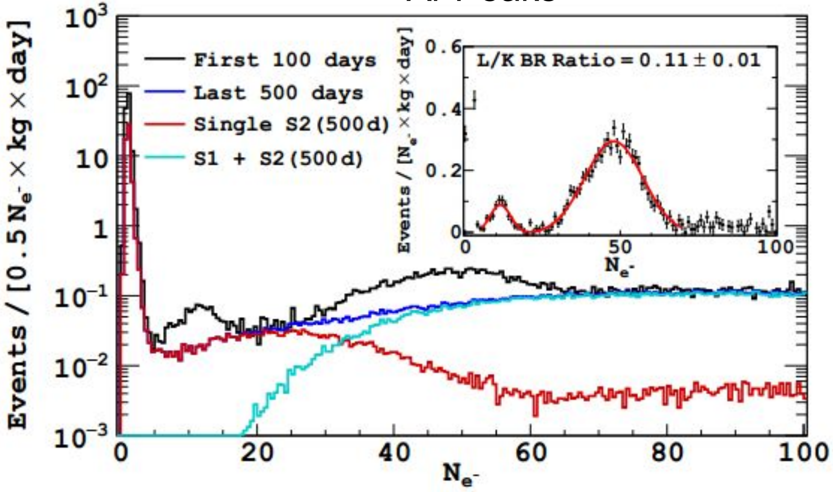
Electron recoil does not have quenching.

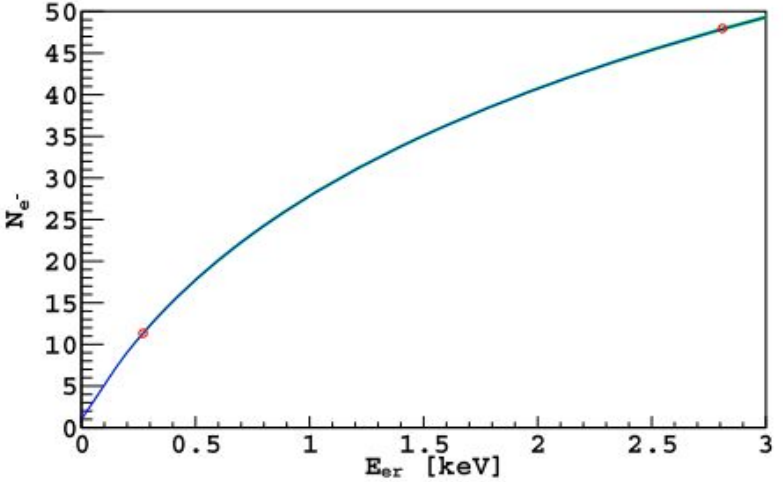
Thomas-Imel recombination model.(Phys. Rev. A 36, 614 (1987).)

$N_{ex} / N_i = 0.21$ (Phys. Rev. B 13, 1649 (1976).)

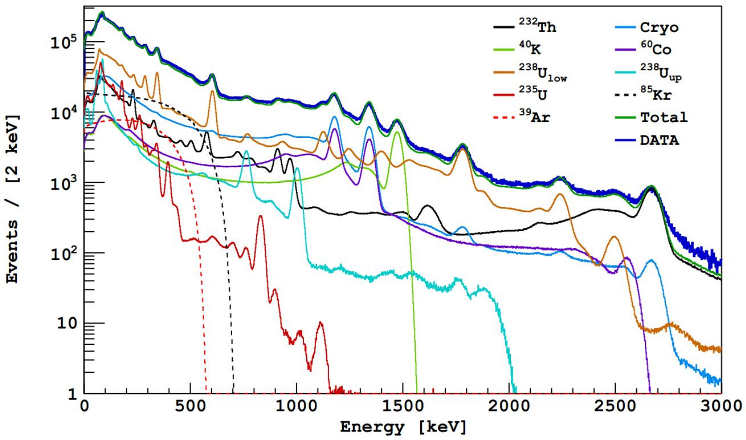


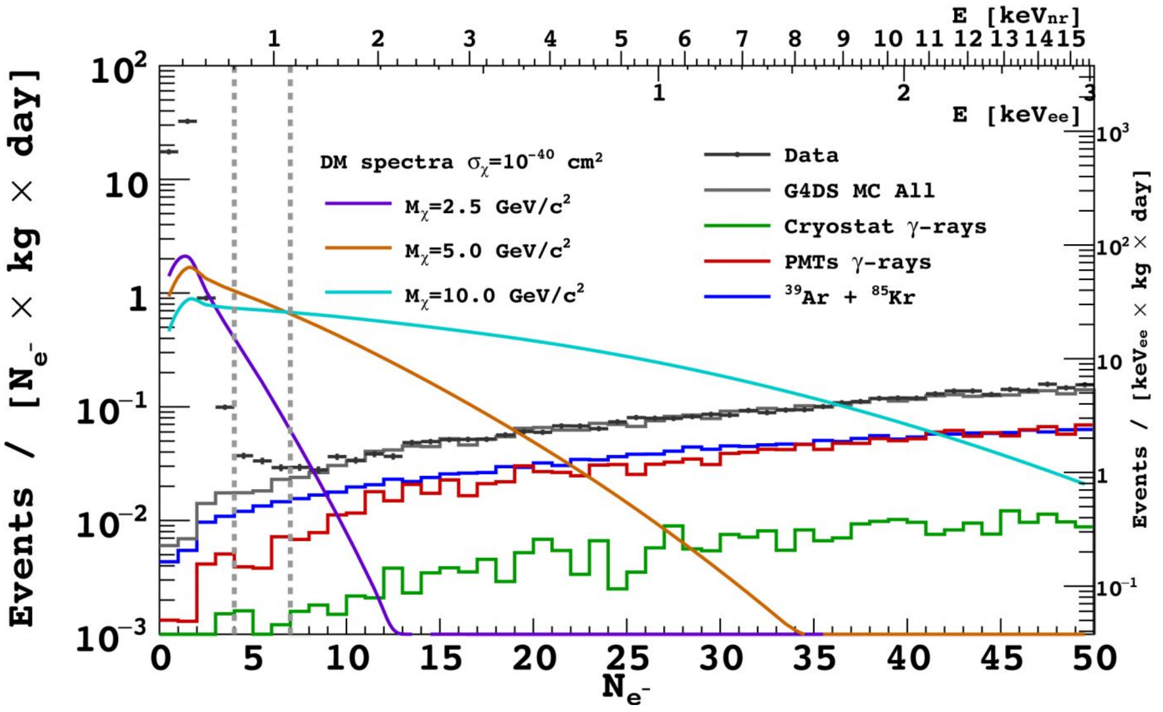
^{37}Ar Peaks





Background in Low Energy Region

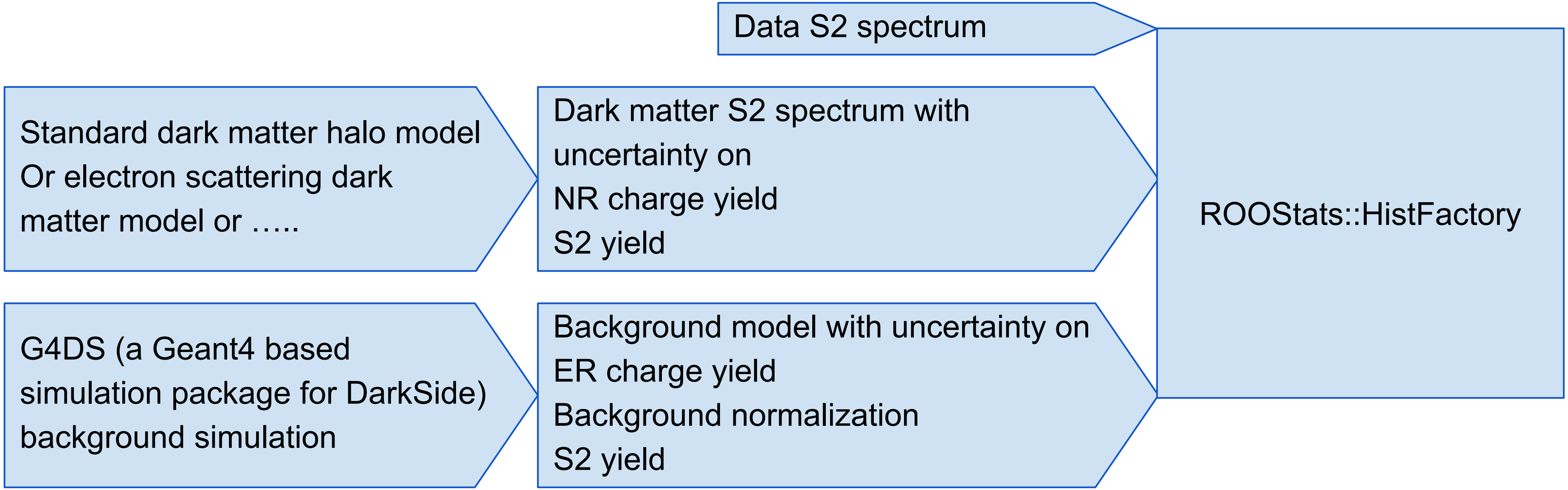




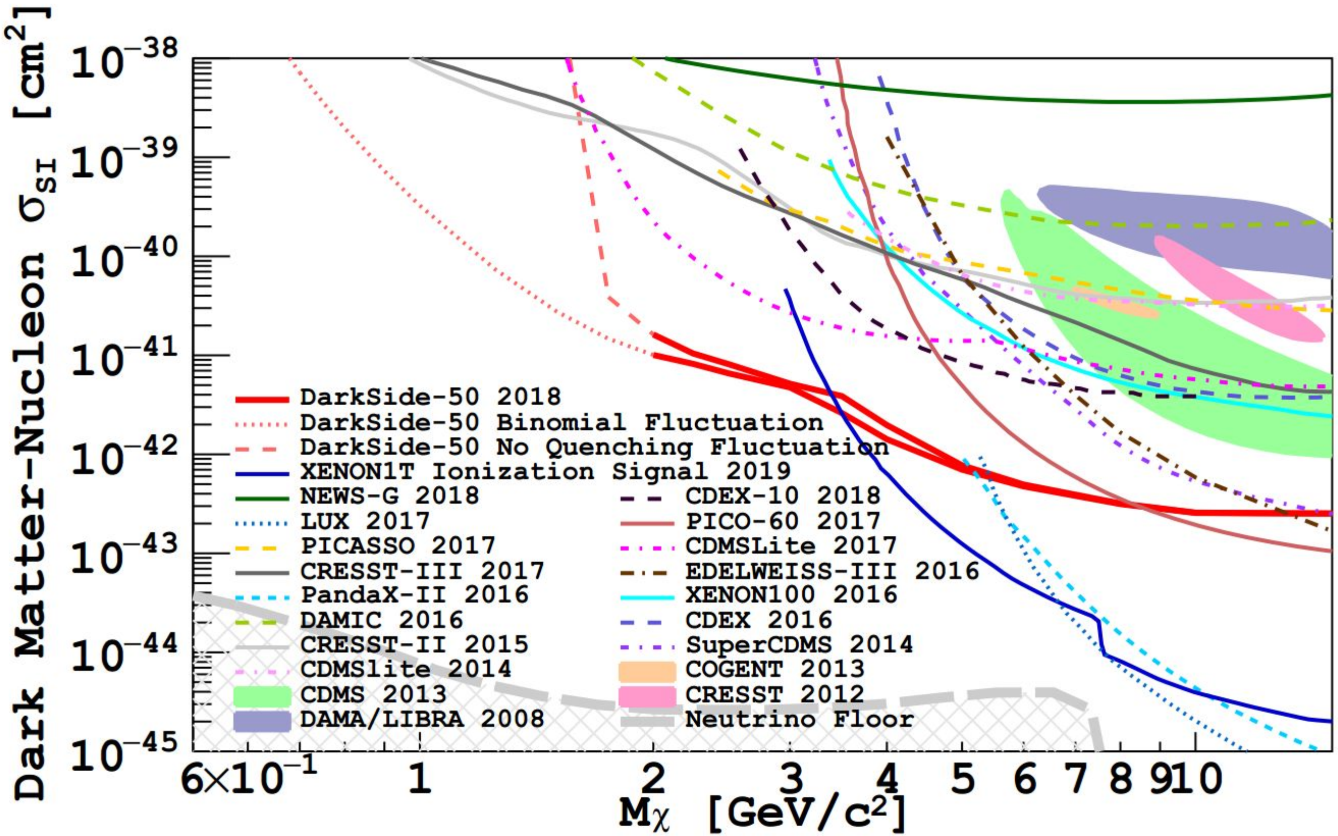
Without PSD, ER background is dominant. Simulation agrees with data in full energy range, except for events with S2 less than 7 N_{e-}

Excess below 4 N_{e-} is caused by electrons trapped and then released by impurities.

Profile Likelihood Analysis



The Exclusion Curve for SI WIMP-nucleon Scattering, Ionization Signals Only

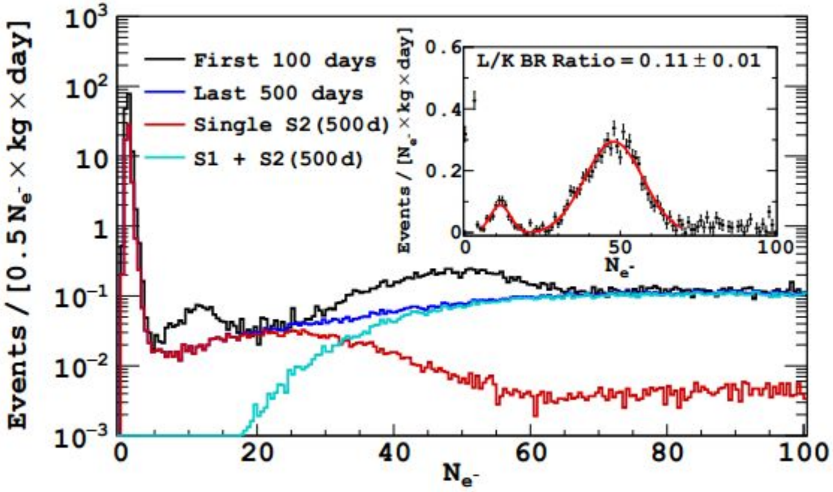


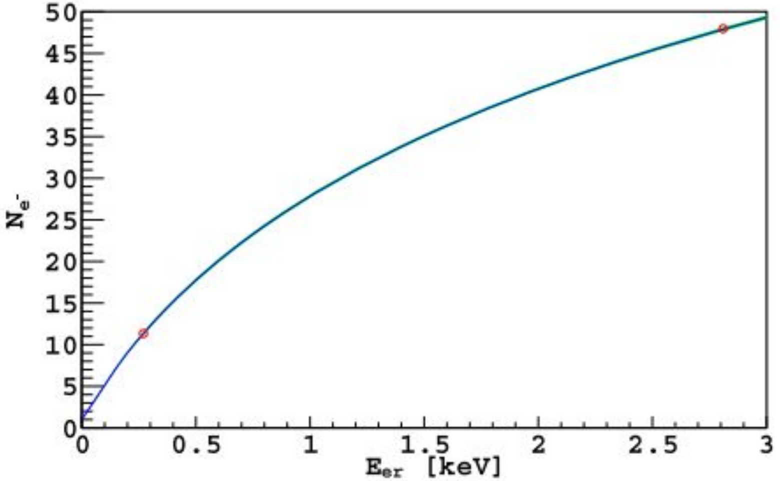
Sub-GeV Dark-Matter-Electron Scattering

Depending on the mass of the mediator ($m_{A'}$), the dark matter form factor (F_{DM}) has different asymptotic momentum (q) dependence:

$$F_{\rm DM}(q) = \frac{m_{A'}{}^2 + \alpha^2 m_e{}^2}{m_{A'}{}^2 + q^2} \simeq \begin{cases} 1, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e{}^2}{q^2}, & m_{A'} \ll \alpha m_e \end{cases}$$

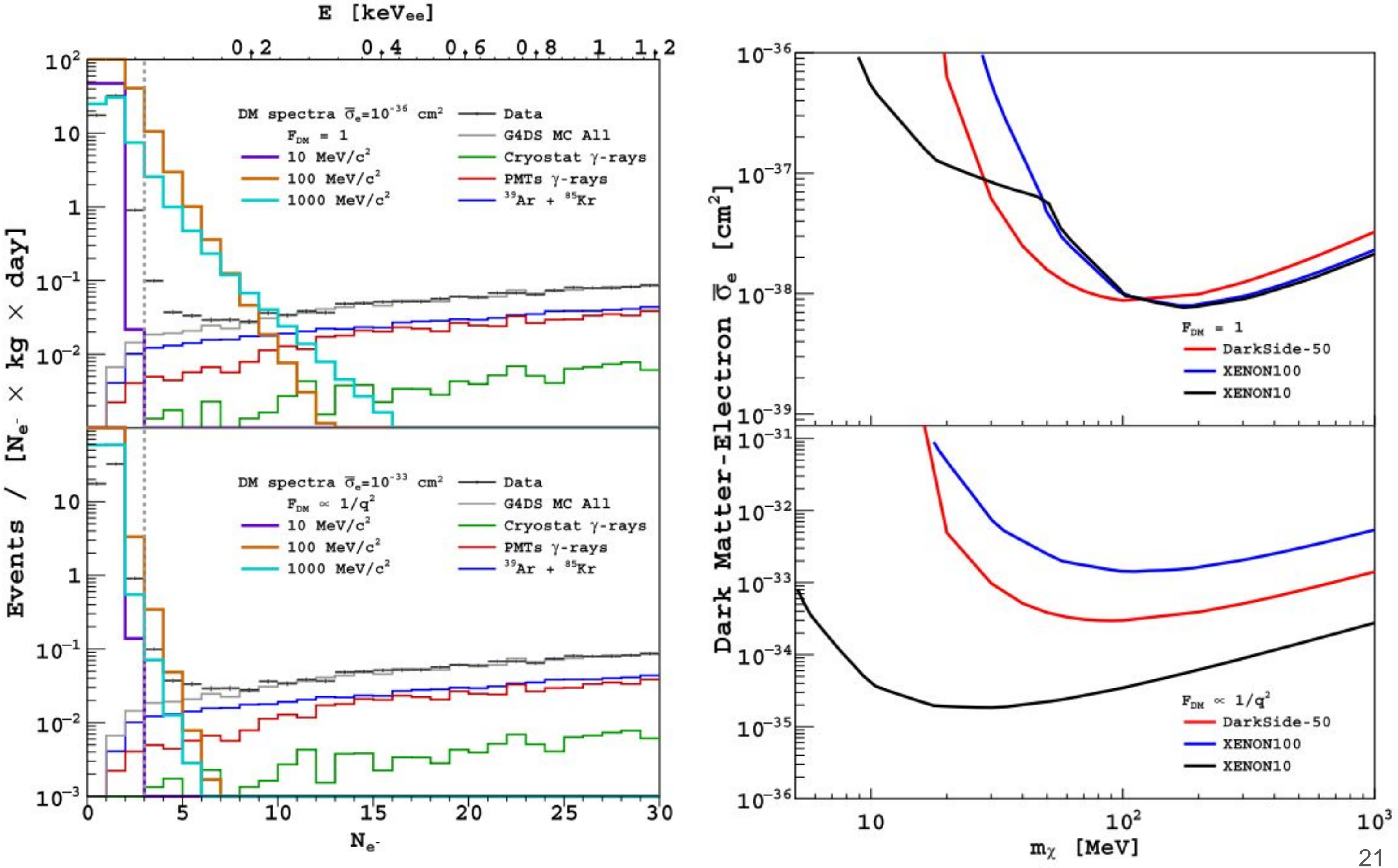
Electron recoil energy scale calibrated from ^{37}Ar decay.





$F_{DM} = 1$

$F_{DM} = 1/q^2$



E [keV_ee]
DM spectra $\bar{\sigma}_e=10^{-36}$ cm²
F_{DM} = 1
10 MeV/c²
100 MeV/c²
1000 MeV/c²
Data
G4DS MC All
Cryostat γ-rays
PMTs γ-rays
^{39}Ar + ^{85}Kr
DM spectra $\bar{\sigma}_e=10^{-33}$ cm²
$F_{DM} \propto 1/q^2$
Events / [N_e- × kg × day]
N_e-
Dark Matter-Electron $\bar{\sigma}_e$ [cm²]
F_{DM} = 1
DarkSide-50
XENON100
XENON10
$F_{DM} \propto 1/q^2$
m_χ [MeV]

Milestones

DarkSide-50 is a 50 kg liquid argon TPC operating with underground argon and a highly efficient active veto.

DarkSide-50 performed a background-free high mass WIMP search with a 16660±270 kg d exposure.

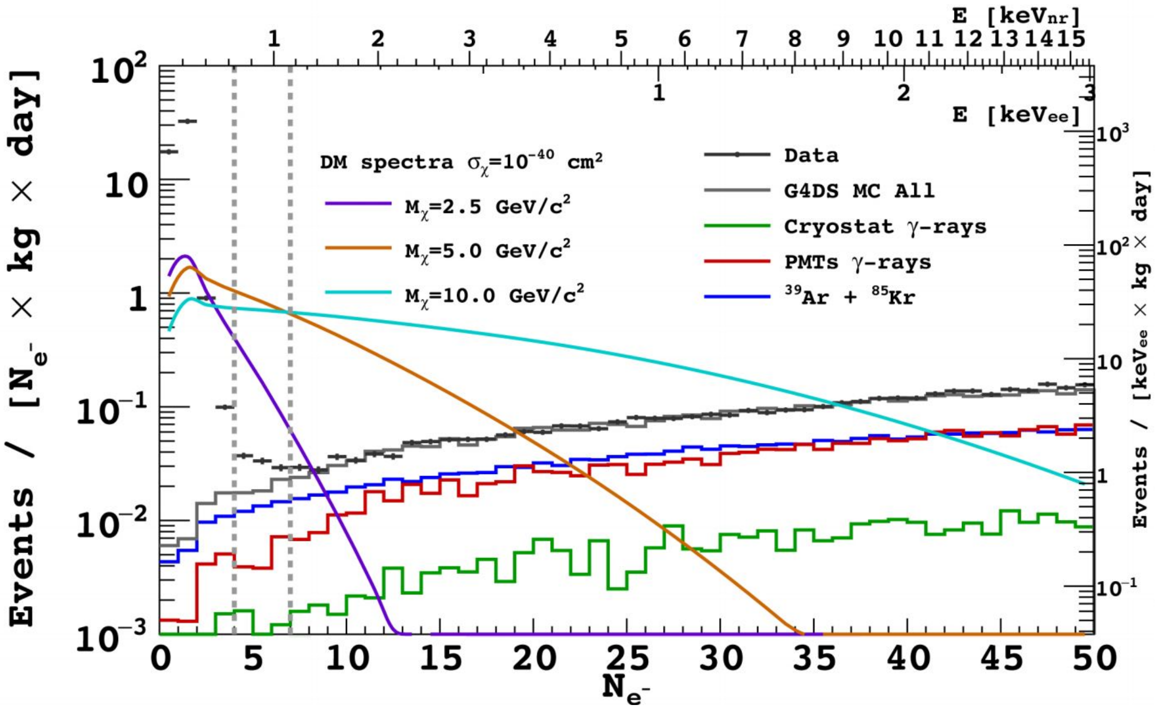
DarkSide-50 also performed a world-leading low-mass dark matter search using S2-only signals, demonstrating the power of the liquid argon TPC technology in this mass regime.

The Ultimate Sensitivity of LAr Detector in Low Mass Region

What could be the ultimate sensitivity of a LAr TPC to low mass dark matter?

Threshold:
Minimum 2 electrons. No rejection power to random electron release below 2 e^-.

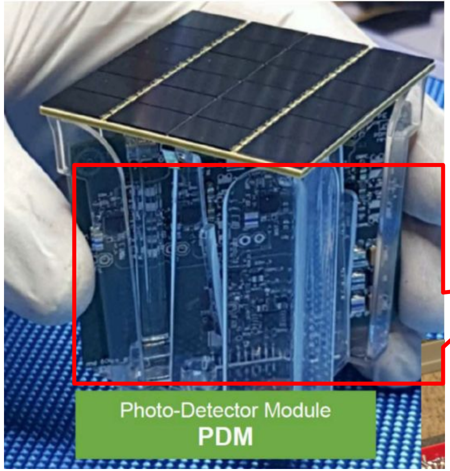
Background:
Larger volume, self-shielding.
^{39}Ar, ^{85}Kr and neutrino.



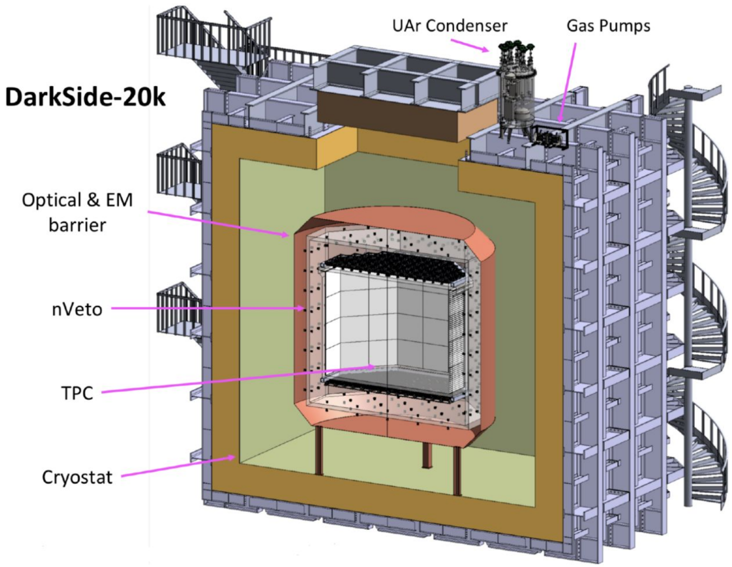
Reduce Background for Low Mass

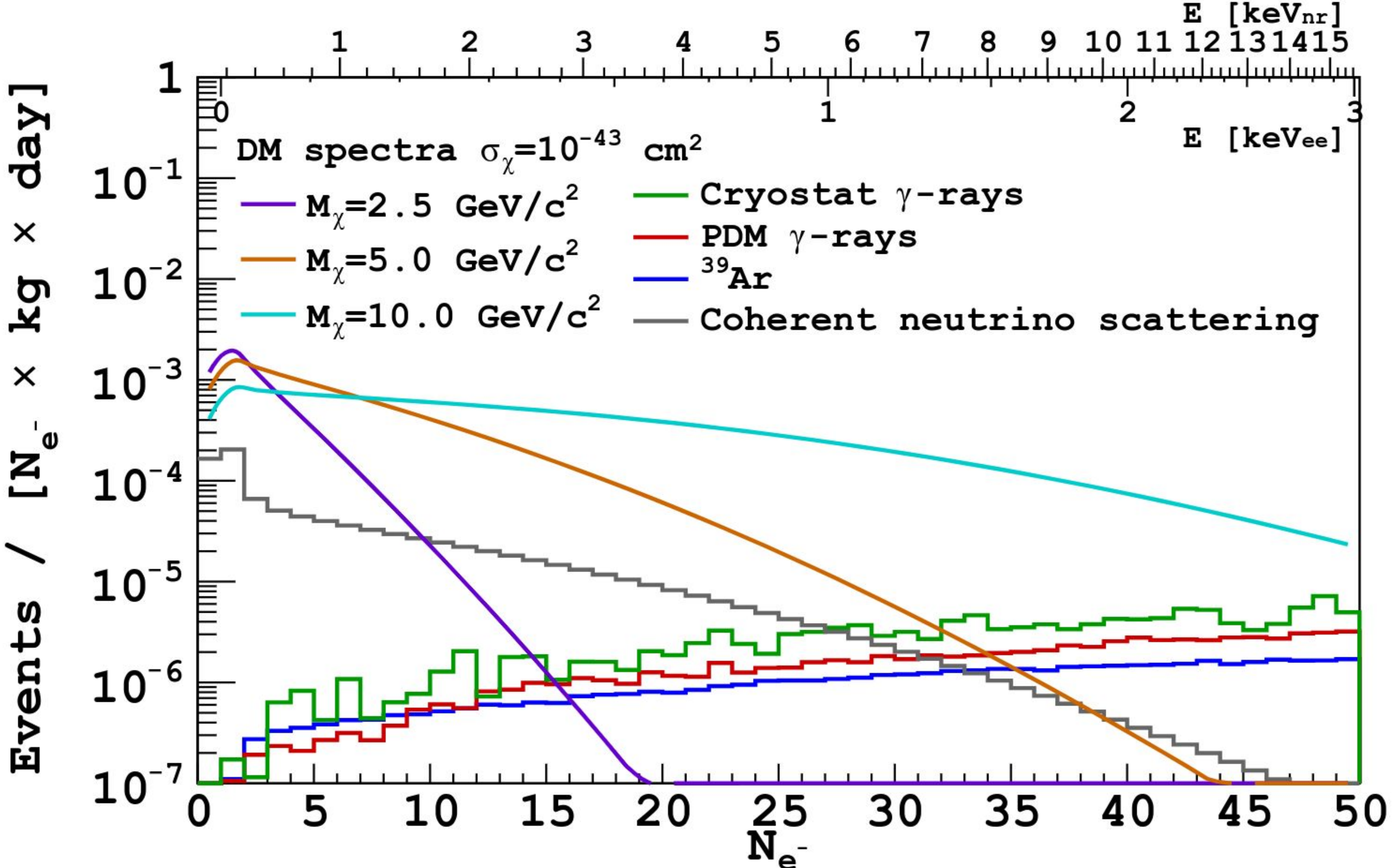
PMT → SiPM (silicon photomultiplier)
Cryostat → Copper vessel
PTFE TPC with copper field cage → Acrylic TPC with conductive polymer
^{39}Ar, ^{85}Kr → Underground argon and large cryogenic distillation towers.

	DarkSide-50	Ultimate LM
^{39}Ar + ^{85}Kr	0.7mBq/kg +1.9mBq/kg	0.1~1uBq/kg +0
Cryostat / container	3.5Bq	30uBq/kg copper
Photo detector	$0.22Bq/46cm^2$	$1uBq/25cm^2$

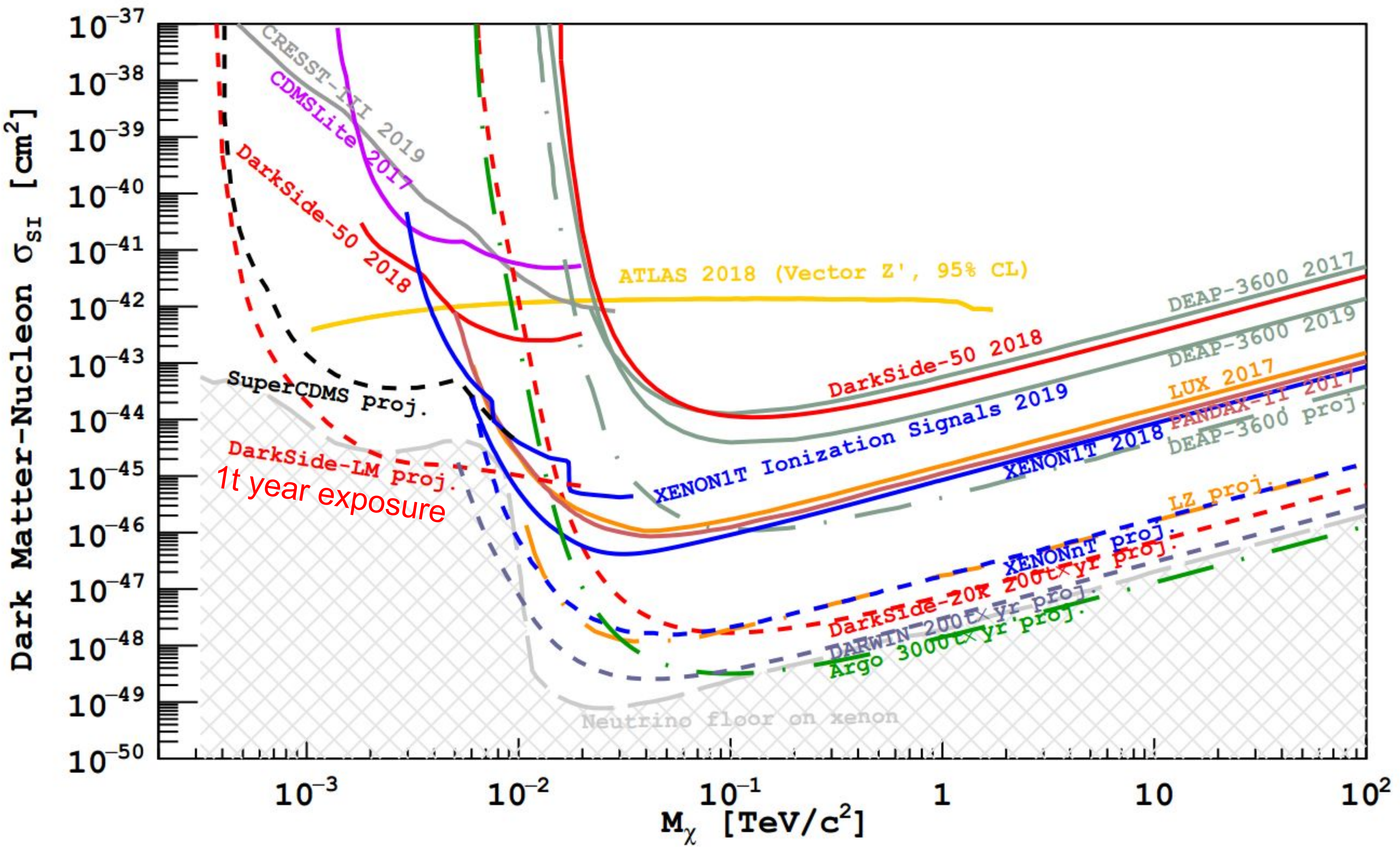


Substitute with ASIC chips and 3D bump-bonding. Minimize PCB area.





E [keVnr]
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 1 2 3
E [keVee]
DM spectra σχ=10^-43 cm^2
Mχ=2.5 GeV/c^2
Mχ=5.0 GeV/c^2
Mχ=10.0 GeV/c^2
Cryostat γ-rays
PDM γ-rays
39Ar
Coherent neutrino scattering
Events / [Ne- × kg × day]
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0 5 10 15 20 25 30 35 40 45 50
Ne-


Dark Matter-Nucleon σ_{SI} [cm^2]
M_χ [TeV/c^2]
CRESST-III 2019
CDMSLite 2017
DarkSide-50 2018
ATLAS 2018 (Vector Z', 95% CL)
DEAP-3600 2017
DEAP-3600 2019
DarkSide-50 2018
XENON1T Ionization Signals 2019
LUX 2017
PANDAX-II 2017
DEAP-3600 proj.
XENON1T 2018
SuperCDMS proj.
DarkSide-LM proj.
1t year exposure
LZ proj.
XENONnT proj.
DarkSide-20K 200t×yr proj.
DARWIN 200t×yr proj.
Argo 3000t×yr proj.
Neutrino floor on xenon

Conclusion

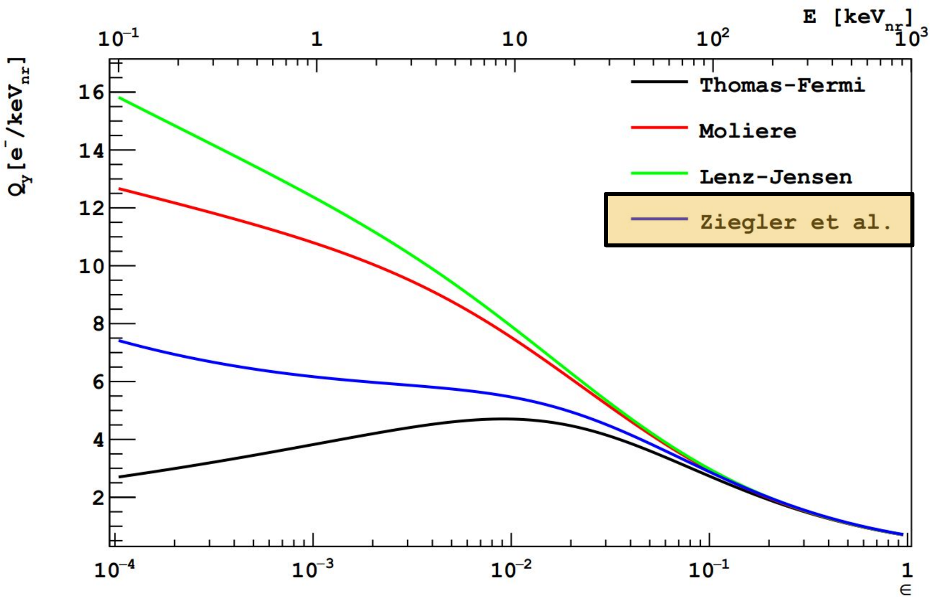
DarkSide collaboration has demonstrated the excellent sensitivity of LAr TPC in low mass dark matter search using S2-only signals.

There is a great potential to design and propose a dedicated LAr TPC experiment looking for dark matter in this low mass regime.

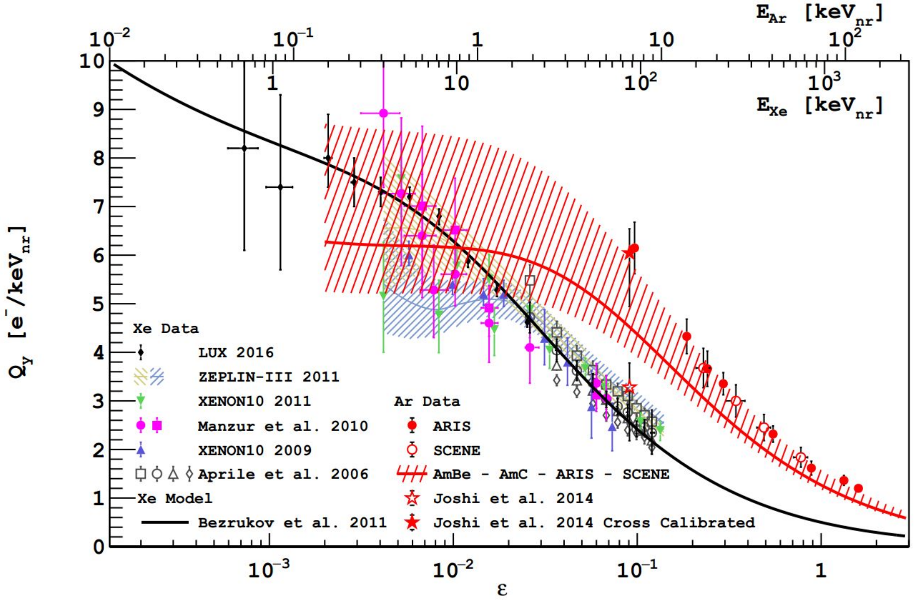
Thanks for your attention!

Backups

Choice of model on NR charge yield



Reproduce of F. Bezrukov et al, Fig 6 down to lower energy.
Different curves shows different model of nuclear stopping power. Ziegler et al. is prefered.



Xe model updated with new fitting including LUX 2016 data points.
Ar data and model plotted on top.

Shape of 1 GeV WIPM S2 Spectrum With Different Fluctuation Model