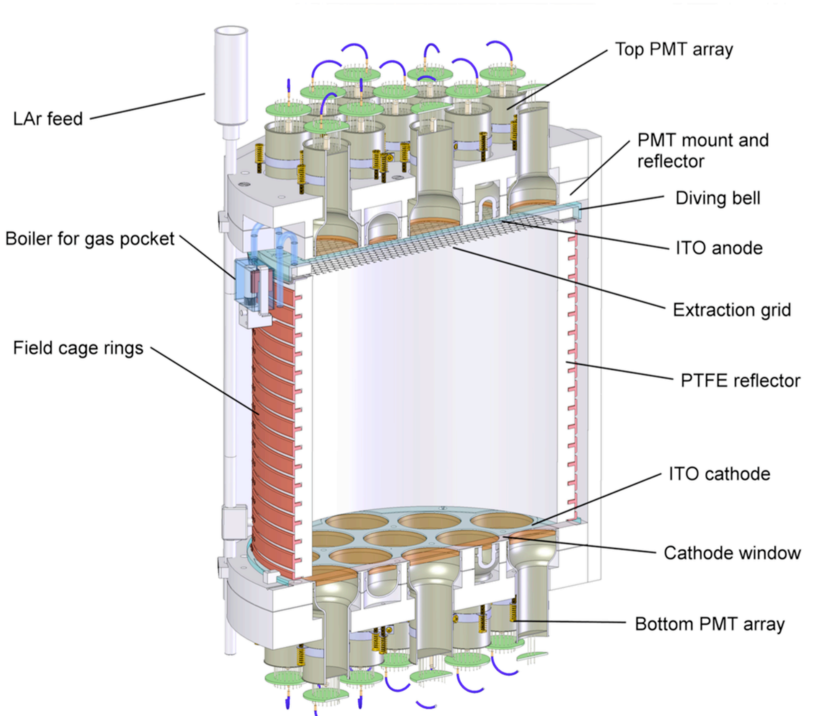
Latest DarkSide Results

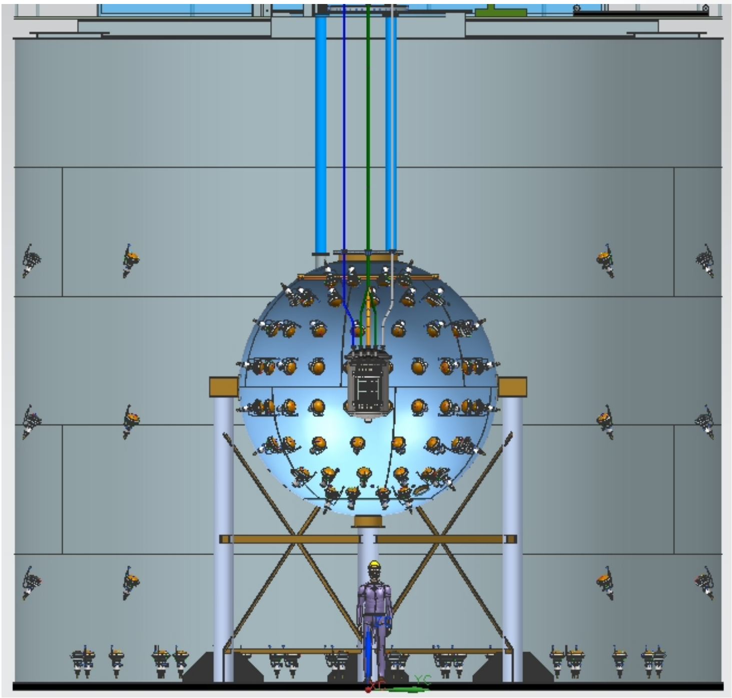
Marco Rescigno INFN/Roma1
For the DarkSide collaboration

Outline

- DarkSide-50 (DS50) detector concept
- Recent results:
  - Blind analysis of 532 live days of Underground Argon data (S1+S2), target high mass WIMP
  - Low mass DM searches interactive through electron or nuclear recoils with a ionization only measurement (S2-only)
- Future DarkSide program:
  - DS-proto
  - DarkSide-20k
- Conclusions

DarkSide-50





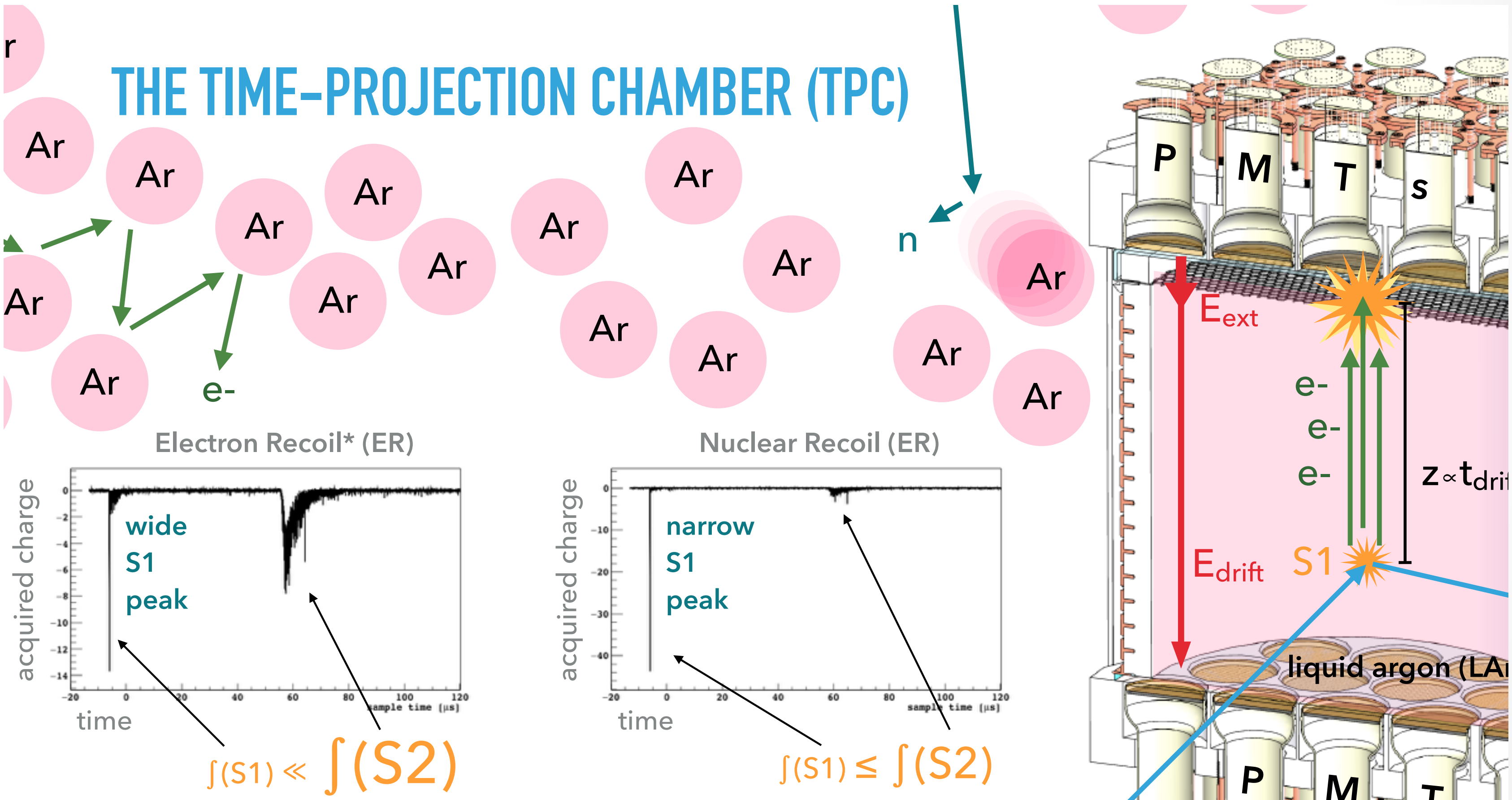
35.6 height diameter x 35.6 cm height TPC
46.4 Kg of Active Liquid Argon

Filled with Low Radioactivity Argon (150 Kg total) tapped from underground $C0_2$ wells in Cortez, CO (UAr)

Viewed by 38 Hamamatsu R11065 PMT

1,000 tonnes of ultrapure water instrumented with 80 photomultiplier tubes as Cherenkov veto for cosmic rays.
4-m diameter liquid scintillator sphere equipped with 120 photomultiplier tubes as a high-efficiency neutron veto.

Two Phase (LAr) TPC

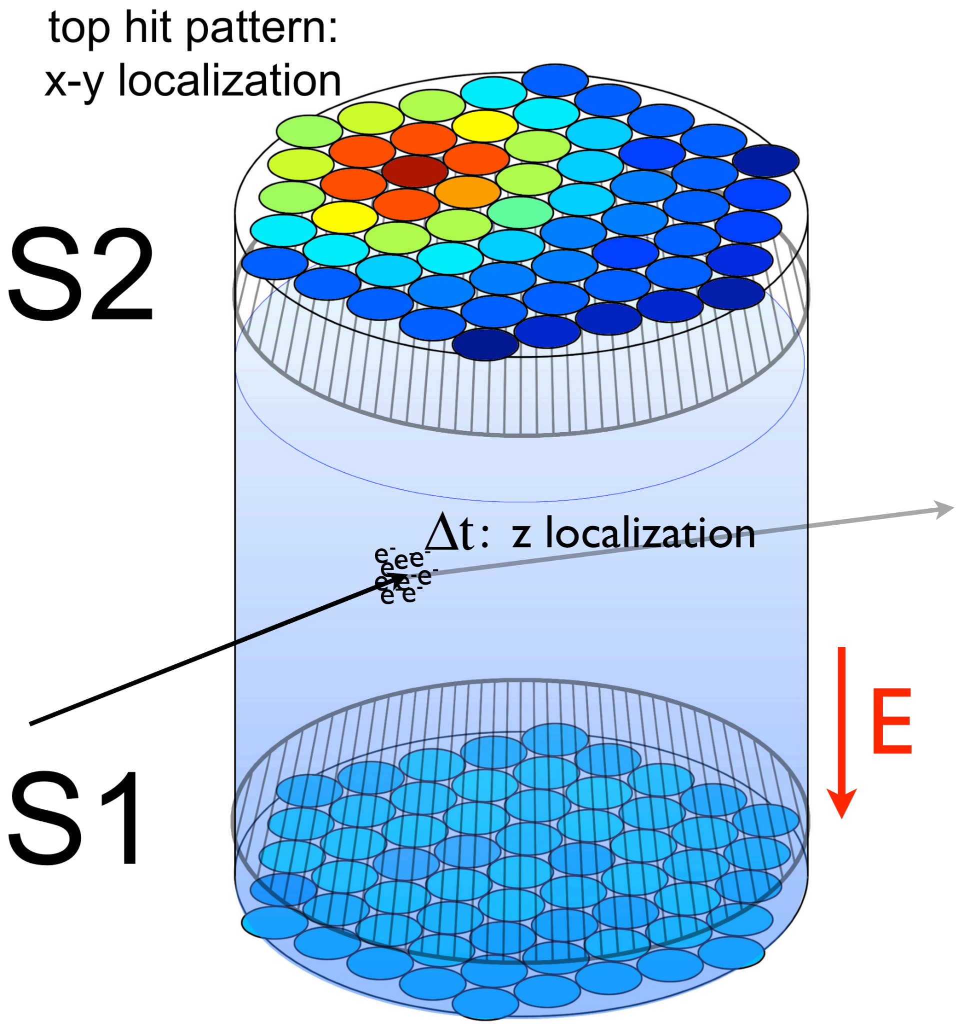


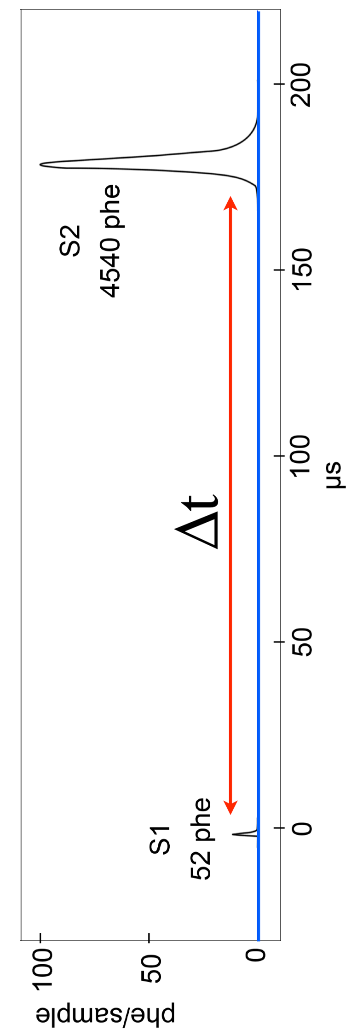
S2/S1 ratio and Pulse Shape Discrimination (PSD)
WIMPs are nuclear recoils

Two Phase-TPC fiducialization method

Dual phase TPC allow precision fiducialization in Z (mm resolution) if both S1 and S2 is measured

Only x-y fiducialization possible for analysis relying only on S2 signal

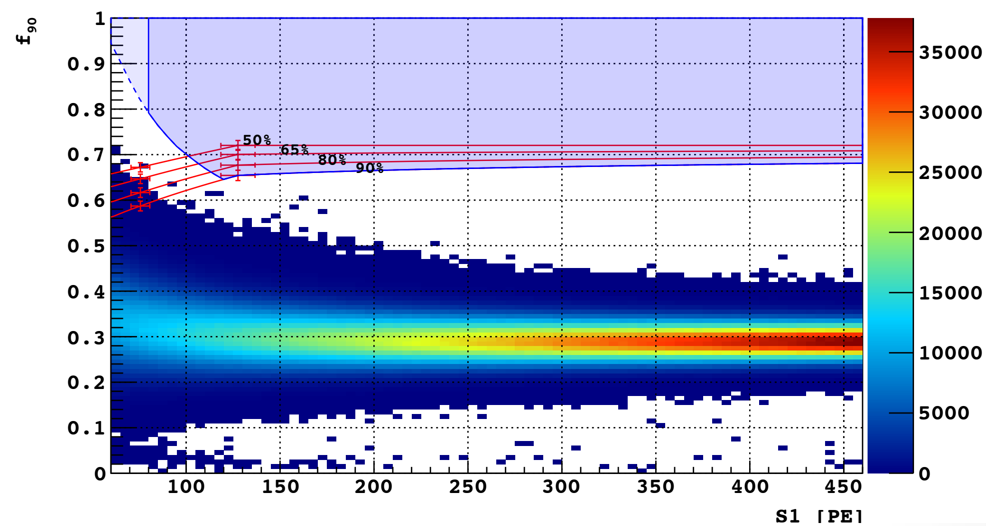


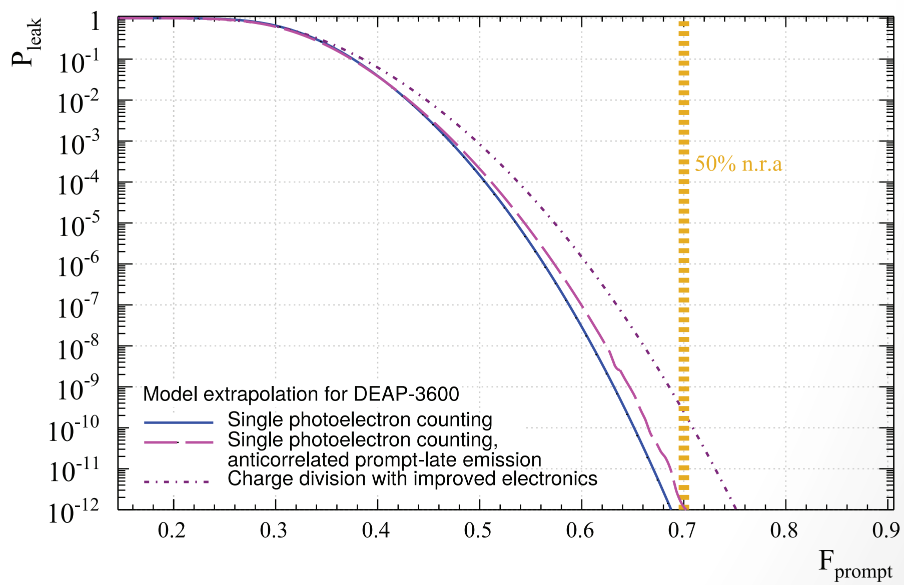


ER rejection using PSD in LAr

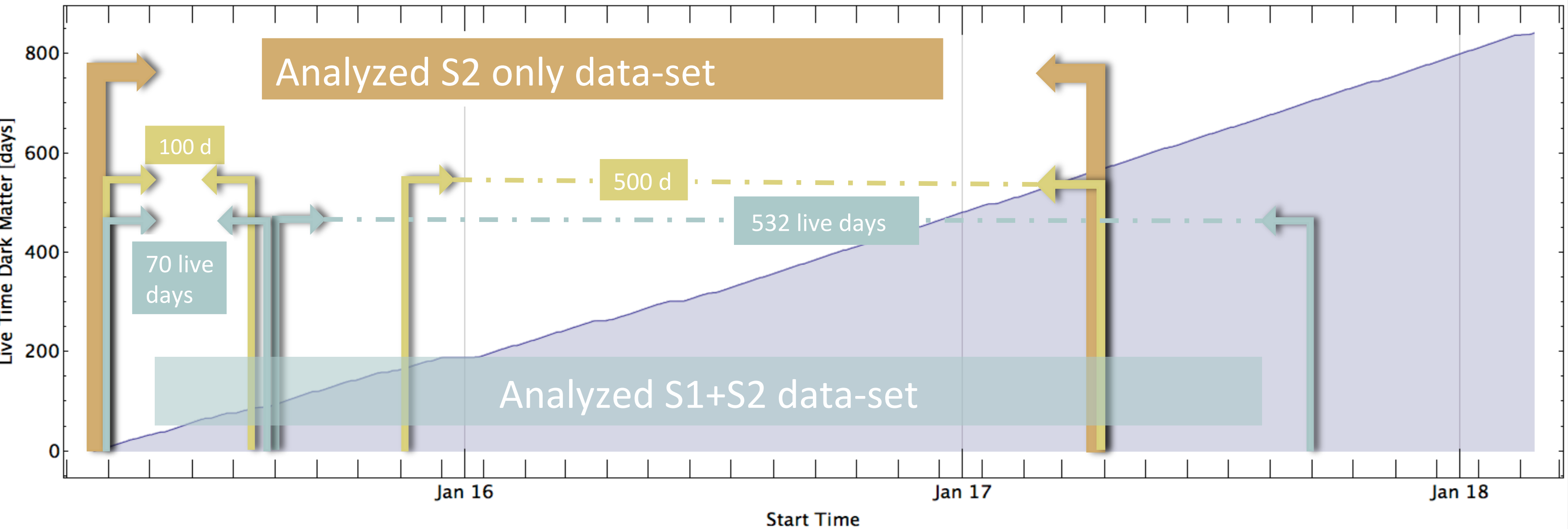
- Bkg rejection in LAr based on S1 pulse shape
- Light emitted from Ar2+ dimers triplet 103 times slower than singlet.
- Triplet vs singlet excitation depends on particle type
- Bkg rejection $>10^7$ reached in DS50 with atmospheric argon target
- DEAP-3600 projects $>10^{10}$ rejection

- Xenon bkg rejection based on S2/S1 ratio, limited to few 10^3





DS50 UAr data set (>800 life days)



PRD 93, 081101(R) (2016)

arxiv:1802.06994

arxiv:1802.06998

arxiv:1802.07198

PHYSICAL REVIEW D 93, 081101(R) (2016)

Results from the first use of low radioactivity argon in a dark matter search

Low-mass Dark Matter Search with the DarkSide-50 Experiment

Constraints on Sub-GeV Dark Matter-Electron Scattering from the DarkSide-50 Experiment

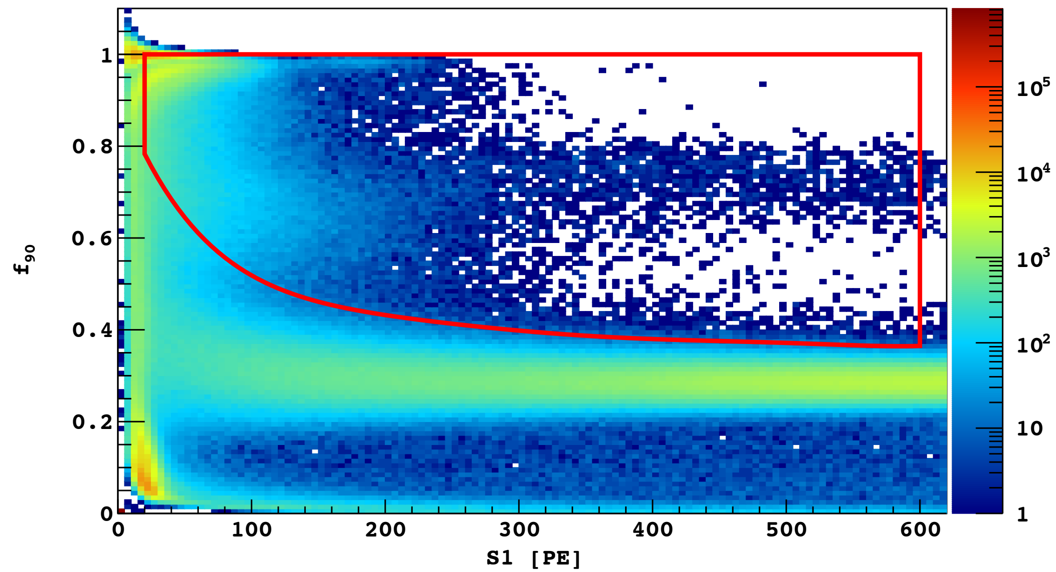
DarkSide-50 532-day Dark Matter Search with Low-Radioactivity Argon

S1+S2 ANALYSIS

First blind analysis of UAr data

arxiv:1802.07198

Initial blind region shown with data from the first UAr publication: PRD 93, 081101(R) (2016)

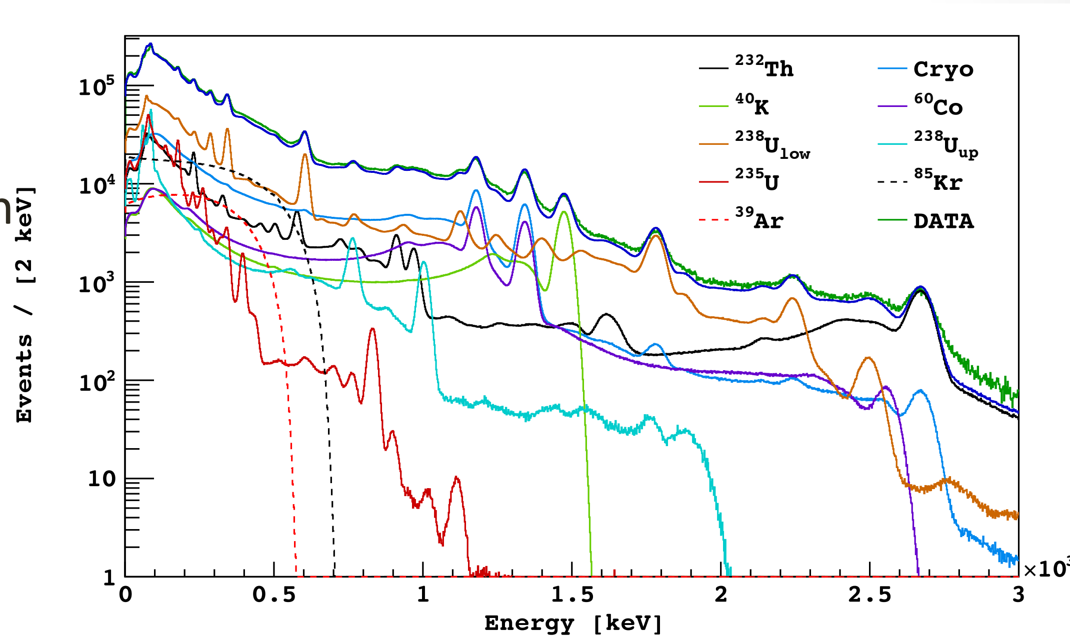


- Design of an analysis delivering a signal region with less than 0.1 bkg events expected
  - Use data driven measurement and methods to identify and reduce background sources
  - First use of radial fiducialization in addition to the usual in Z
  - Extensive external sources campaign to calibrate detector response and efficiencies

DS50 Background modeling

arxiv:1802.07198

- ^{39}Ar emits β^-
- Activity in atmospheric Argon ~1 Bq/Kg
- Reduced by a factor 1400 using Argon from underground sources
- ^{85}Kr also found in the tapped source



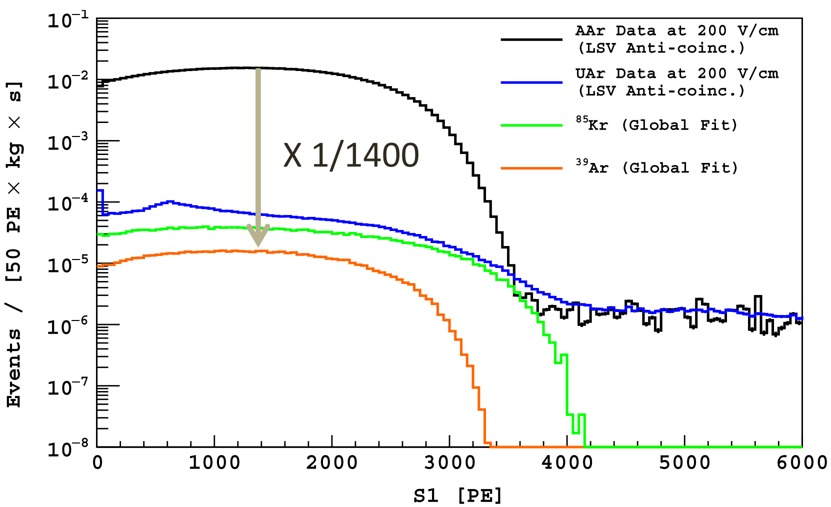


TABLE I. TPC component activities, estimated by fitting $^{232}Th_{PMT}$, $^{238}U^{lower}_{PMT}$, $^{40}K_{PMT}$, and $^{60}Co_{PMT}$ in sequence, followed by $^{235}U_{PMT}$, $^{238}U^{upper}_{PMT}$ while ^{85}Kr and ^{39}Ar are fixed at their measured rates as reported in [15]. Cryostat activities ($_c$) are summed across all cryostat locations, and fixed at their respective measured rates from assays. PMT activities ($_p$) are summed across all PMT locations, and across all 38 tubes.

Source	Activity [Bq]	Source	Activity [Bq]
$^{232}Th_p$	0.277±0.005	$^{232}Th_c$	0.19±0.04
$^{40}K_p$	2.74±0.06	$^{40}K_c$	$0.16^{+0.02}_{-0.05}$
$^{60}Co_p$	0.15±0.02	$^{60}Co_c$	1.4±0.1
$^{238}U^{low}_p$	0.84±0.03	$^{238}U^{low}_c$	$0.378^{+0.04}_{-0.1}$
$^{238}U^{up}_p$	4.2±0.6	$^{238}U^{up}_c$	$1.3^{+0.2}_{-0.6}$
$^{235}U_p$	0.19±0.02	$^{235}U_c$	$0.045^{+0.007}_{-0.02}$
^{85}Kr	1.9±0.1 mBq/kg	^{39}Ar	0.7±0.1 mBq/kg

Blind Analysis/Neutron bkg

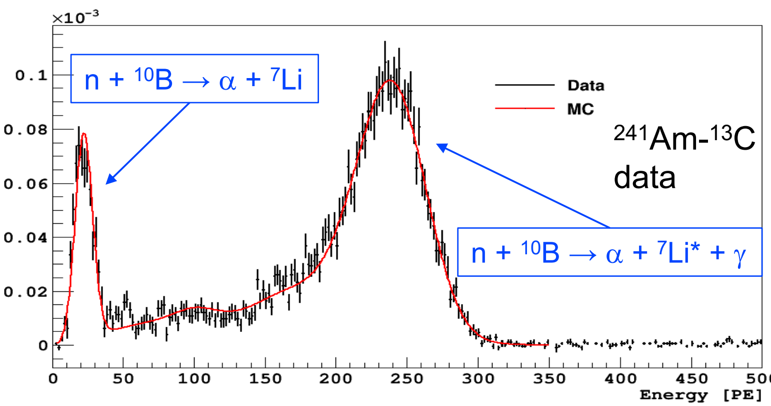
arxiv:1802.07198

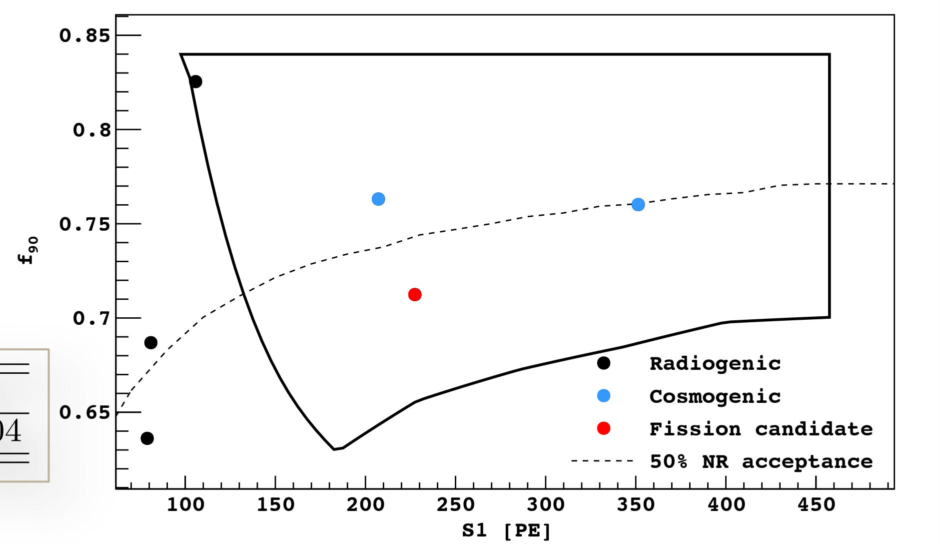
Neutron veto cuts:

- Prompt: 1PE in [-50,250] ns of the TPC S1 trigger
- Delayed: 6PE in 500 ns sliding window in [0,185] μs of the TPC trigger

Prompt cut only	Delayed cut only	Combined
0.9927 ± 0.0005	0.9958 ± 0.0004	0.9964 ± 0.0004

- Neutron Veto efficiency from AmC / AmBe calibrations

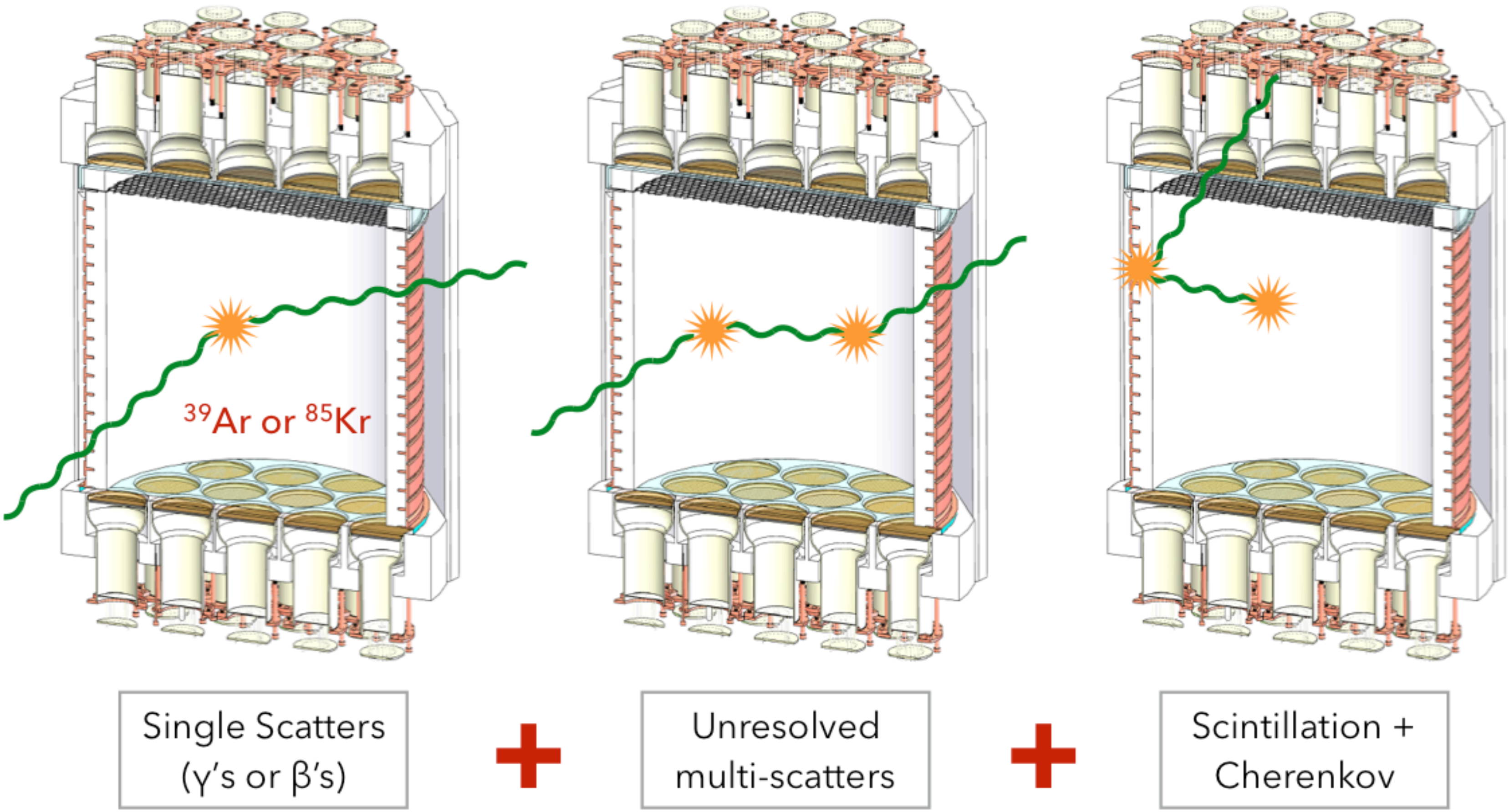




- VETO PROMPT TAG (pass all cuts but fail veto prompt selection) sample with neutrons identified by the late coincidence
- Only 1 neutron consistent with radiogenic origin
- Scale 1 event with data driven efficiency to estimate final neutron background

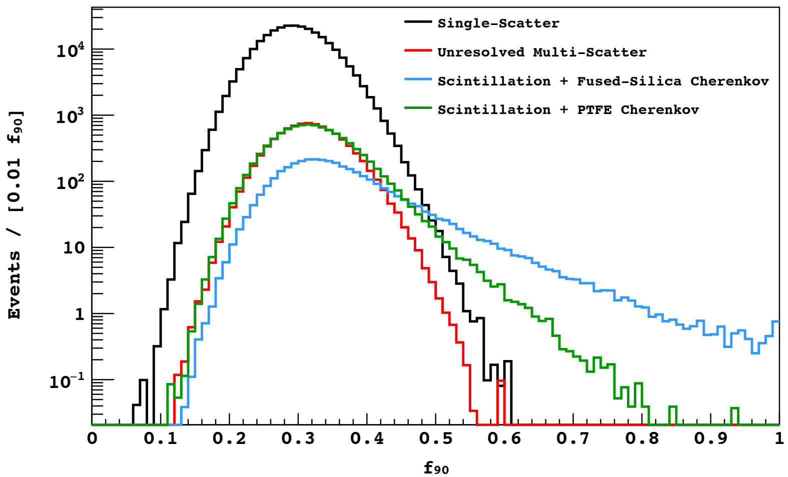
Blind analysis/ER+Cherenkov

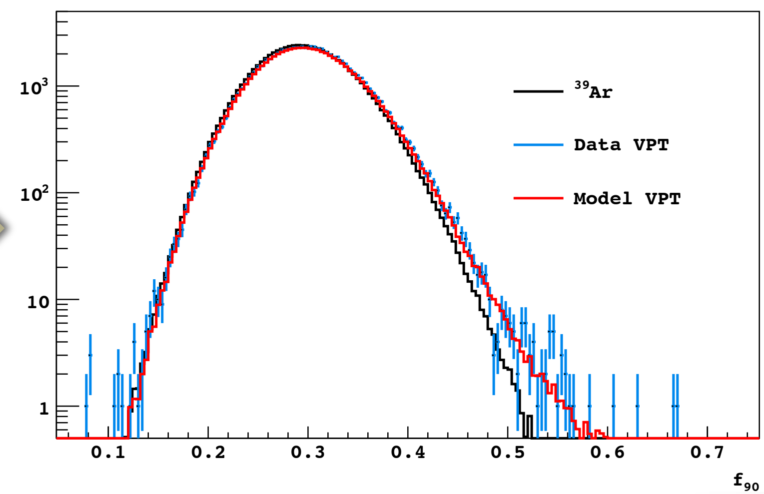
arxiv:1802.07198



Blind analysis/ER+Cherenkov

arxiv:1802.07198

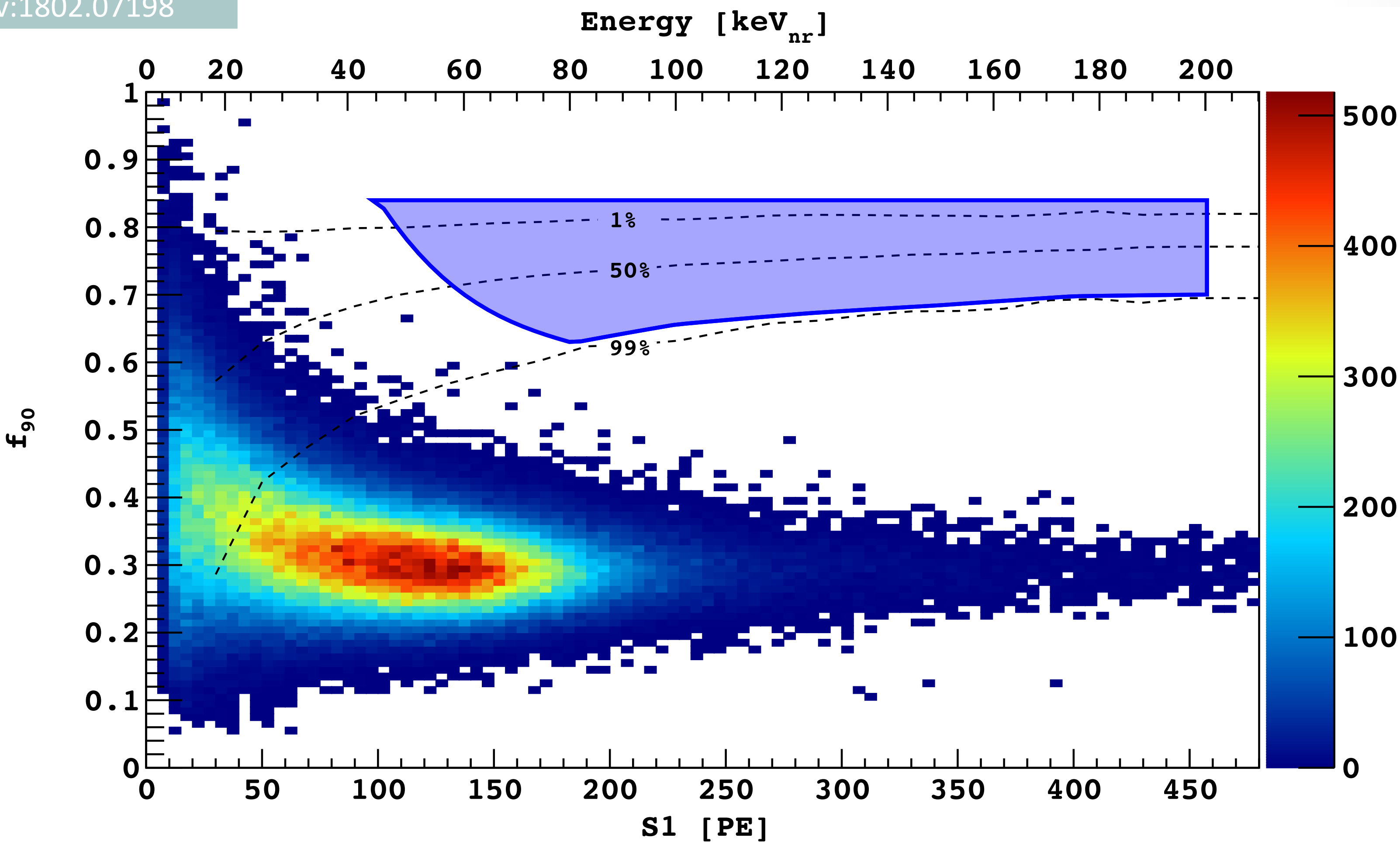




Making an hybrid model using Ar39 data (model pure ER) + Cherenkov light in PTFE and Fused Silica (simulation)
Check rate and shape with a background enhanced sample from Na22 source
Final check/normalization in VETO PROMPT TAG sample

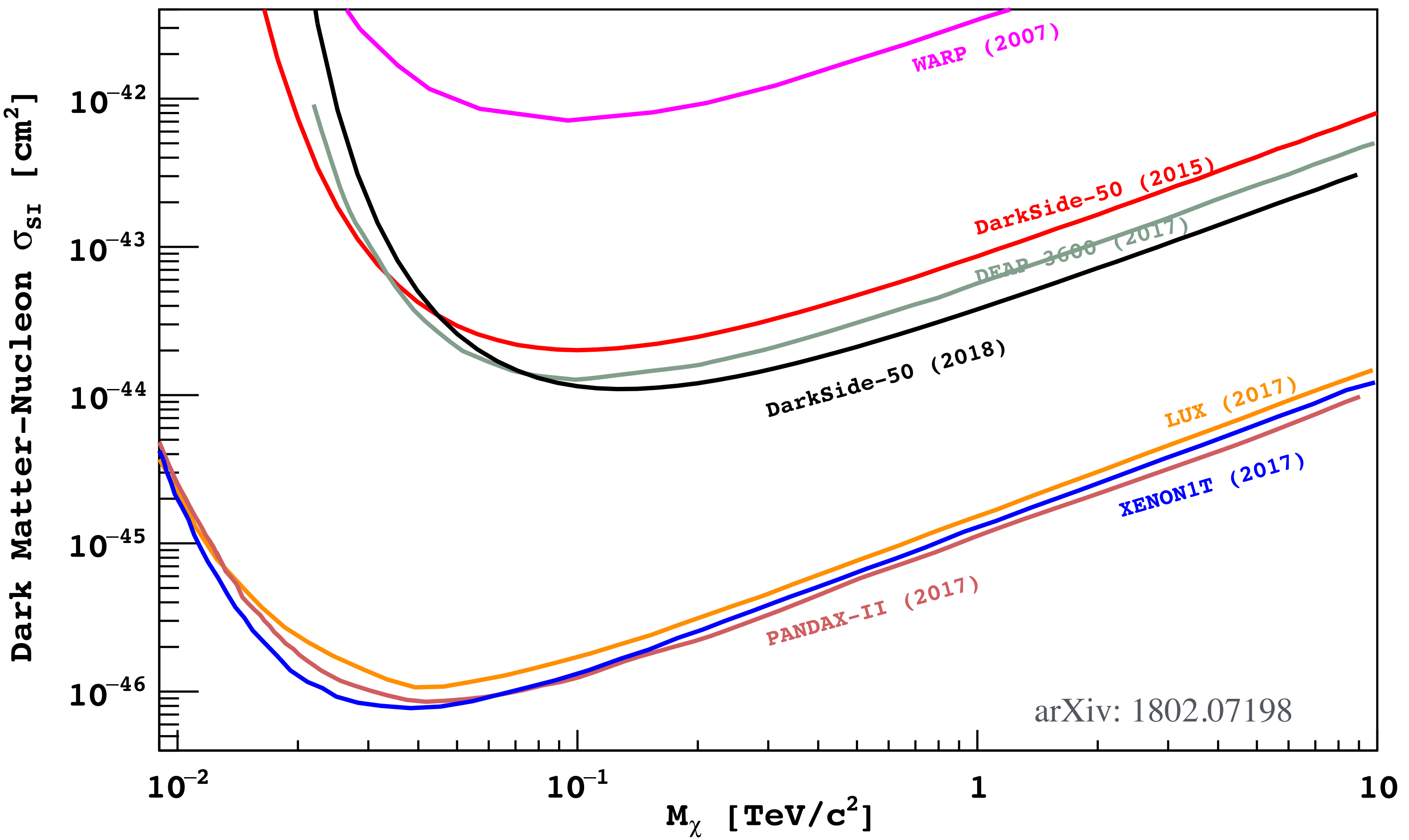
Blind analysis/unblinded data

arxiv:1802.07198



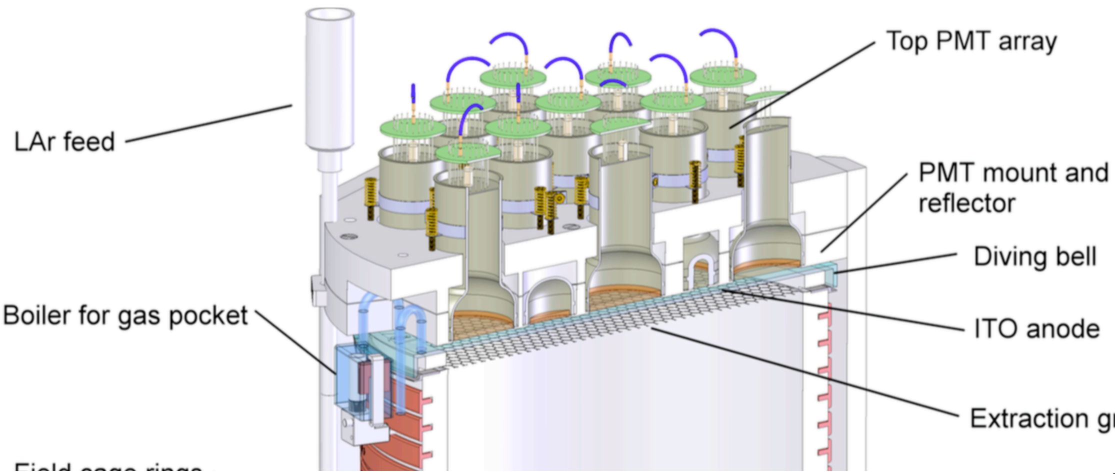
Blind analysis/results

arxiv:1802.07198



S2-ONLY ANALYSIS

S2-only/S2 Pulse Shape



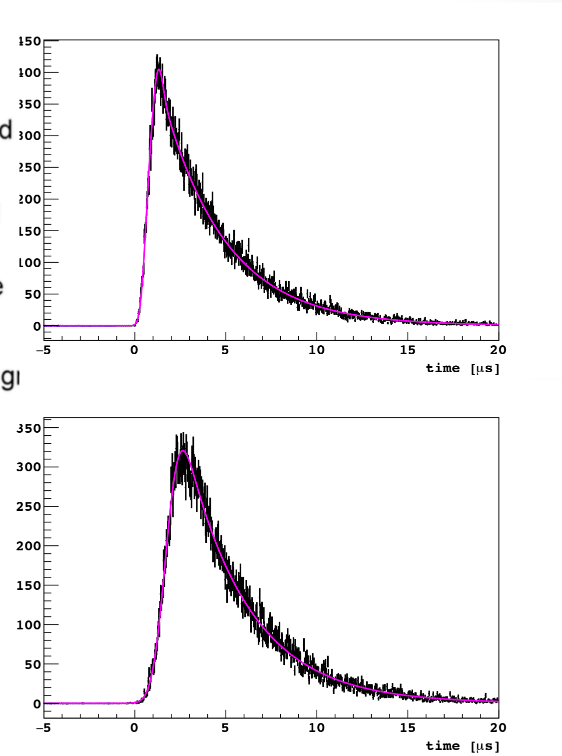


FIG. 8: Examples of S2 pulse shape fits for the electron diffusion measurement. Left: Event with a 22 μs drift time. Right: Event with a 331 μs drift time. The waveforms have been re-binned to 32 ns sampling, and the x-axes redefined such that $t = 0$ is at the S2 start.

Electrons extracted from the liquid and accelerated through a ~6 mm gas volume.

Proportional emission of VUV photons amplify signal.

Rise-time is influenced by diffusion of the charge cloud in the liquid and transit time through the gas

Decay constant of light in gaseous Argon different then in liquid (τ_{slow}~3.2 us)

→ Slow signal !

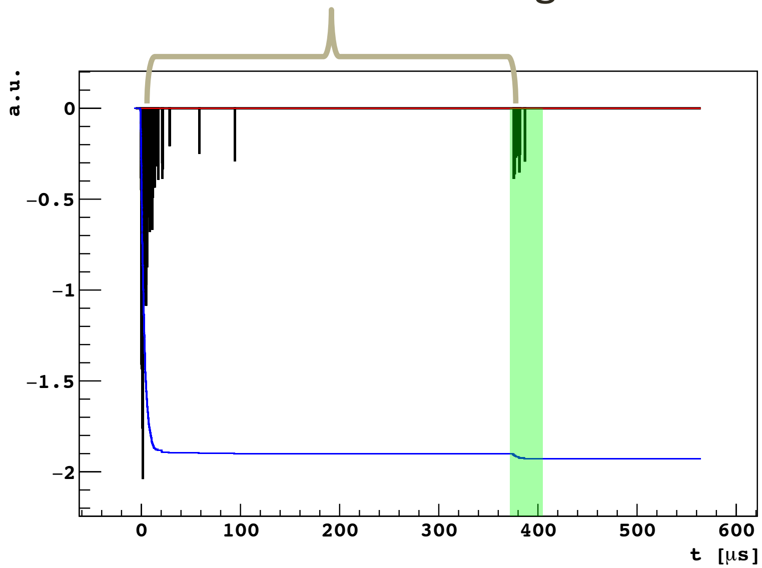
We are looking for very small excitations!

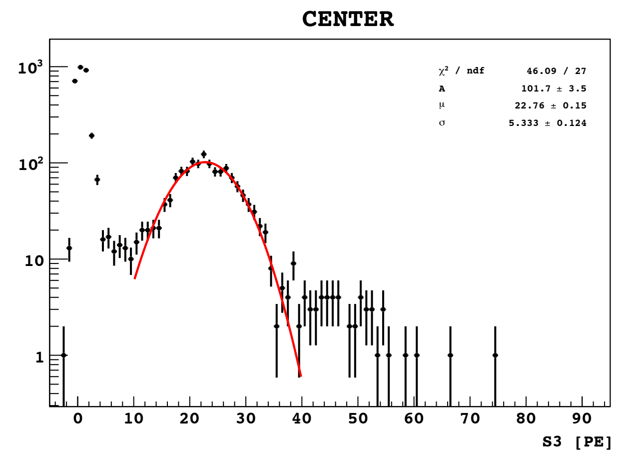
arXiv: 1802.01427

S2-only/ S2 PE per extracted e⁻ from S2 echoes

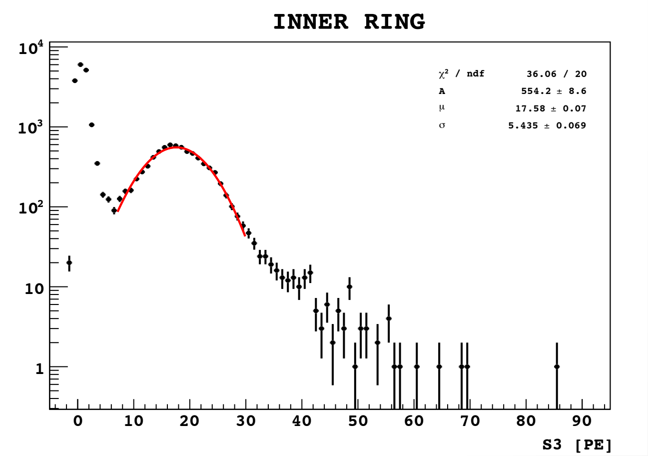
Luca Pagani's Phd thesis:
[fermilab-thesis-2017-11]

380 us = max drift length





(a)

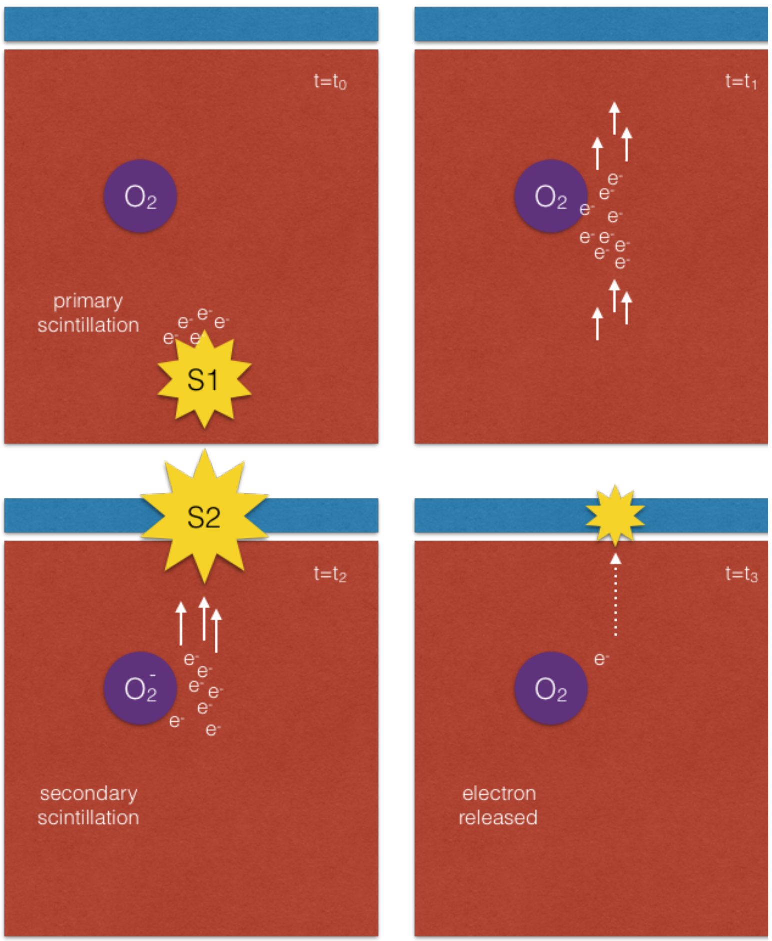


(b)

Single electron extracted from the cathode by S2 VUV photon (S2 echoes):

Det. zone	ε_2^{1e} [PE/e]	$\langle\kappa\rangle$	ε_2^{1e} (corr) [PE/e]
CENTER	22.76 ± 0.15	0.94	24.2 ± 0.2
INNER RING	15.58 ± 0.07	0.70	25.2 ± 0.1

S2-only/ S2 PE per extracted e$^-$ from impurities

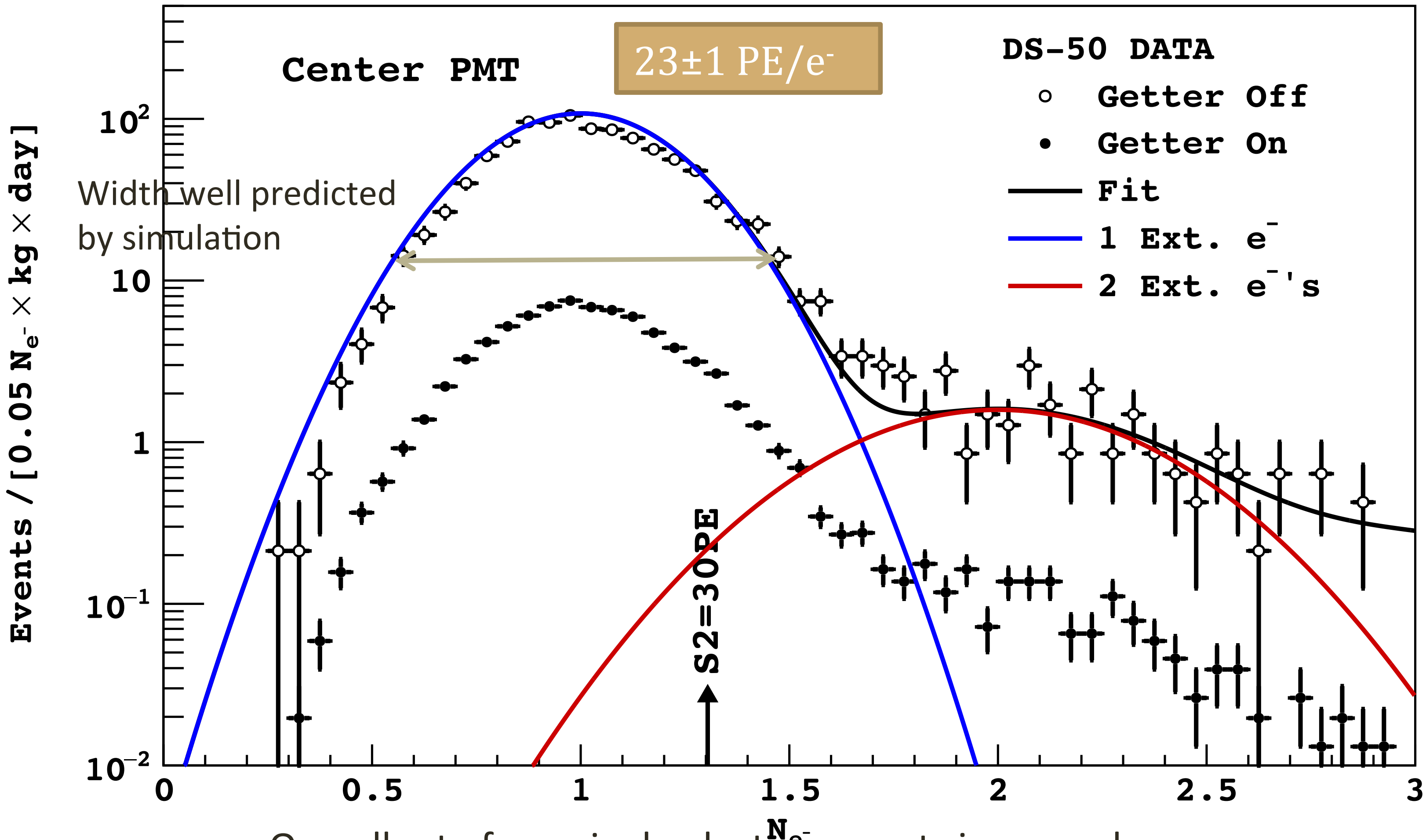


Cartoon from Luca Pagani's Phd thesis: fermilab-thesis-2017-11

- Electronegative molecules (e.g. O_2, H_20), might be present at the ppb levels in LAr
- Ionization electrons might attach to impurities during drift and later be released with time scales of O(10 ms)
- Signals are time/spatially correlated with preceding ionization events
- Rate increased significantly during the several days where filter (getter) was excluded from the Argon circulation due to servicing

S2-only/ S2 PE per extracted e$^-$ from impurities

arxiv:1802.06994



Overall rate from single electron events in normal condition: 0.5 x 10^{-5} e$^-$/e$^-$ (x 10 with getter off)

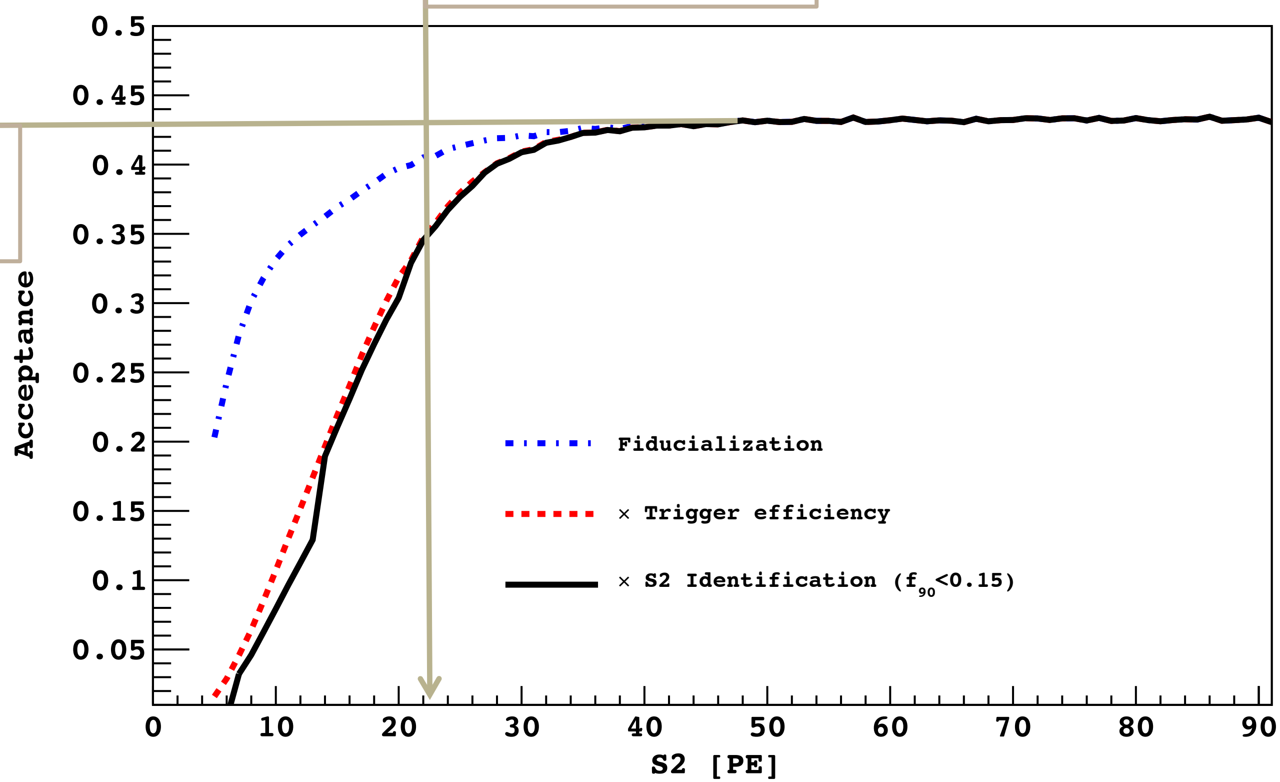
S2-only/Detection Threshold

arxiv:1802.06994

Sensitive to 1 e^- !

Fid. Vol. 43%
~20 Kg

events within the inner circle of PMT

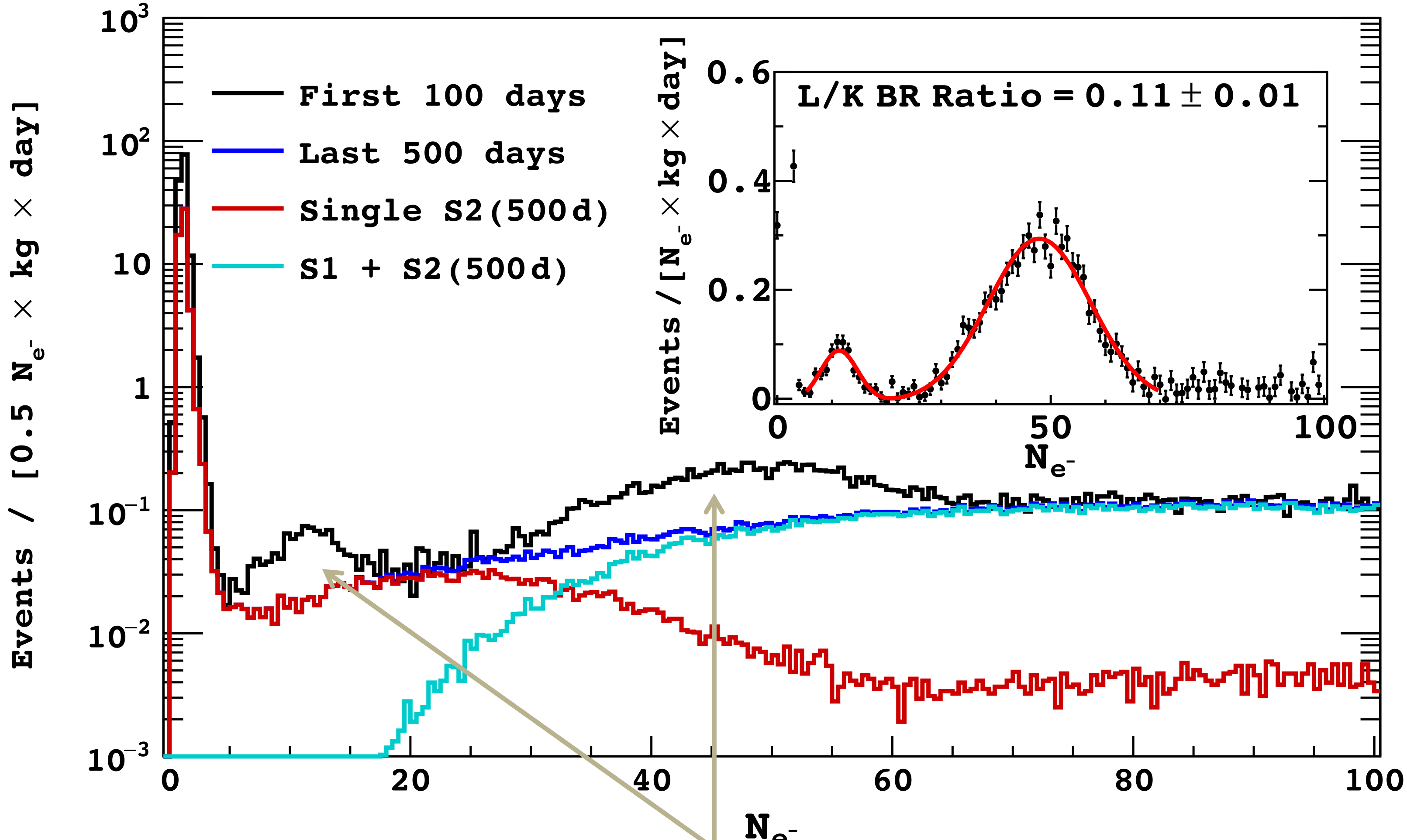


Trigger on two PMT hits (60% efficiency for single Photo-Electrons) in 100 ns :
reach 100% at ~30 PE (50% ~15 PE)

Extraction efficiency for ionization electrons >99.9 %
Software pulse finding efficiency 100% for S2>30 PE

S2-only/ER scale

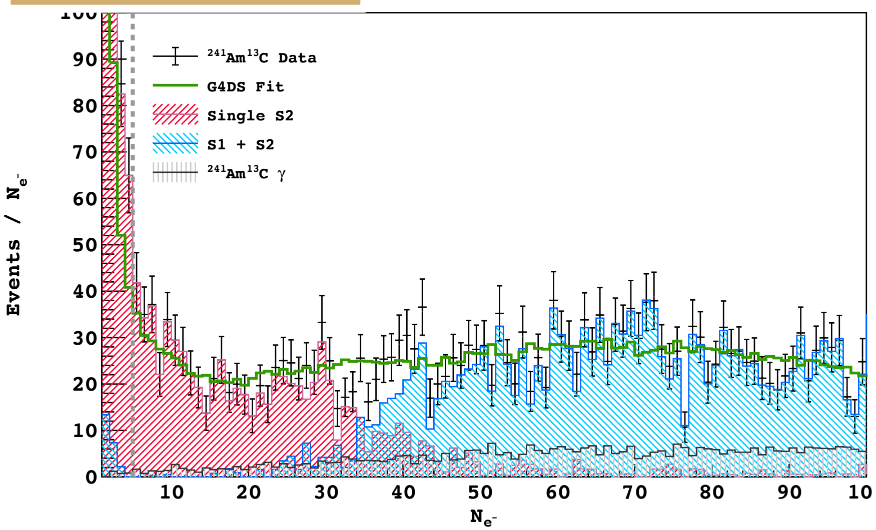
arxiv:1802.06994

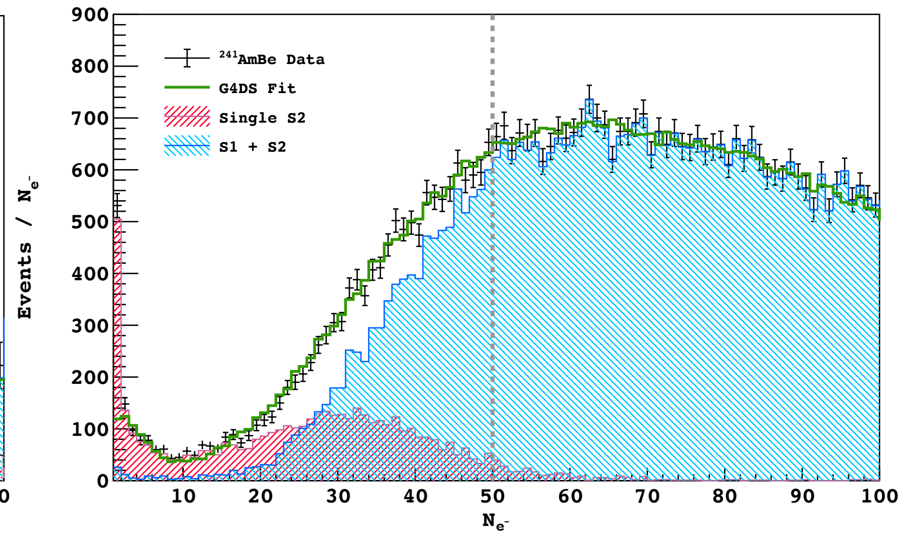


^{37}Ar from cosmic ray activation during UAr transport: 35 d $\tau_{1/2}$ to ^{37}Cl via electron capture

S2-only/NR scale (in situ)

arxiv:1802.06994





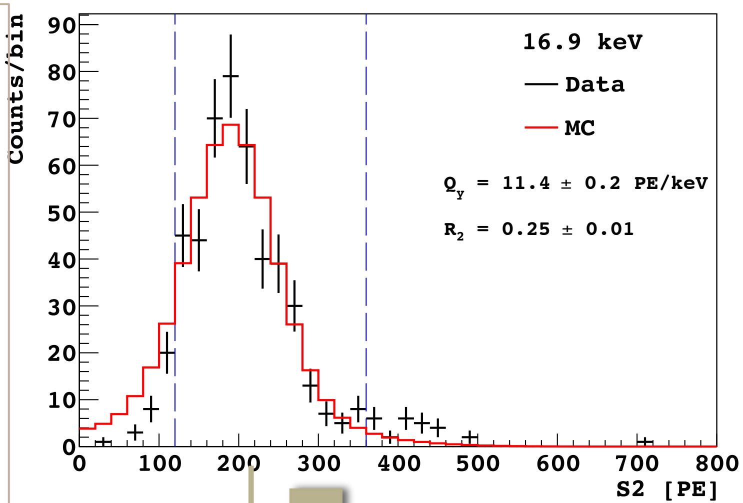
- In situ calibration with ^{241}Am^{13}C source
- Low rate source with little gamma activity
- Find NR scale by fitting simulated spectrum to data +bkg distribution
- Allow measure down to 4 Ne threshold

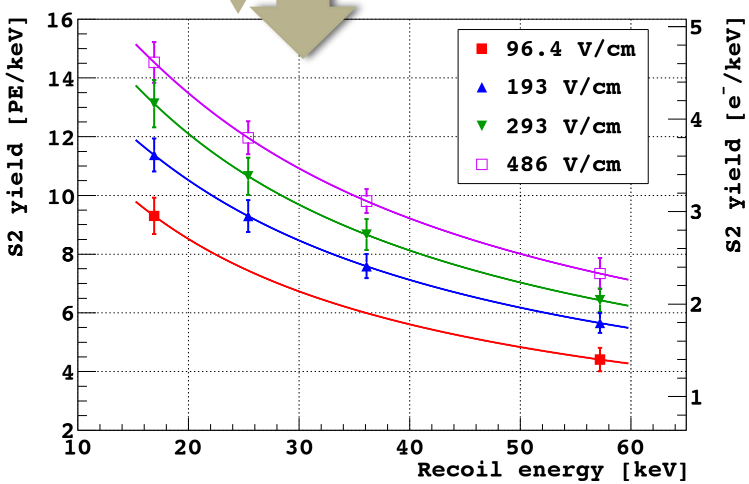
- In situ calibration with ^{241}AmBe source
- High rate source: neutrons produced with associated gamma
- Find NR scale by fitting simulated spectrum to data with 4.4 MeV γ in LSV detector
- Deep at low Ne due to LSV data available only for S1 triggers. Joint fit with AmC data for Ne>50

S2 only/NR scale (external)

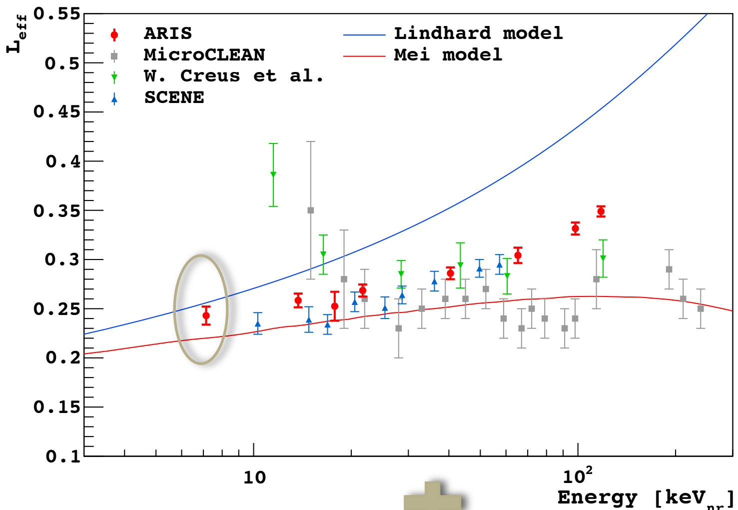
Phys. Rev. D 91, 092007 (2015)

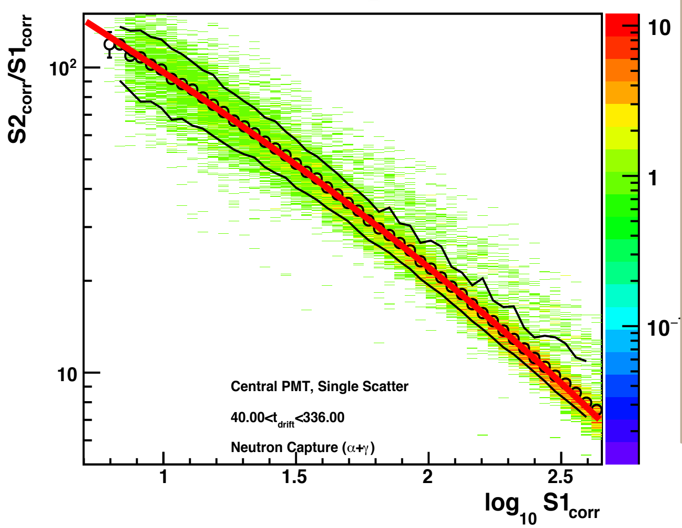
SCENE – Direct Measurement @~ 200 V/cm





arXiv:1801.06653

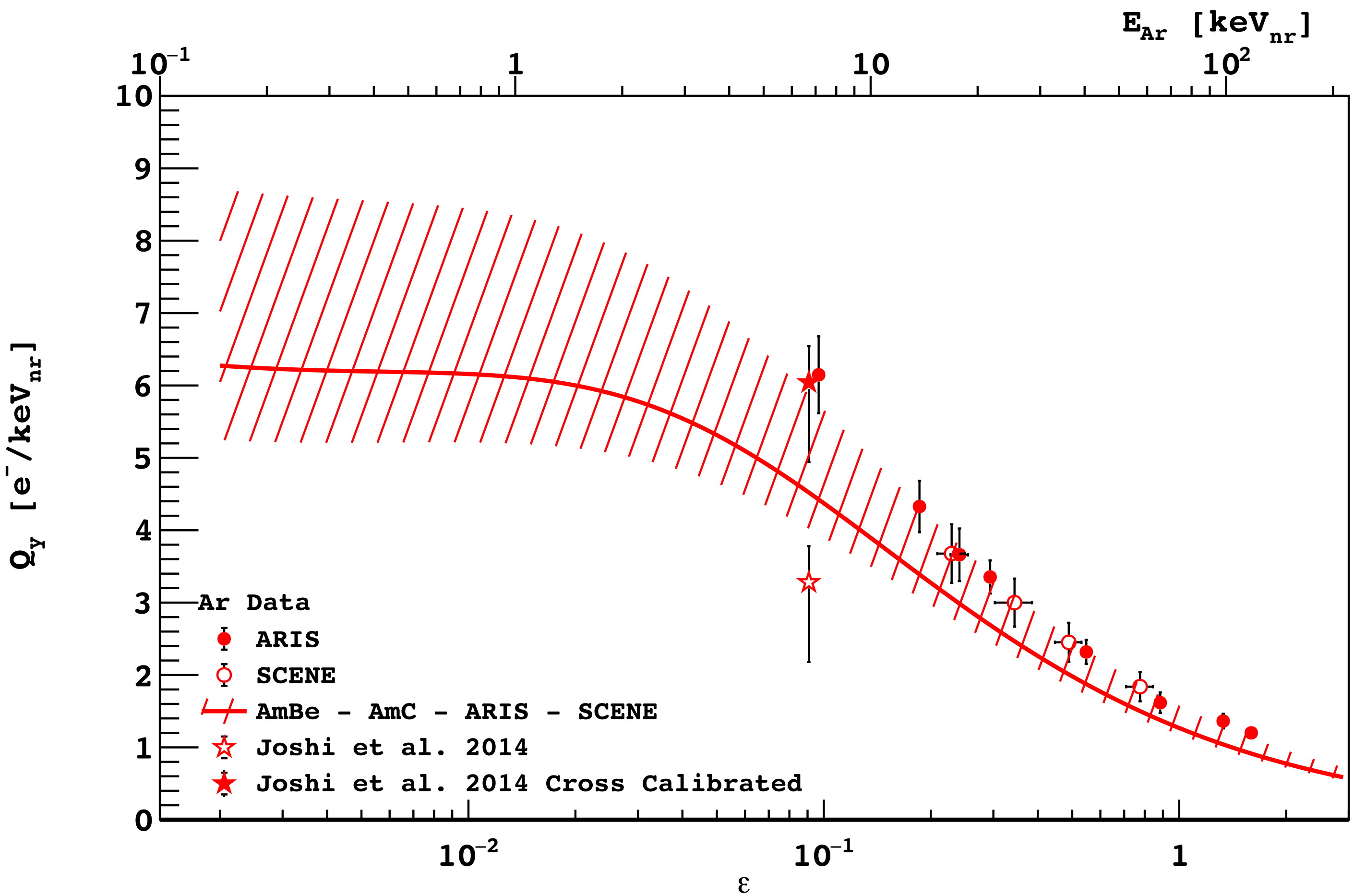




Aris - Measurement of L_{eff} down to 7.1 keVnr + AmBe S2 vs S1 to provide Qy

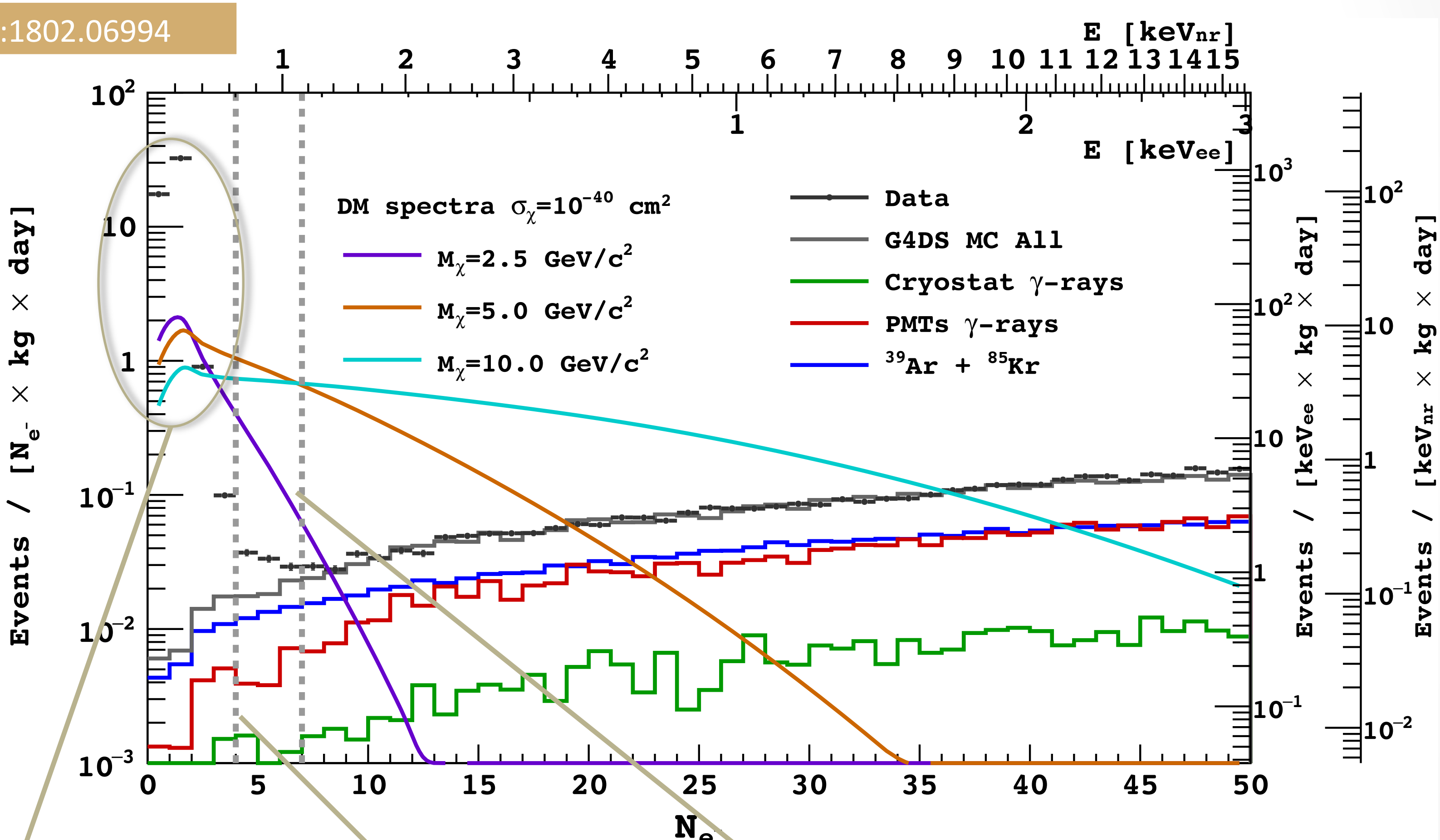
S2-only/ NR scale

arxiv:1802.06994



S2-only/ Ne spetrum

arxiv:1802.06994

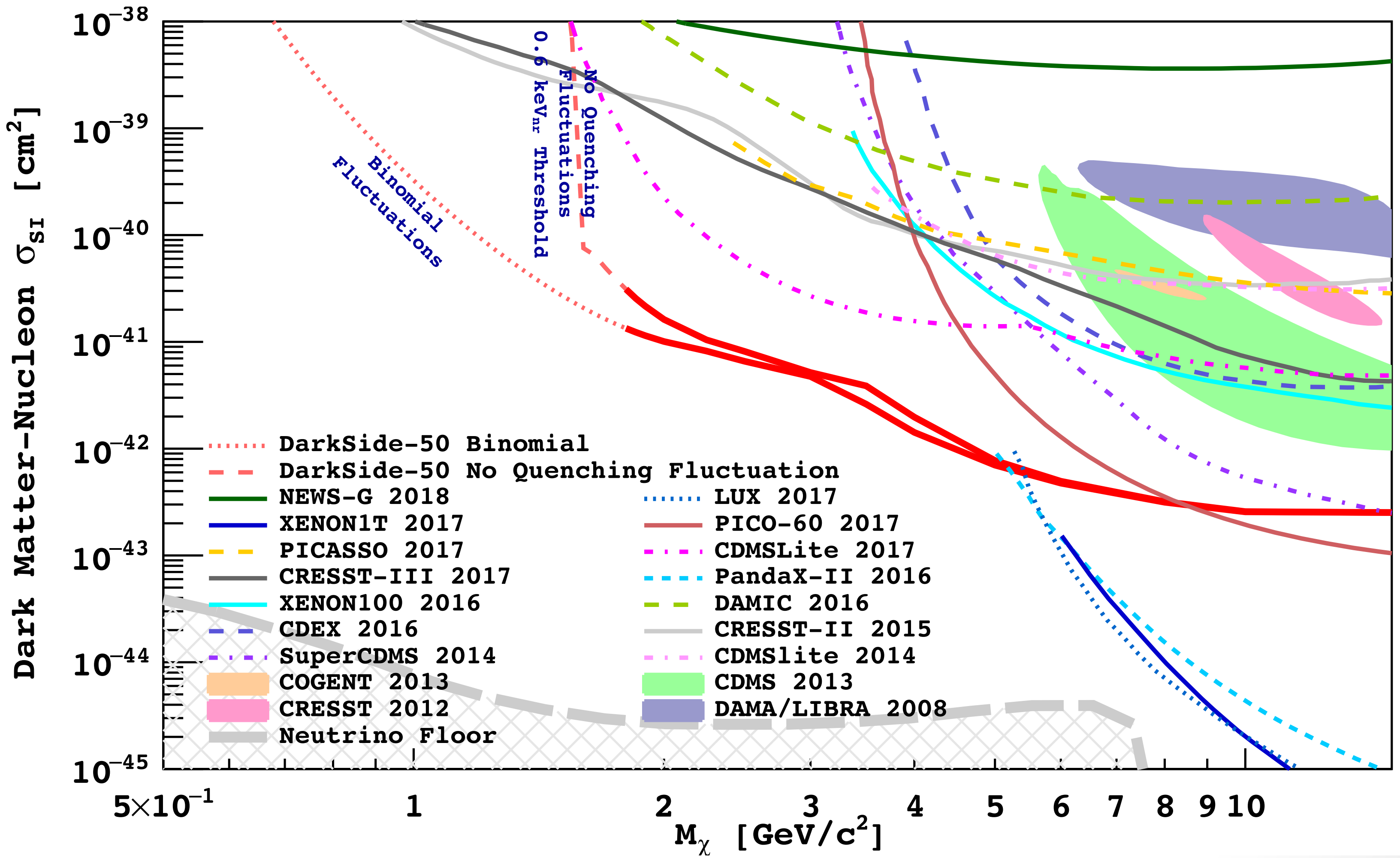


Single electron peak

Analysis Threshold: 4e⁻ ~ 100 eVee / 7e⁻ ~ 170 eVee
600 eVnr/ 1.1 keVnr

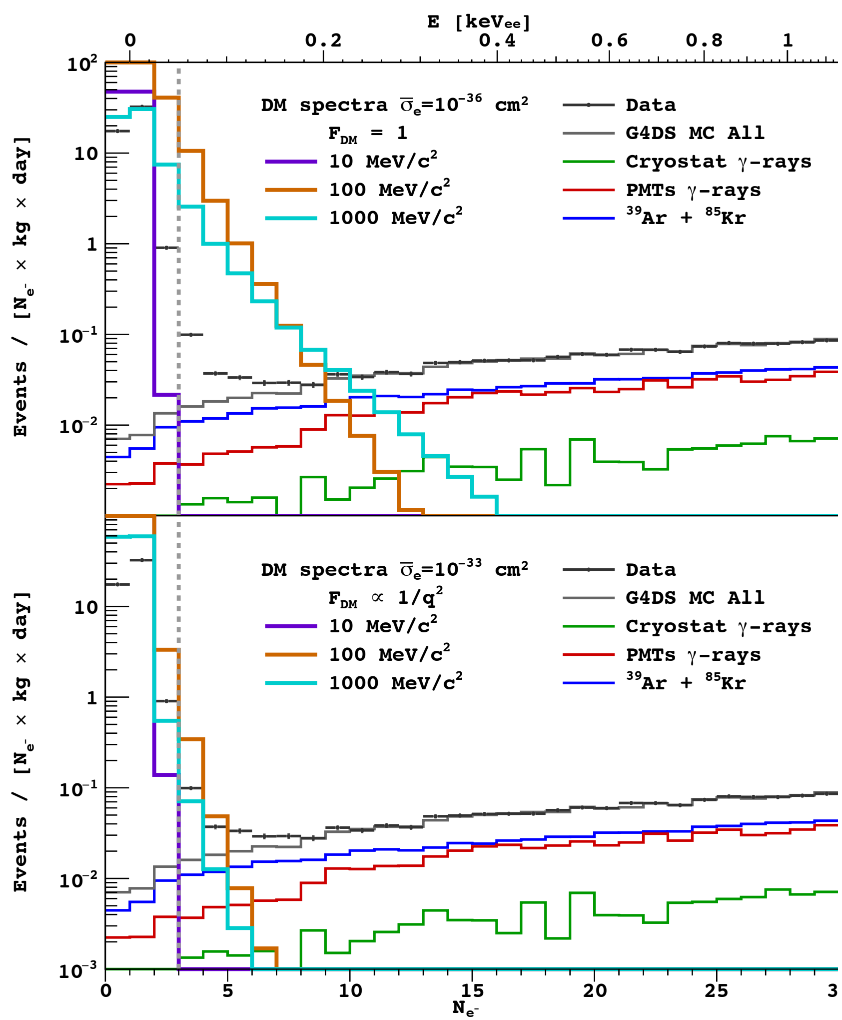
S2-only/ Result

arxiv:1802.06994



Sub GeV DM interacting with e⁻

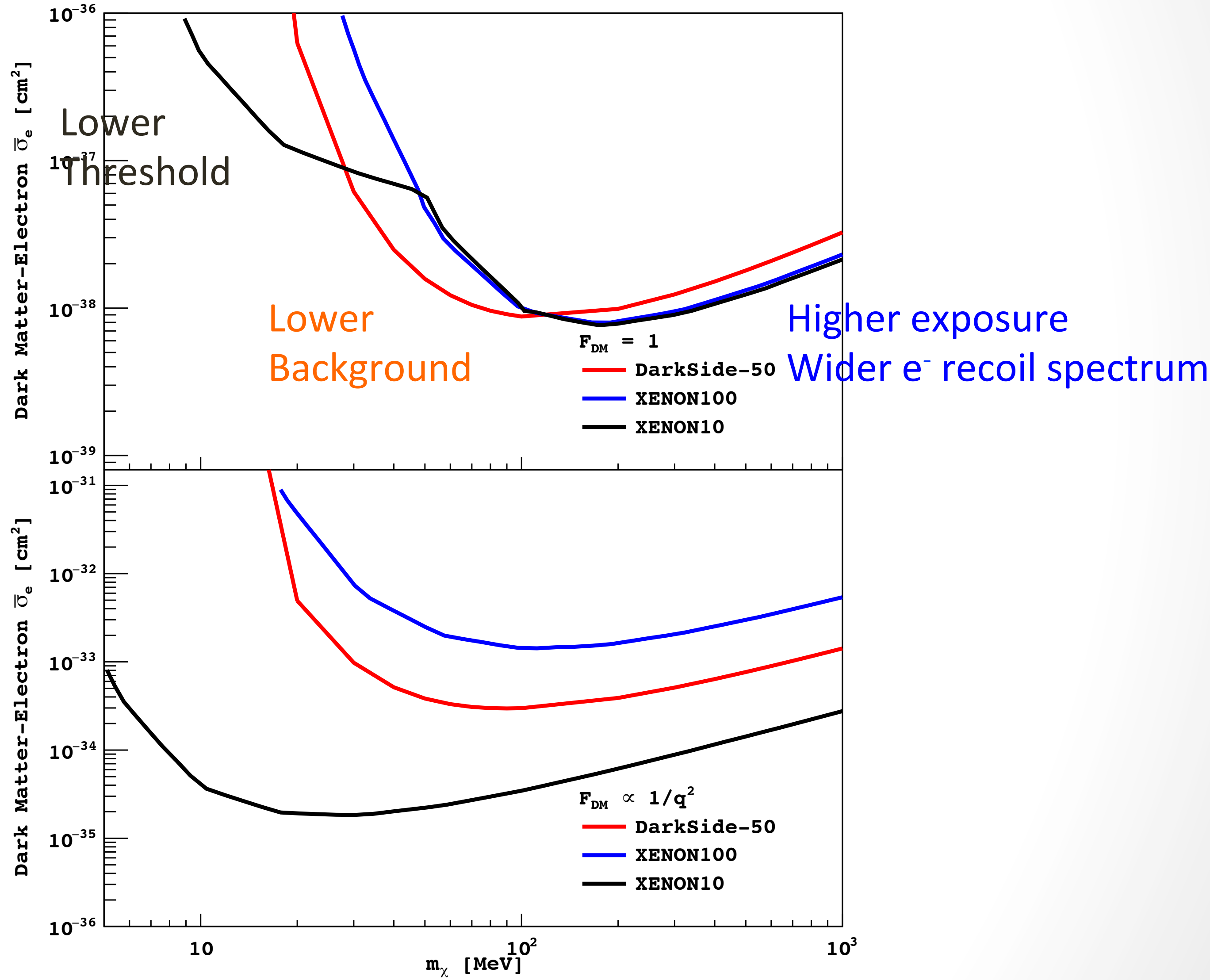
arxiv:1802.06998



- Interpretation of the same spectrum in the context of DM coupled to light mediators. Masses below 1 GeV of interest
- Generally have couplings to electrons → easier to detect
- Require evaluation of atomic physics effects for the exact orbitals of the target material. First calculation for Argon in this paper (M.Lisanti et al.)
- Two kinds of form factors generally employed:
  - Constant (high mass mediator - top)
  - $\alpha m_e/q^2$ (low mass mediator - bottom)

Sub GeV DM interacting with e^-

arxiv:1802.06998

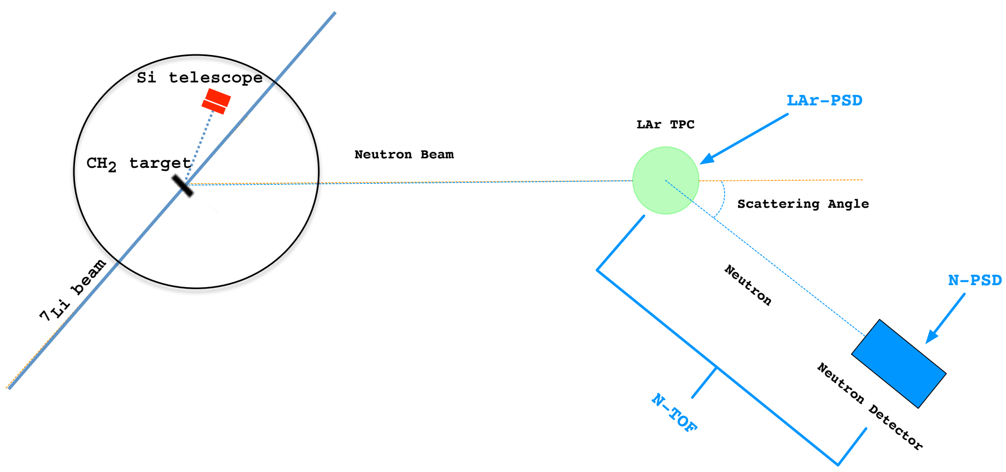


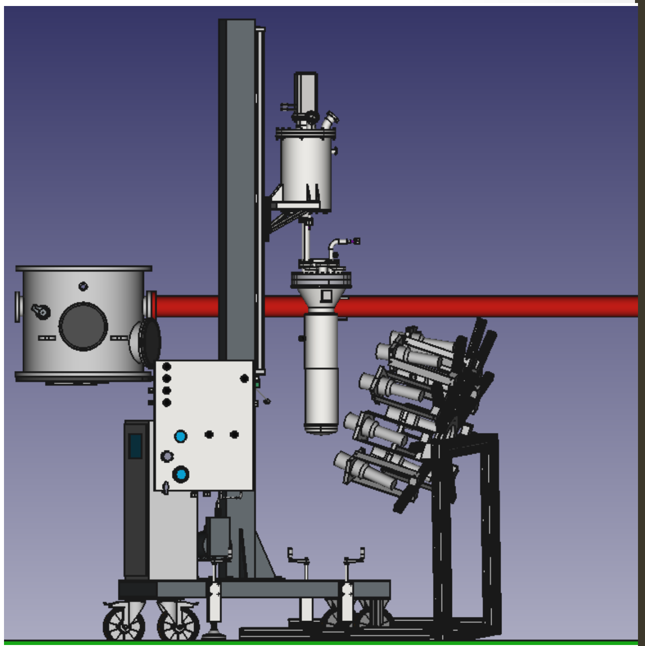
DS50 + ReD and future LAr DM program

- Main thrust on improved calibration for low energy nuclear recoil
  - A significant reduction in Q_y uncertainty and "some" indication of the underlying distribution of the number of ionization electrons at very low recoil would allow significant improvement in the sensitivity at lower masses (1-2 GeV/c^2)
- DS50 will be extremely valuable to perform a number of optimization studies for low energy ionization search: optimize fields, recirculation, trigger
  - Reduction and/or modeling of the single-electron background would allow to move the analysis threshold down to 1-2 e^- corresponding to 2-300 eVnr and possibly extend the sensitivity well below 1 GeV/c^2
- Darkside-Proto is around the corner in the path towards the construction of Darkside-20k (20 Ton Fiducial Mass dual phase TPC)

S2-ONLY PROSPECTS

ReD experiment





- ReD experiment has first beam in June @ LNS TANDEM
- Original goal is the directionality measurement (high energy nuclear recoils), now aiming also at a direct measurement of low energy nuclear recoil with same TPC by tuning appropriately the beam and geometry setups

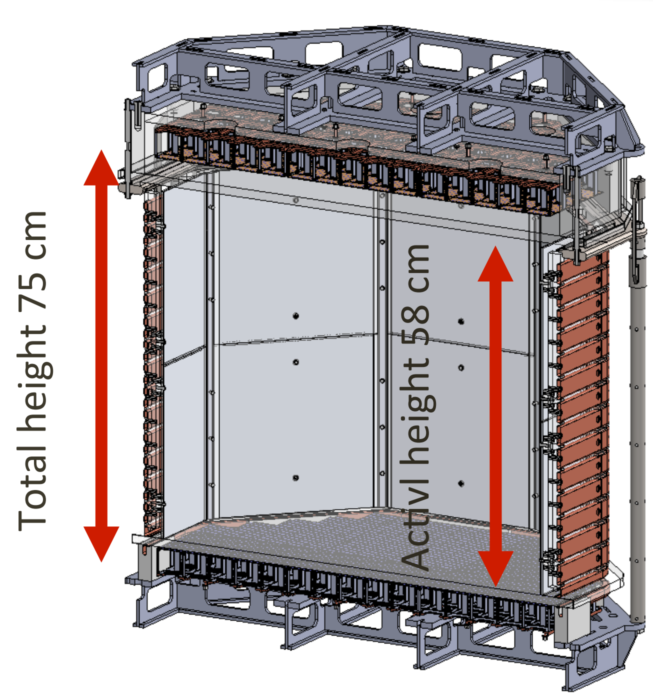
A physics-case for a ton size LAr TPC (DS-proto)

Background limited in DS50 S2-only analysis.

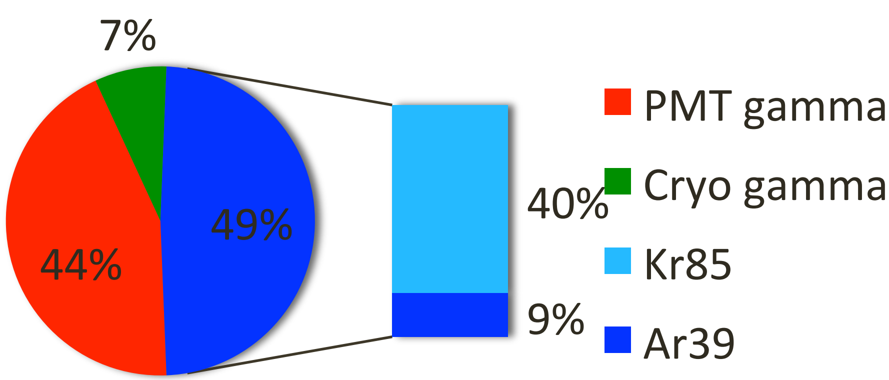
Potential breakthroughs:

- Urania/Aria program
- Use of SiPM
- Larger mass in Ds-Proto

Investigating the possibility to use DS-proto for a physics run



Bkg [0-50 Ne] composition



Test bed for DS-20k technology

370 SiPM tile photo-sensors

Low backround SS cryostat

Possible installation in LNGS in late 2019.

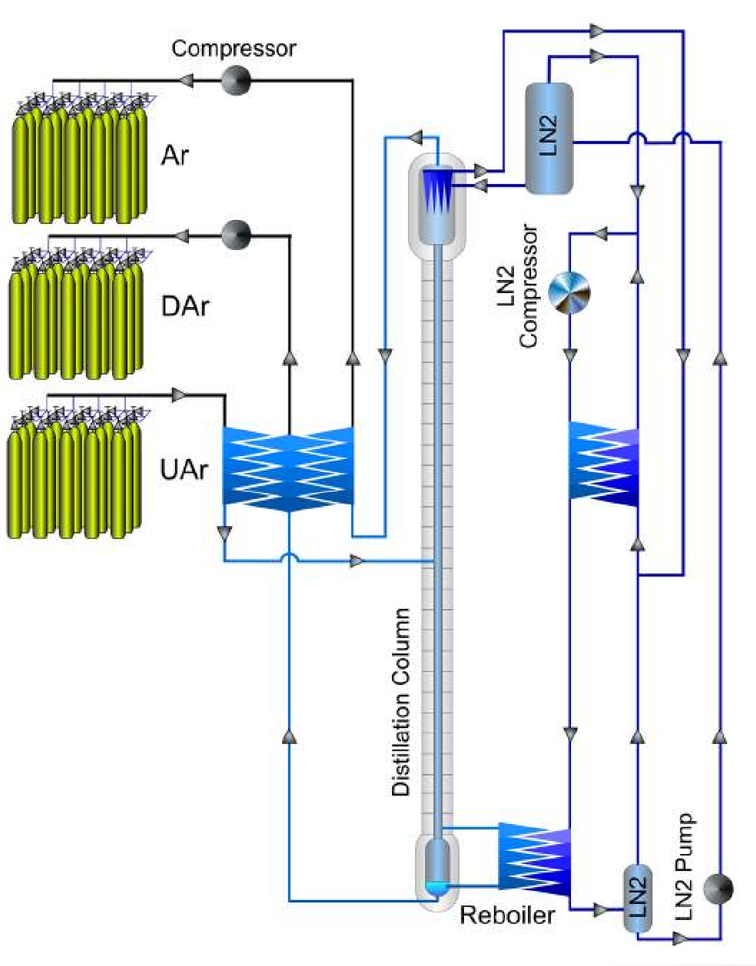
Run in 2020?

^{39}Ar depletion in Urania+Aria

- Urania plant is able to remove ^{85}Kr
- By design more air leak tight wrt to DS50 plant (also possible a reduced ^{39}Ar content)

- Relative volatility b/w ^{39}Ar and ^{40}Ar is 1.0015±0.0001*
- Thousands of distillation stages in a 350 m tall column (Seruci I) under construction in Nuraxi-Figus mine (Sulcis Iglesiente)
- Would allow reduction of ^{39}Ar content by a factor 10 per pass
- Seruci I production rate is calculated at 10 kg/day, perfectly matching the capacity needed to feed Ds-Proto (800 Kg total LAr)

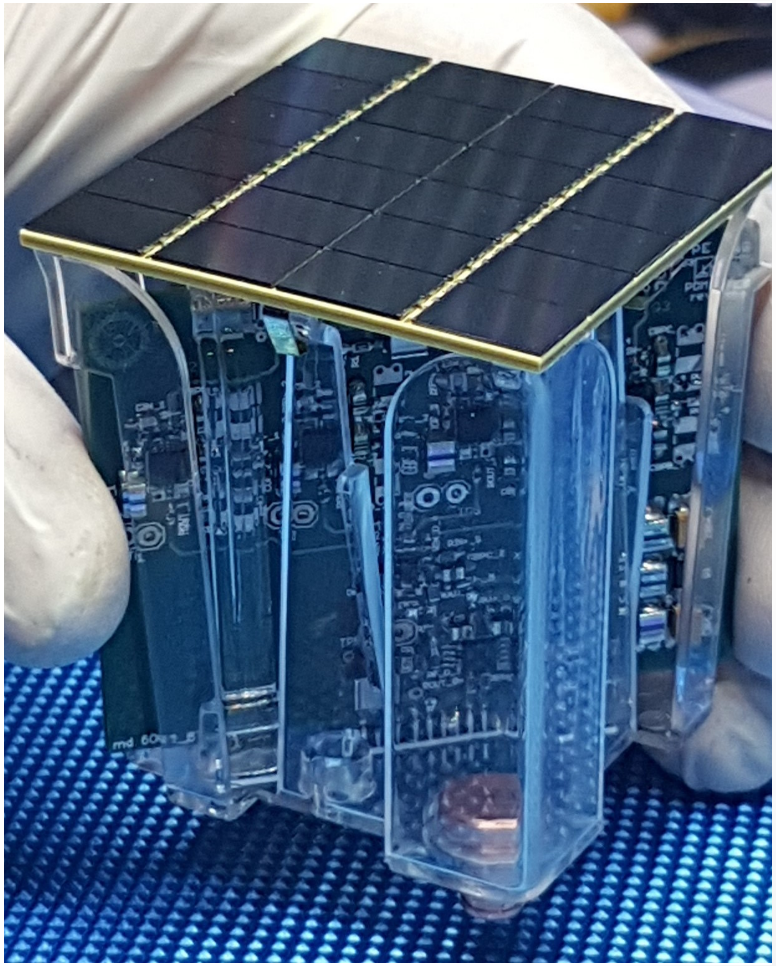
*from calculations



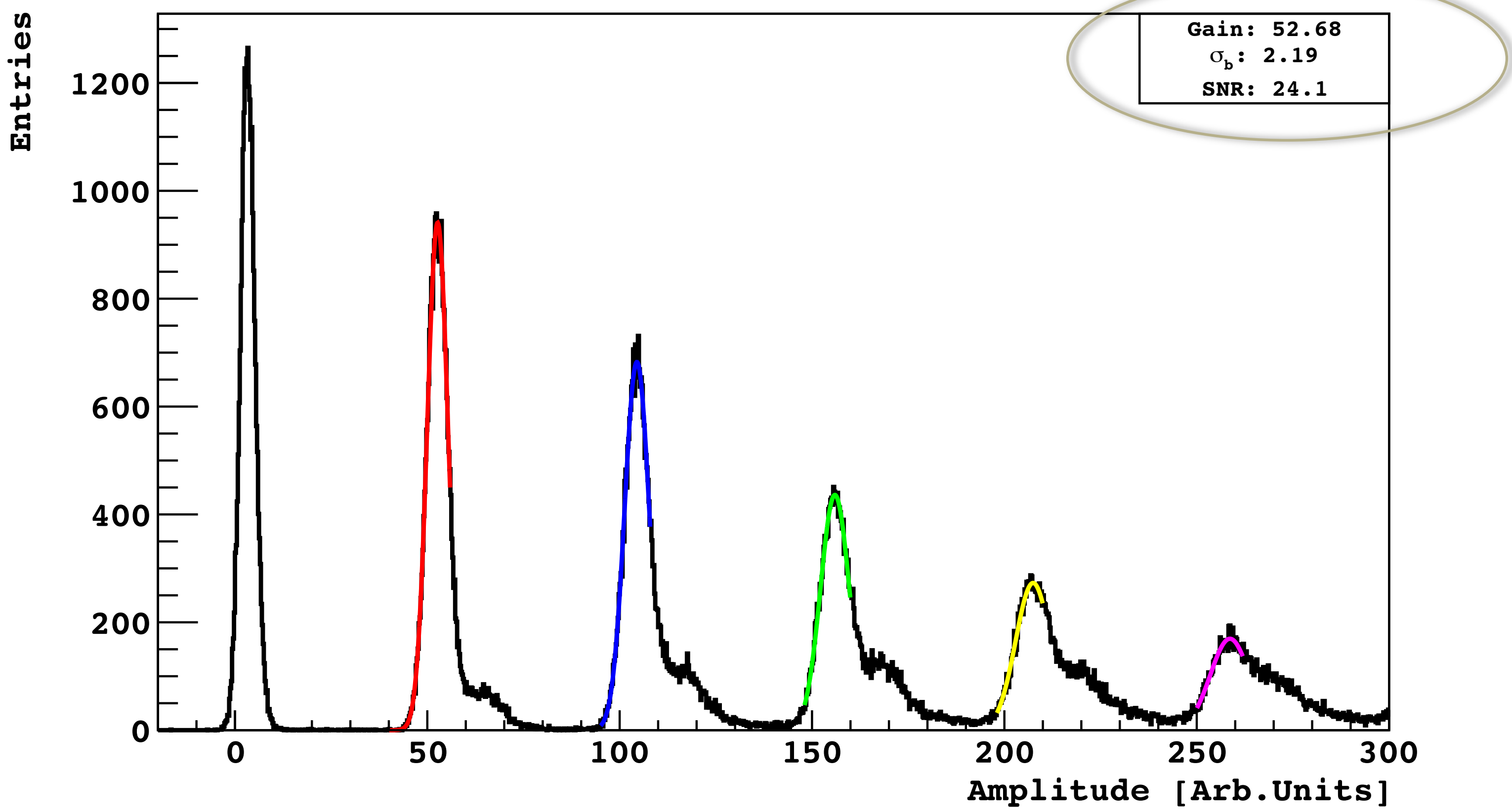
Aria modules shipped and assembled at Seruci (May 2018)

Low radioactivity photo-sensor

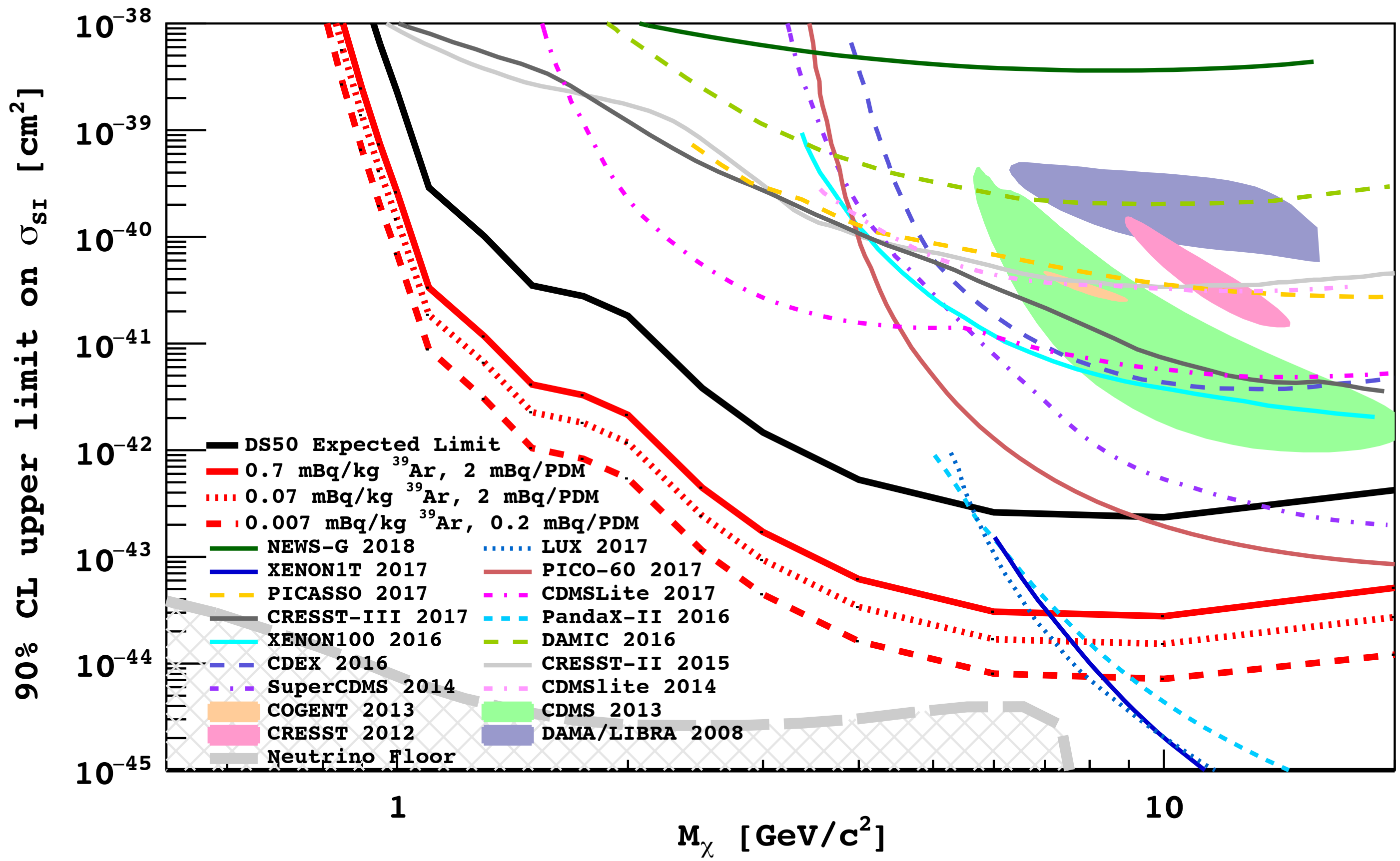
- 5x5 cm SiPM tile with a front-end amplification & summing stage in an acrylic cage: a Photo Detector Module (PDM)
- Intrinsically radio-pure Silicon
- Screening of cryogenic electronic components and substrates to achieve the lowest possible radioactivity
- Current estimate – including all services– is about 2 mBq/PDM, dominated by Arlon 55 NT substrates (for SiPM and front-end)
- On-going fused silica substrates R&D can achieve factor 10 reduction (200 μBq/PDM)
- Remind, even 2 mBq/PDM much better than current DS50 PMT (compare to ~200 mBq/PMT)!



First PDM performance (prelim.)



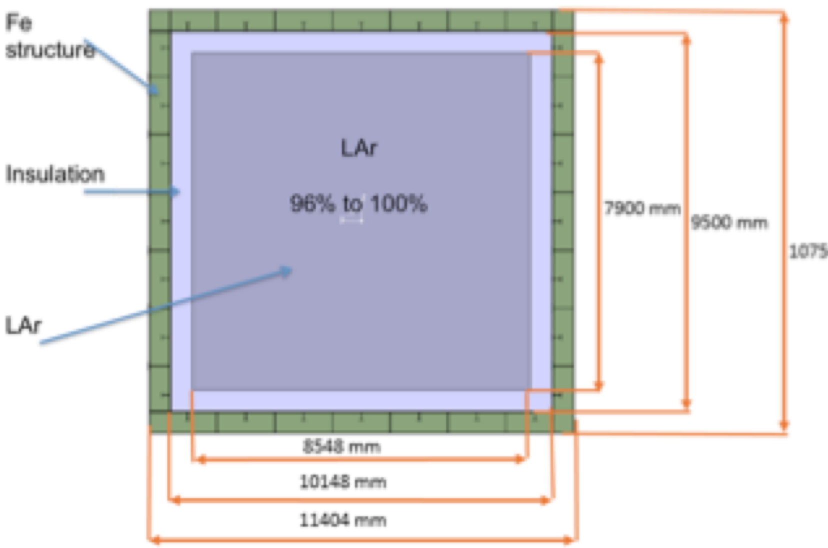
Future Darkside Low-Mass Searches

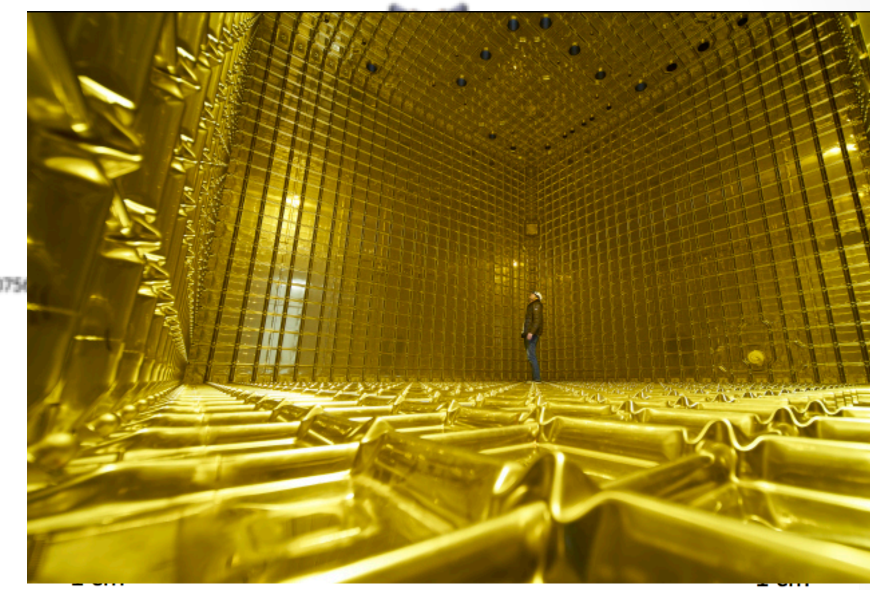


1 year data taking with DS-proto underground vs radiopurity levels of target and electronics (ambitious).

DARKSIDE-20K PROSPECTS

DS20K conceptual design/ Proto-Dune Cryostat

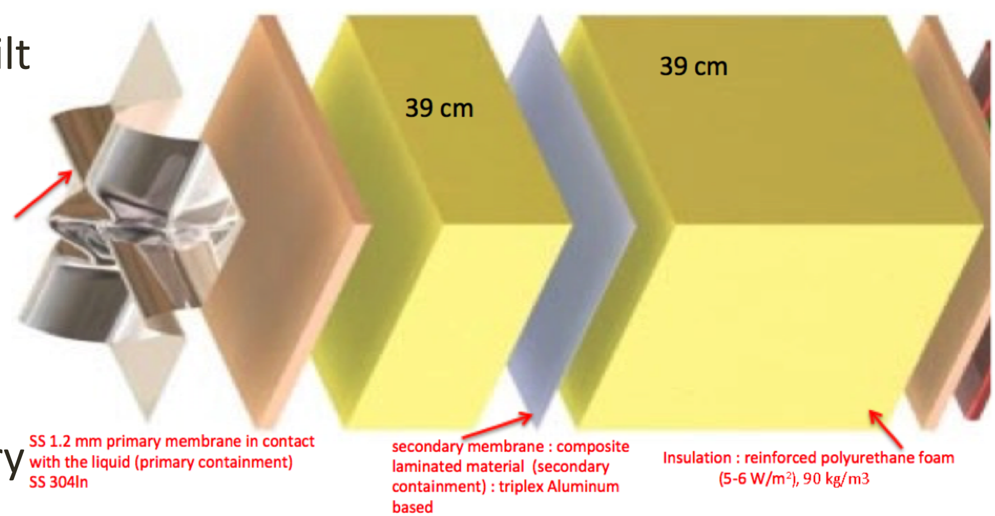




Two identical cryostats already built @CERN in ~40 weeks

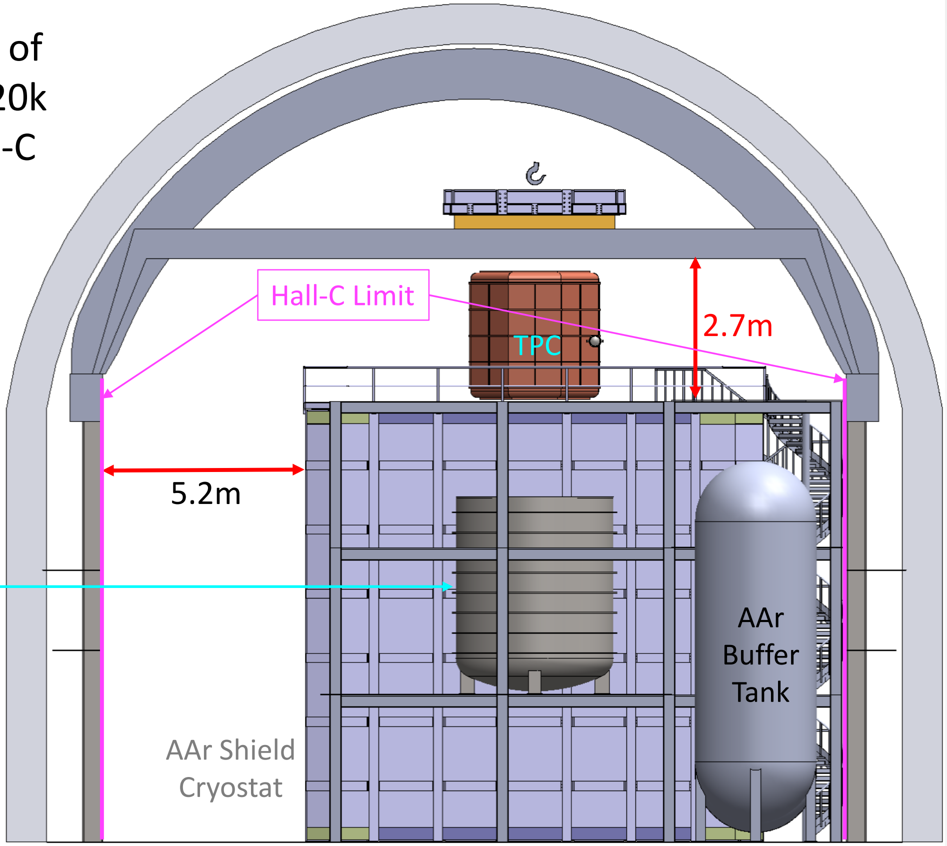
About 8x8x8 m^3 inner volume, 750 ton of LAr

Cryostat technology and expertise from Liquefied Natural Gas industry

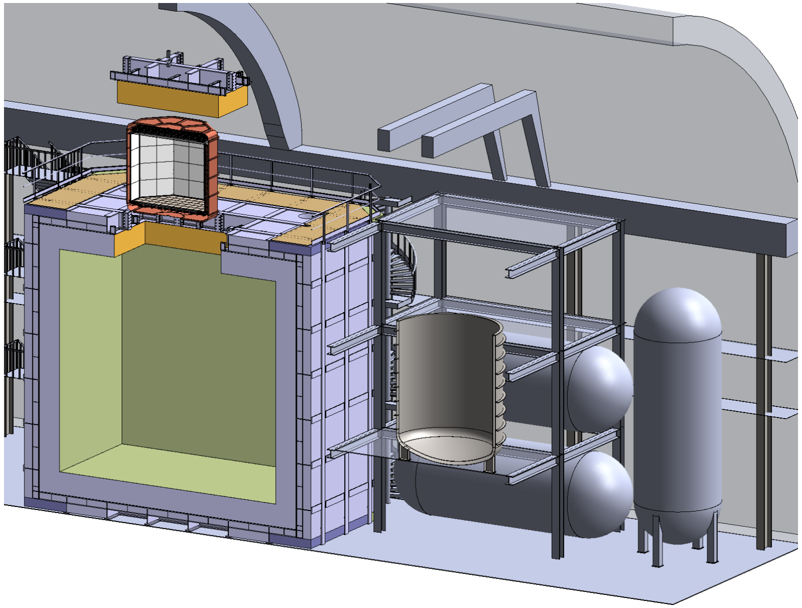


DS20K conceptual design/in Hall-C

Relative sizing of the DarkSide-20k system in Hall-C

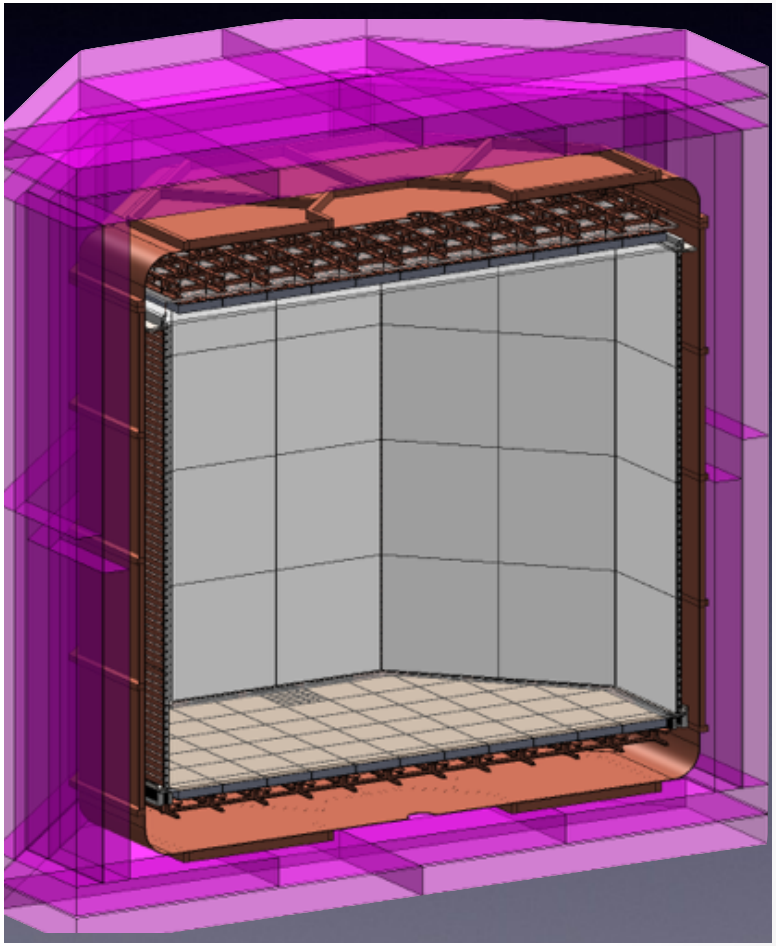


Temporary TPC Test Dewar

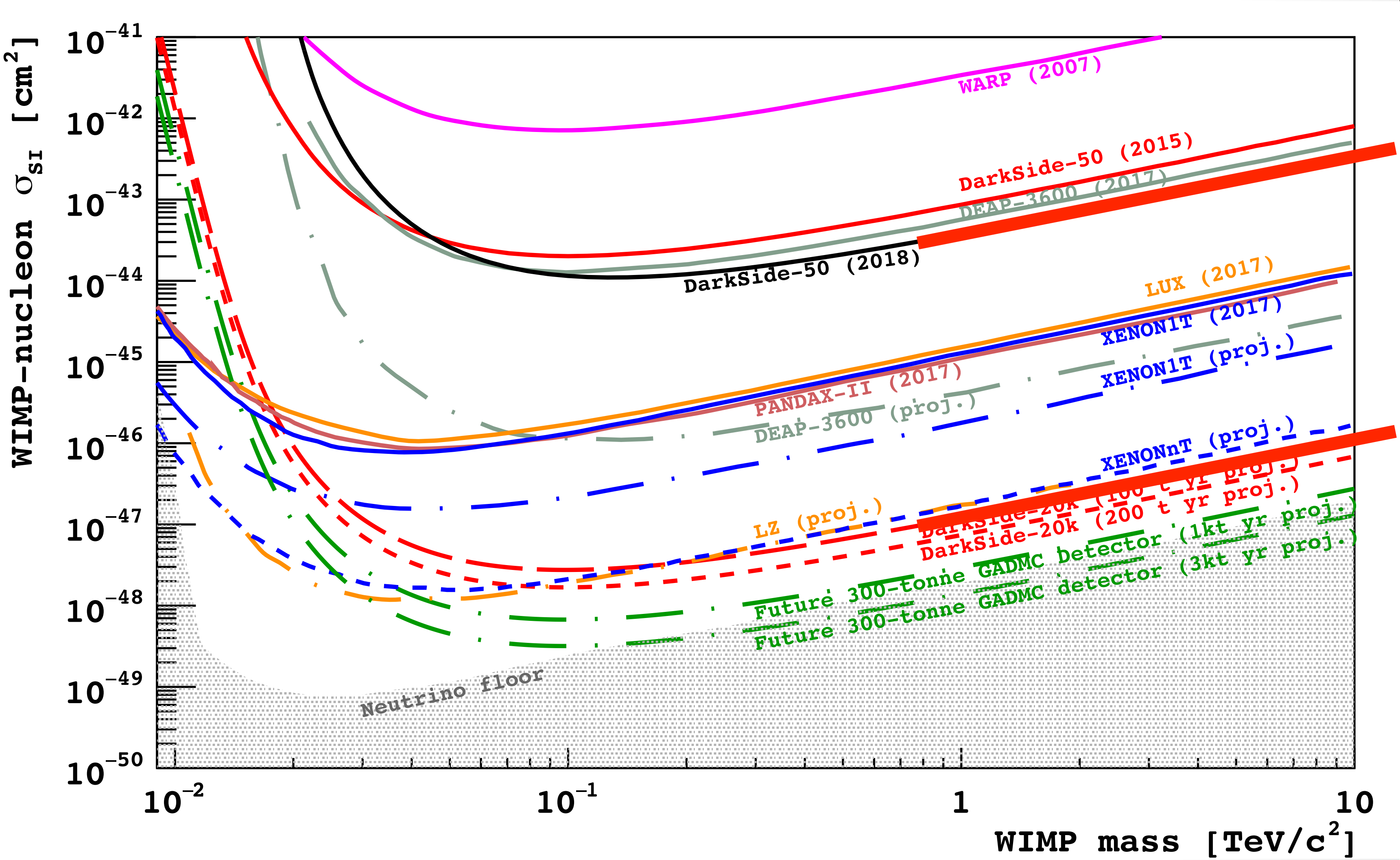


DS20K conceptual design/PS veto

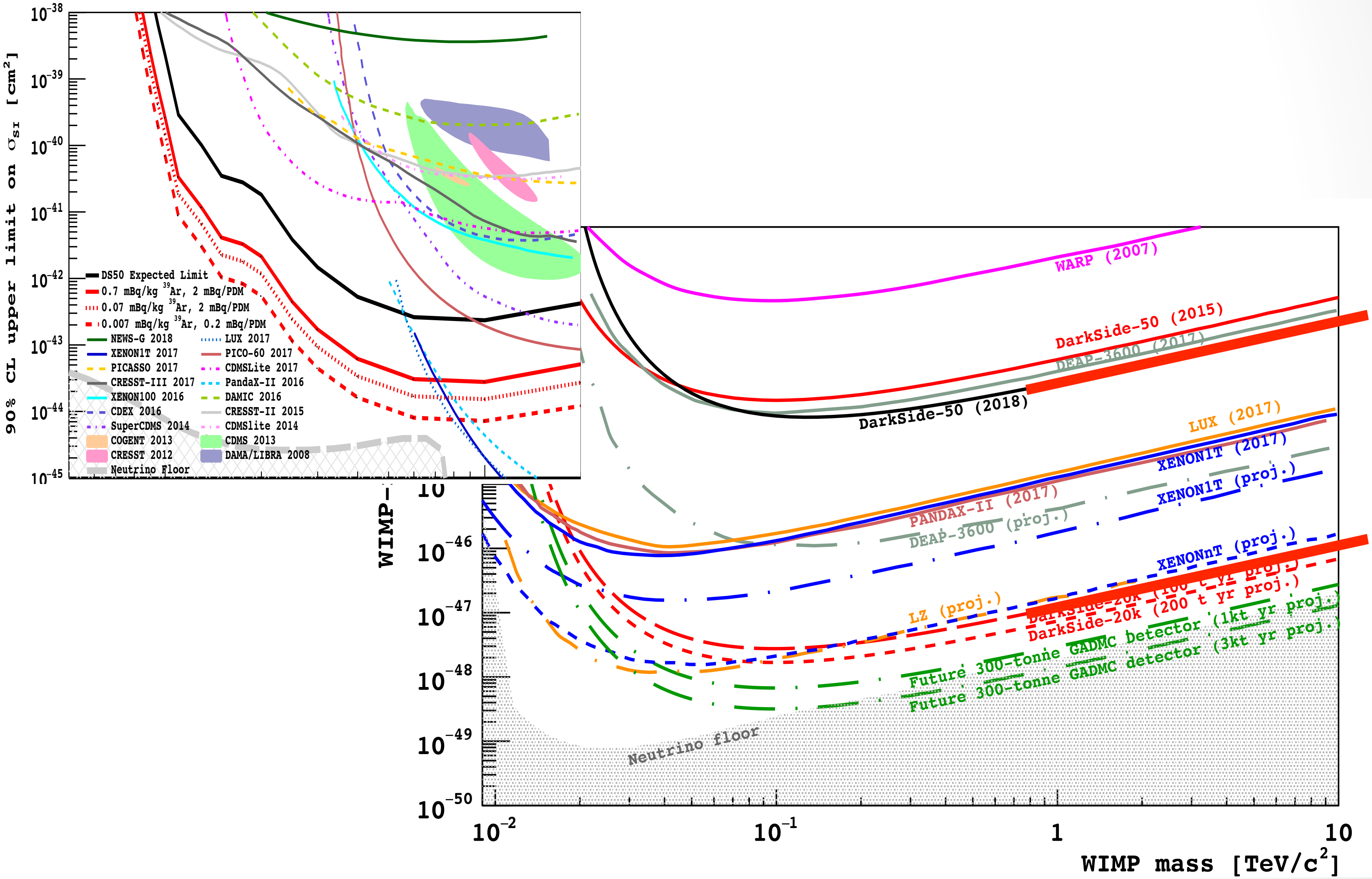
- TPC thin copper vessel to be surrounded by an active plastic scintillator layer as a neutron veto
- Considering options to load with Boron or Gadolinium for increased capture cross section
- Cryogenic SiPM sensors in Liquid sensors similar to those developed for the TPC
- Detector concept minimize internal neutron background sources and allow easier scaling for bigger target mass



DS20K sensitivity prospects



Summing up



DS50 Expected Limit
0.7 mBq/kg 39Ar, 2 mBq/PDM
0.07 mBq/kg 39Ar, 2 mBq/PDM
0.007 mBq/kg 39Ar, 0.2 mBq/PDM
NEWS-G 2018
XENON1T 2017
PICASSO 2017
CRESST-III 2017
XENON100 2016
CDEX 2016
SuperCDMS 2014
COGENT 2013
CRESST 2012
Neutrino Floor
LUX 2017
PICO-60 2017
CDMSLite 2017
PandaX-II 2016
DAMIC 2016
CRESST-II 2015
CDMSlite 2014
CDMS 2013
DAMA/LIBRA 2008
90% CL upper limit on σSI [cm2]
WARP (2007)
DarkSide-50 (2015)
DEAP-3600 (2017)
DarkSide-50 (2018)
LUX (2017)
XENON1T (2017)
XENON1T (proj.)
PANDAX-II (2017)
DEAP-3600 (proj.)
XENONnT (proj.)
LZ (proj.)
DarkSide-20k (200 t yr proj.)
Future 300-tonne GADMC detector (1kt yr proj.)
Future 300-tonne GADMC detector (3kt yr proj.)
Neutrino floor
WIMP mass [TeV/c2]

Conclusions

- A new search window from DS50 S2-only search for LAr
  - Threshold in sub keV range
  - Background at ~1 count/keVee/day (to be reduced further)

- More data in hands:
  - In total almost 3 annual cycle for the S2-only analysis, with a quite stable detector
  - Working on an improved analysis including all data

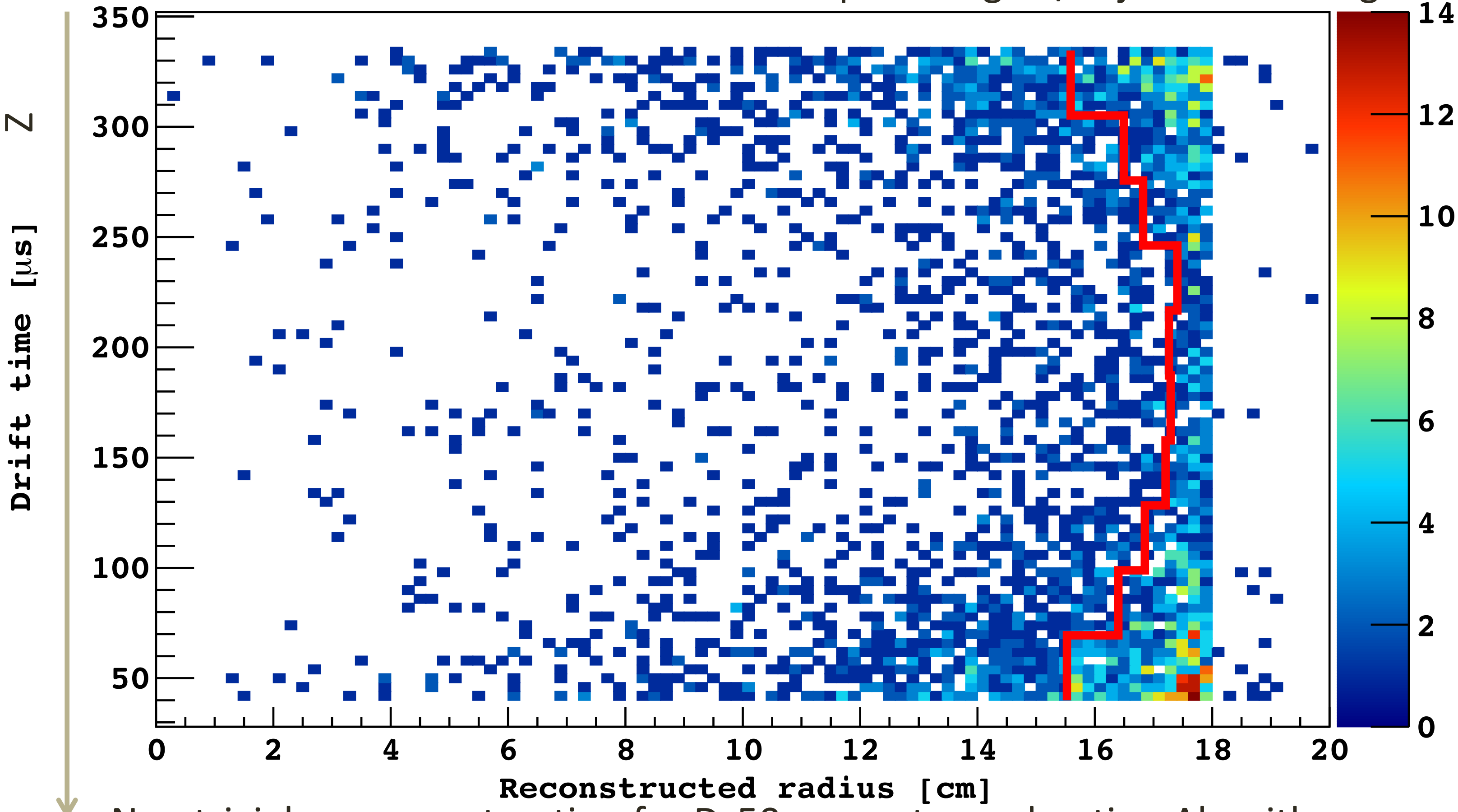
- A clear path to approach the neutrino floor with the next generation of Liquid Argon dark matter experiments for both the low and high mass WIMP searches

SPARES

Blind analysis/Radial cut

arxiv:1802.07198

Keep 84% signal/Reject 50% background



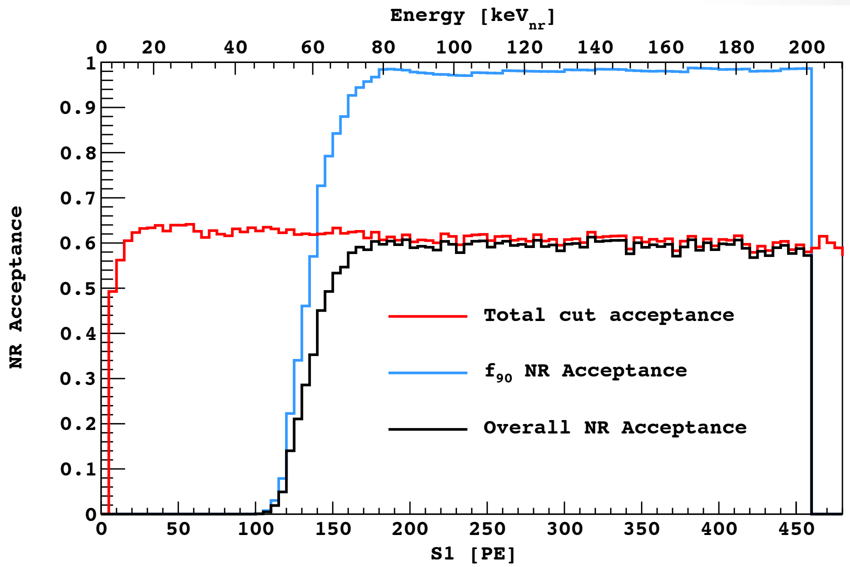
Non trivial x-y reconstruction for Ds50 geometry and optics. Algorithm find best position based on expected light sharing among the PMT on the top plane. Resolution ~6 mm for large enough signals.

In addition usual 40 μs cut in Z direction from anode and cathode (~4 cm)

Blind analysis/acceptance & bkg

arxiv:1802.07198

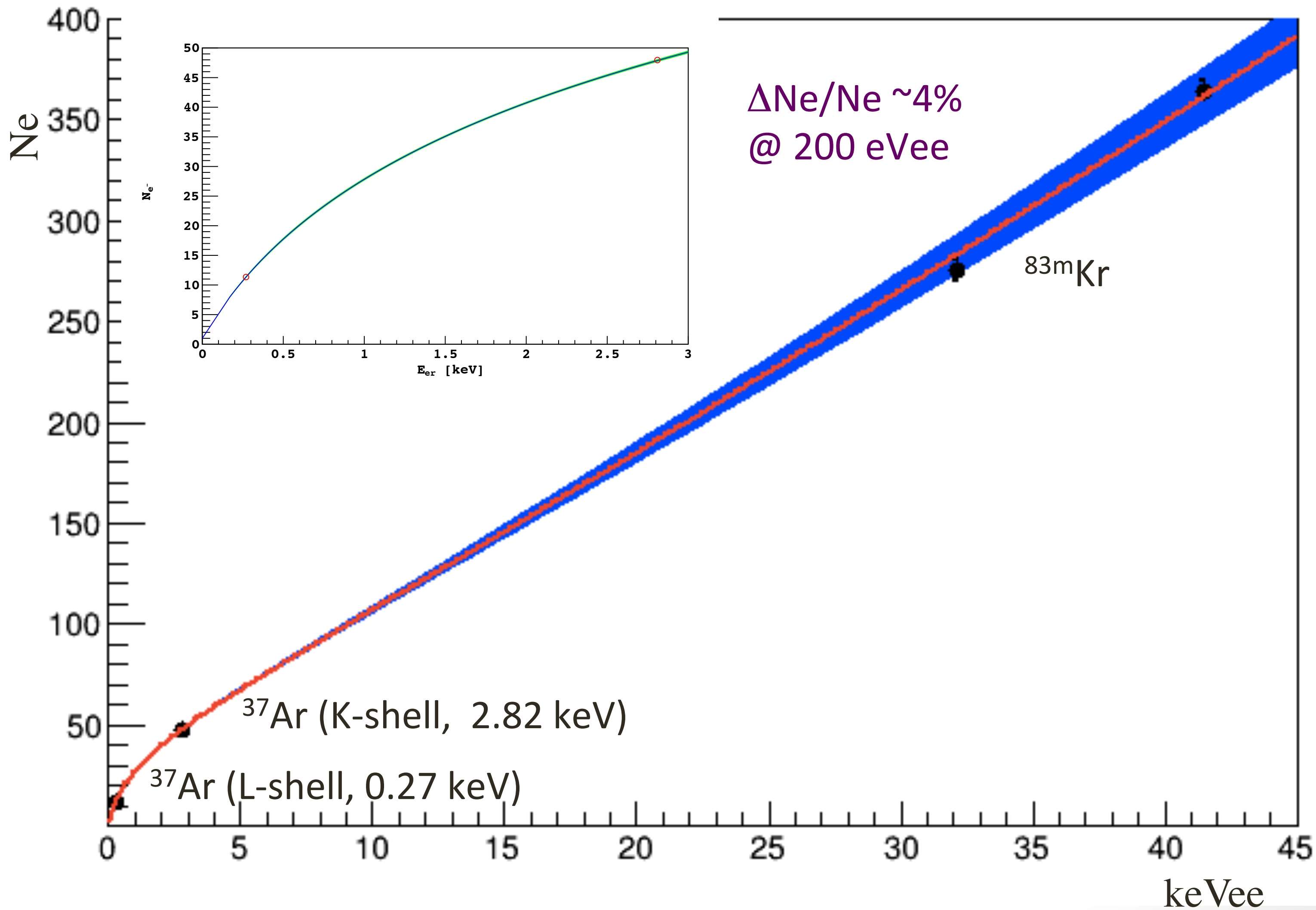
Cut	Livetime/Acceptance
All channels	545.6 d
Baseline	545.6 d
Time since prev	545.3 d
Veto present	536.6 d
Cosmo activ	532.4 d
Muon signal	0.990
Prompt LSV	0.995
Delayed LSV	0.835
Preprompt LSV	0.992
N pulses	0.978
S1 start time	1
S1 saturation	1
Min uncorr S2	0.996
xy-recon	0.997
S2 F90	1
Min corr S2/S1	0.995
Max corr S2/S1	0.991
S2 LE shape	1
$S1_p$ max frac	0.948
S1 TBA	0.998
Long S1 tail	0.987
Radial cut	0.84
S1 NLL	>0.99
Combined	0.609



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

S2-only/ER scale

arxiv:1802.06998



Compare with Xenon100 – ionization only

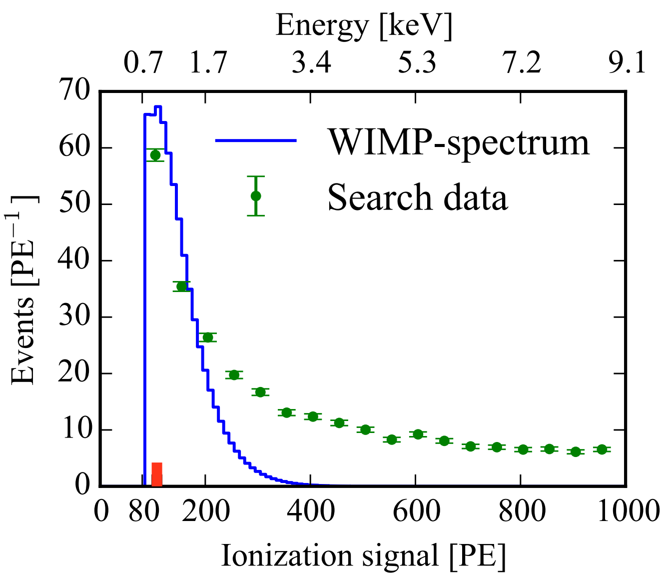
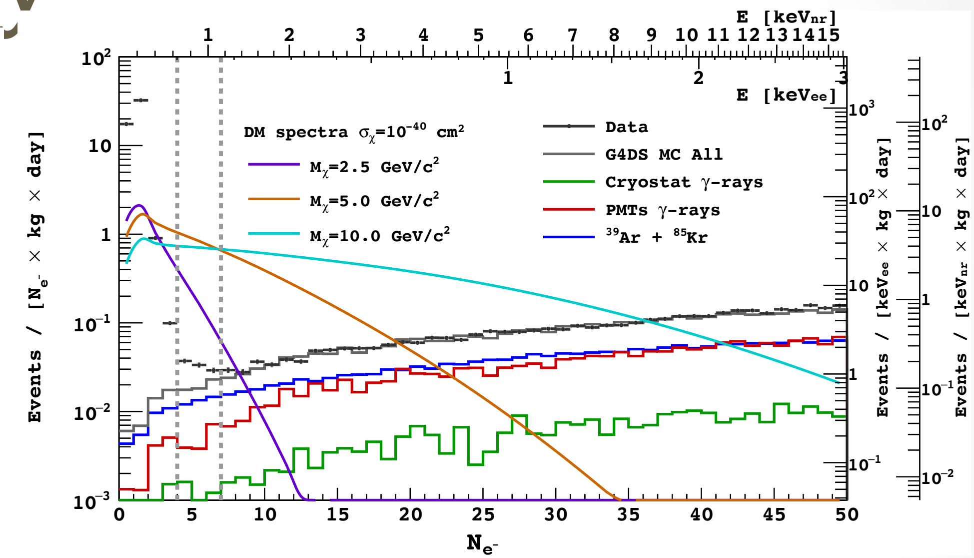


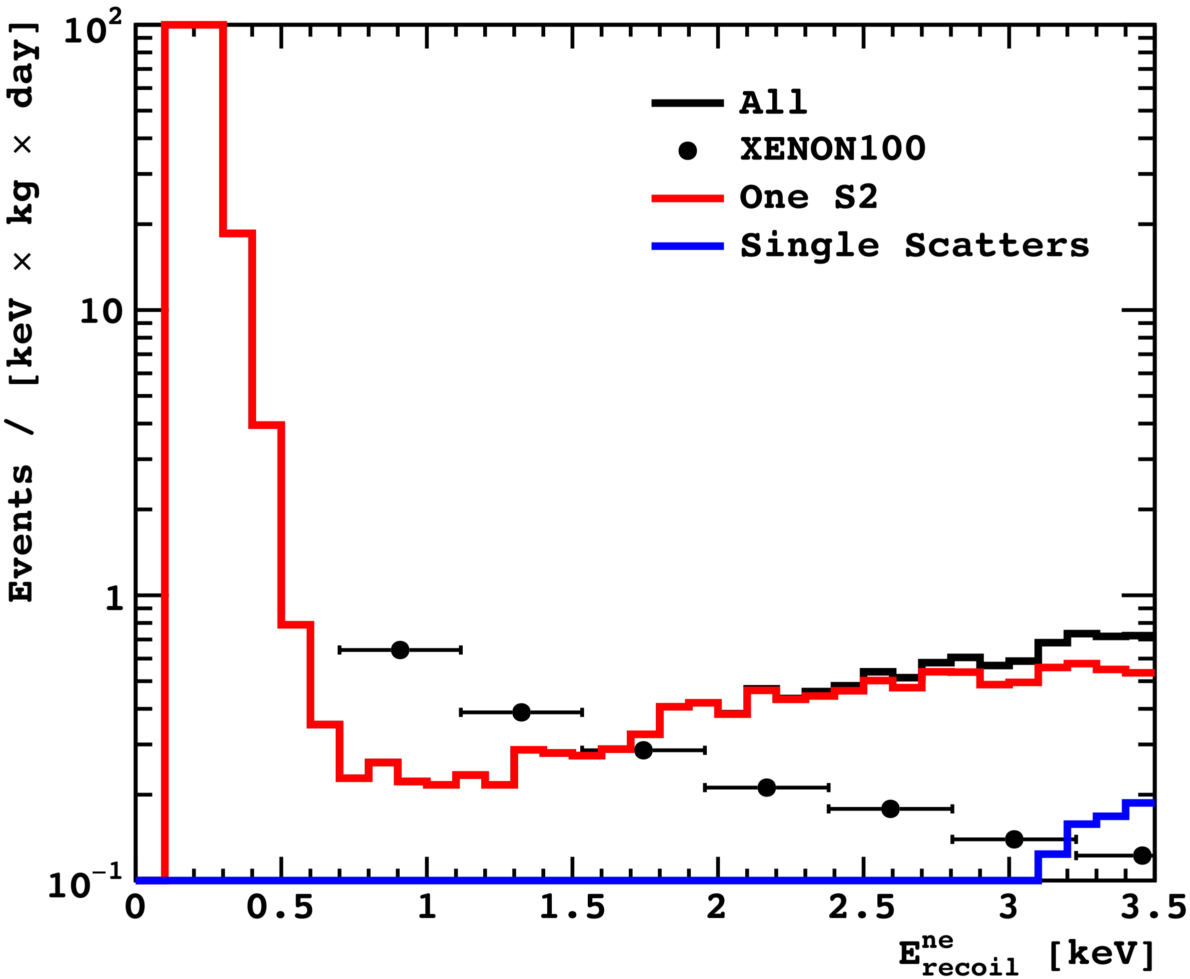
FIG. 4. Energy distribution of the events remaining in the data set after all data selection cuts. As an example, the expected spectrum for a WIMP of $6\,\mathrm{GeV}/c^2$ and a spin-independent WIMP-nucleon scattering cross section of $1.5 \times 10^{-41}\,\mathrm{cm}^2$ is also shown. The corresponding nuclear recoil energy scale is indicated on the top axis. The charge yield model assumed here has a cutoff at 0.7 keV, which truncates the WIMP spectrum. The optimum interval (thick red line) is found in the S2 range [98, 119] PE and contains 1173 events.

Phys. Rev. D 94, 092001 (2016)



	Xenon 100	Darkside-50
Bkg [ev/keVnr/kg/d]	0.5 in [0.7,1.7] keV	0.2 @ 1.1 keV
Bkg [ev/keVnr/kg/d]	0.07 in [3.4-9.1] keV	0.4 @ 6 keV
Analysis Threshold	0.7 keVnr	0.6 keVnr

Compare with Xenon100 – ionization only

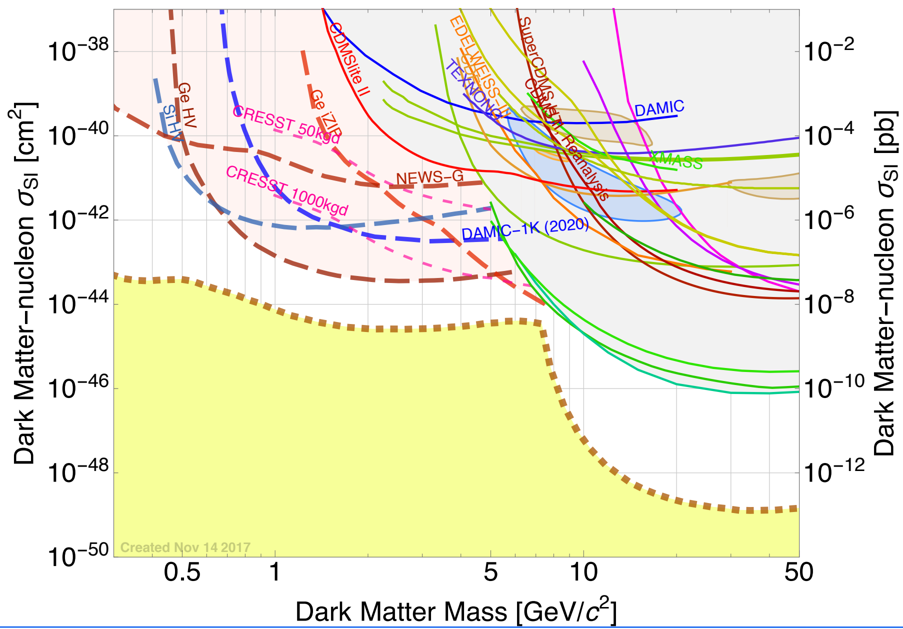


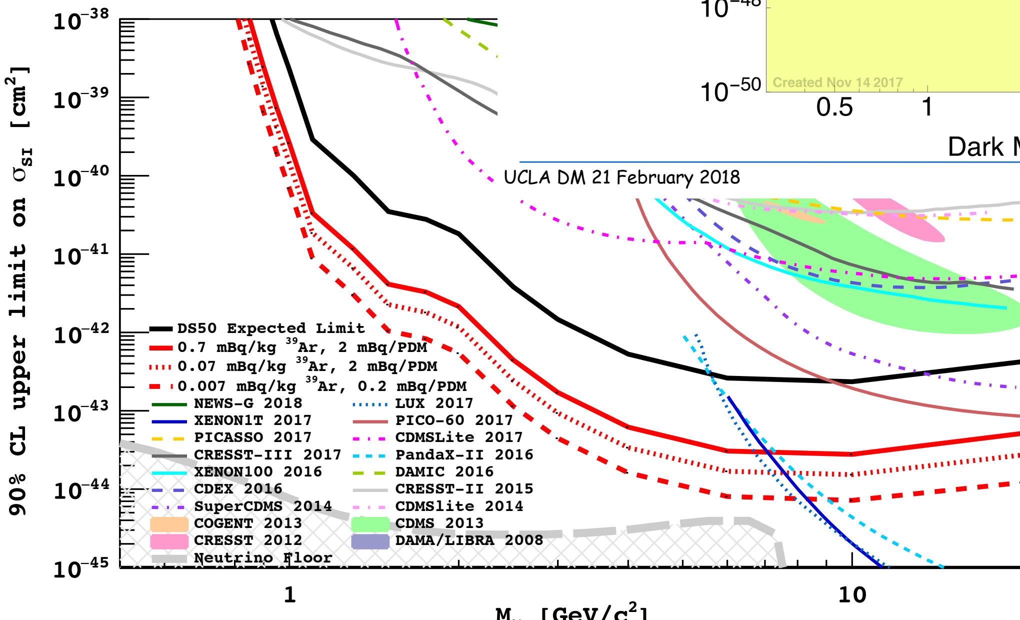
NR scale

Low Mass Region Projections

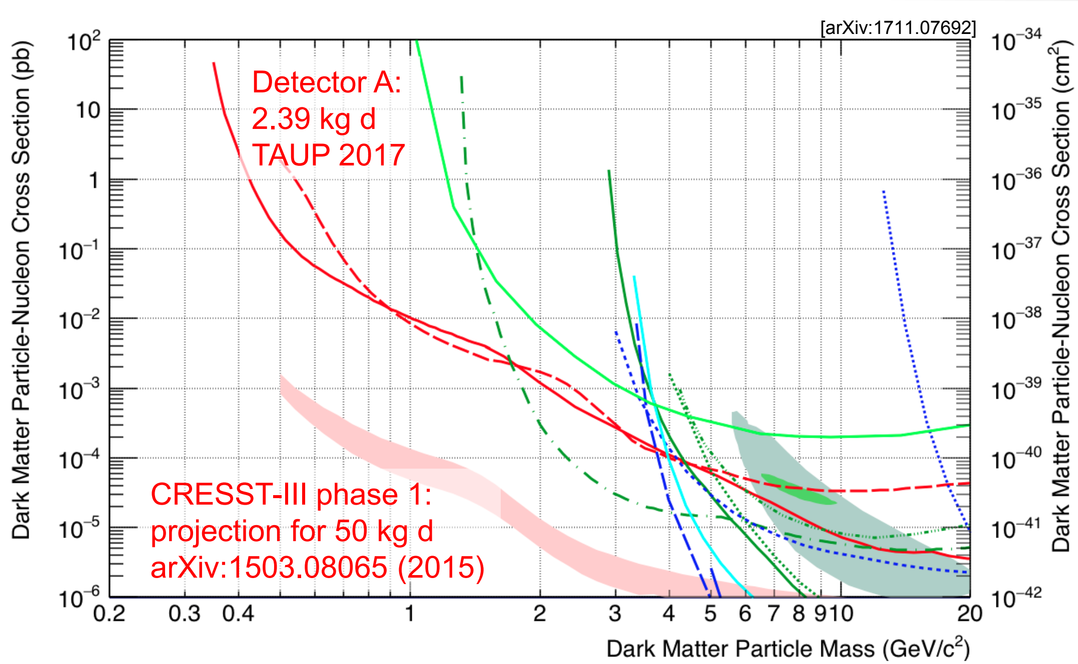
≈2020

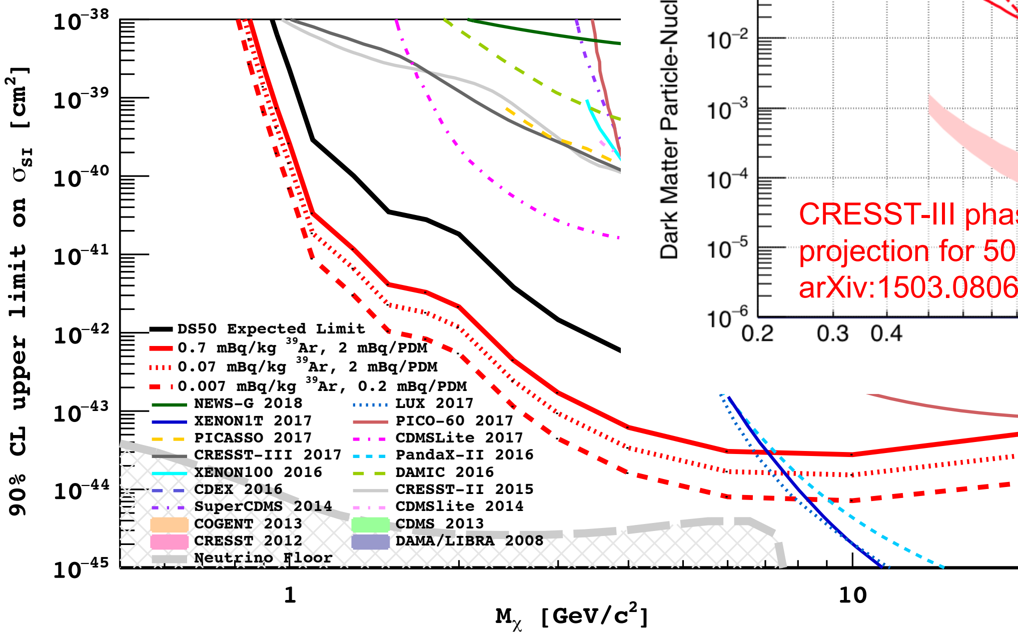
DAMIC/SENSEI CCD
NEWS-G (Spherical Proportional Counter)
Low temperature calorimeters: SuperCDMS, CRESST, Edelweiss)





M.Rescigno - 7th Workshop on Theory, Phenomenology and Experiments in Flavour Physics


[arXiv:1711.07692]
Detector A:
2.39 kg d
TAUP 2017
CRESST-III phase 1:
projection for 50 kg d
arXiv:1503.08065 (2015)
Dark Matter Particle-Nucleon Cross Section (pb)
Dark Matter Particle-Nucleon Cross Section (cm^2)
Dark Matter Particle Mass (GeV/c^2)


DS50 Expected Limit
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0.07 mBq/kg ^{39}Ar, 2 mBq/PDM
0.007 mBq/kg ^{39}Ar, 0.2 mBq/PDM
NEWS-G 2018
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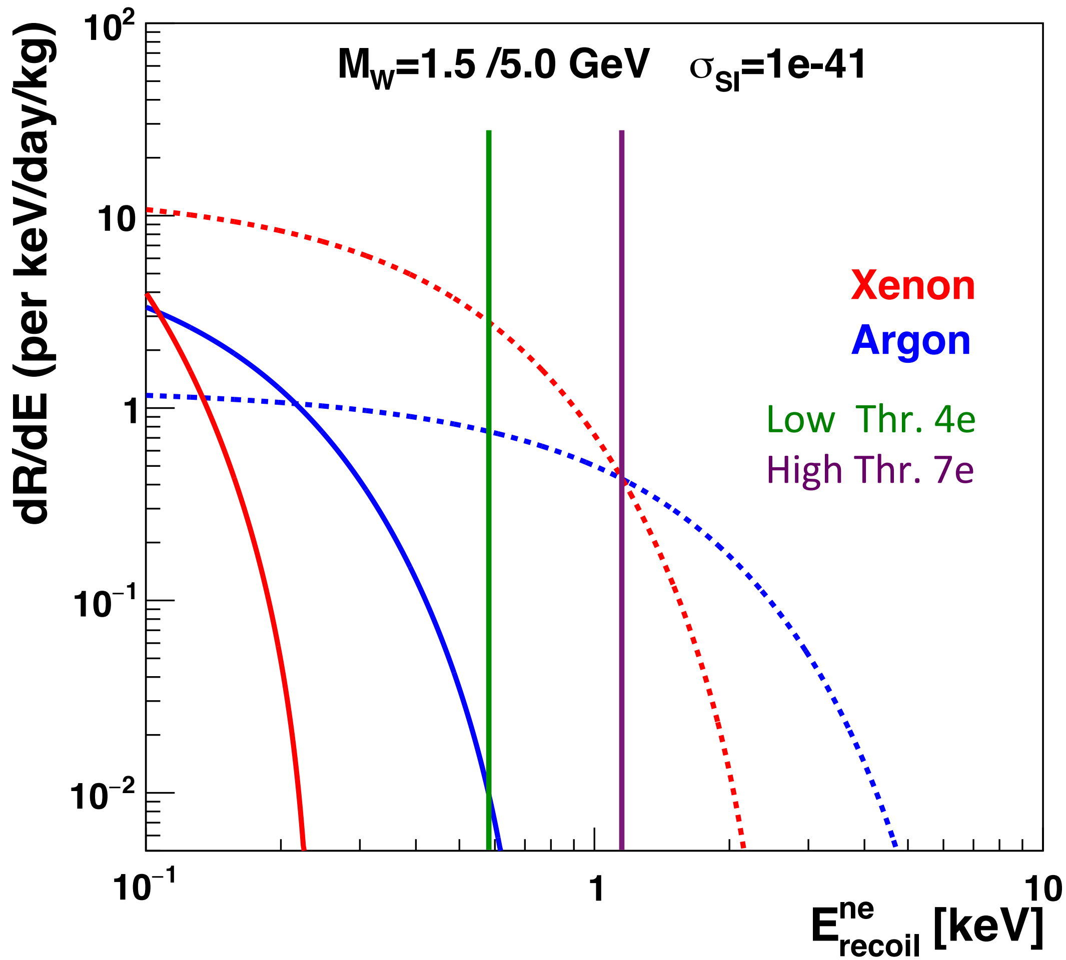
CDEX 2016
SuperCDMS 2014
COGENT 2013
CRESST 2012
Neutrino Floor
LUX 2017
PICO-60 2017
CDMSLite 2017
PandaX-II 2016
DAMIC 2016
CRESST-II 2015
CDMSlite 2014
CDMS 2013
DAMA/LIBRA 2008
90% CL upper limit on σ_{SI} [cm^2]
M$_\chi$ [GeV/c^2]

Nuclear recoil spectra



Ar39 and Kr85 forbidden spectra

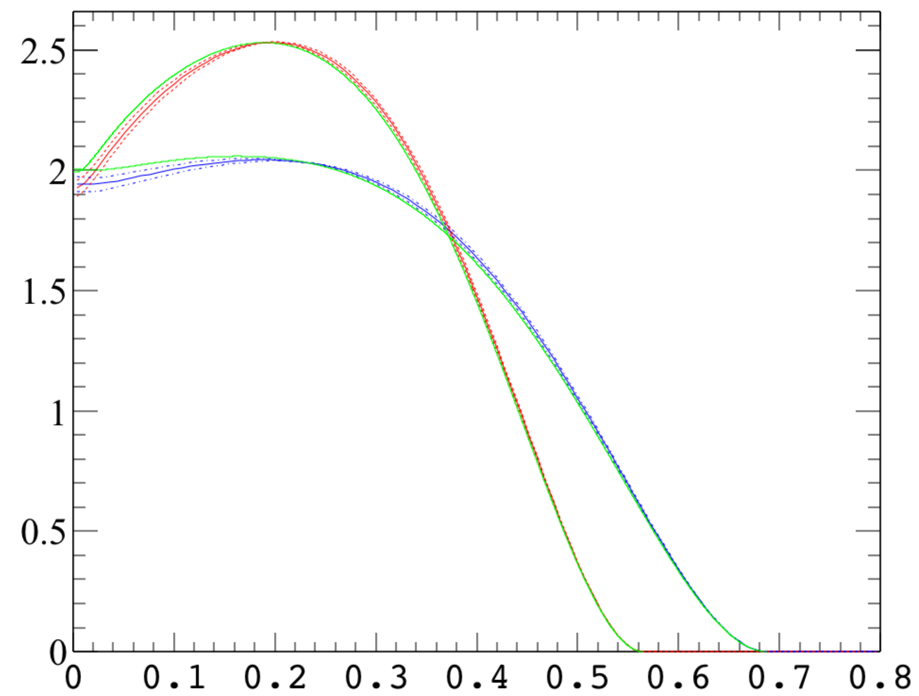
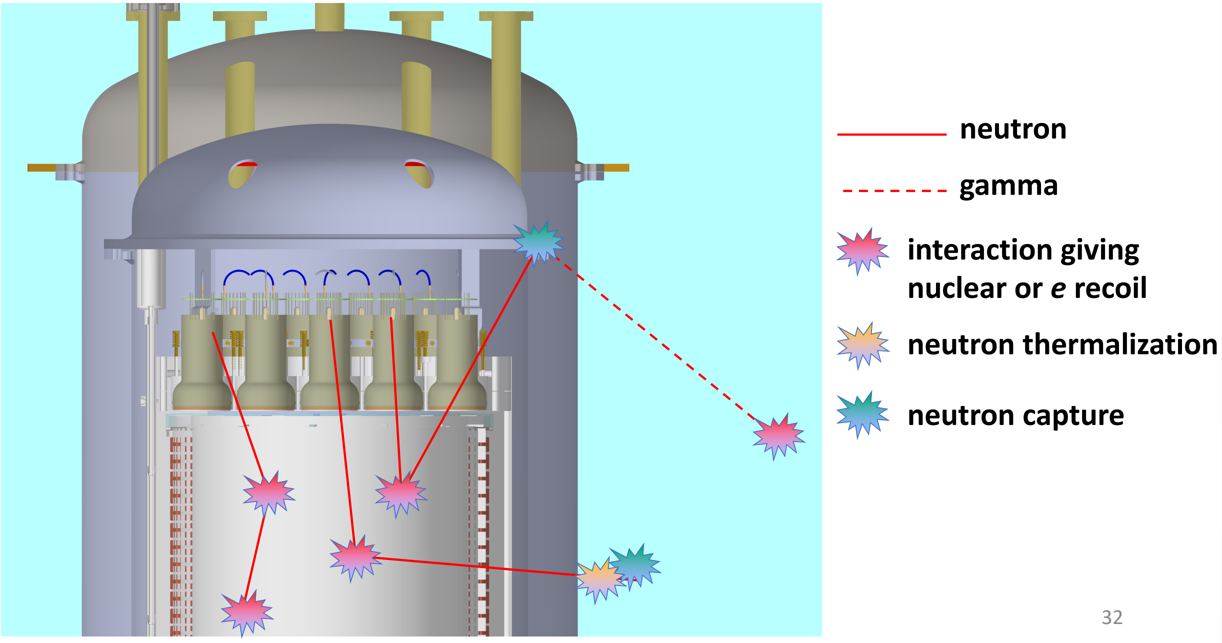


FIG. 12. Updated energy spectra of ^{39}Ar (red curve) and ^{85}Kr (blue curve). The dashed curves represent $\pm 1\sigma$ theoretical uncertainties. The x-axis is units of MeV.

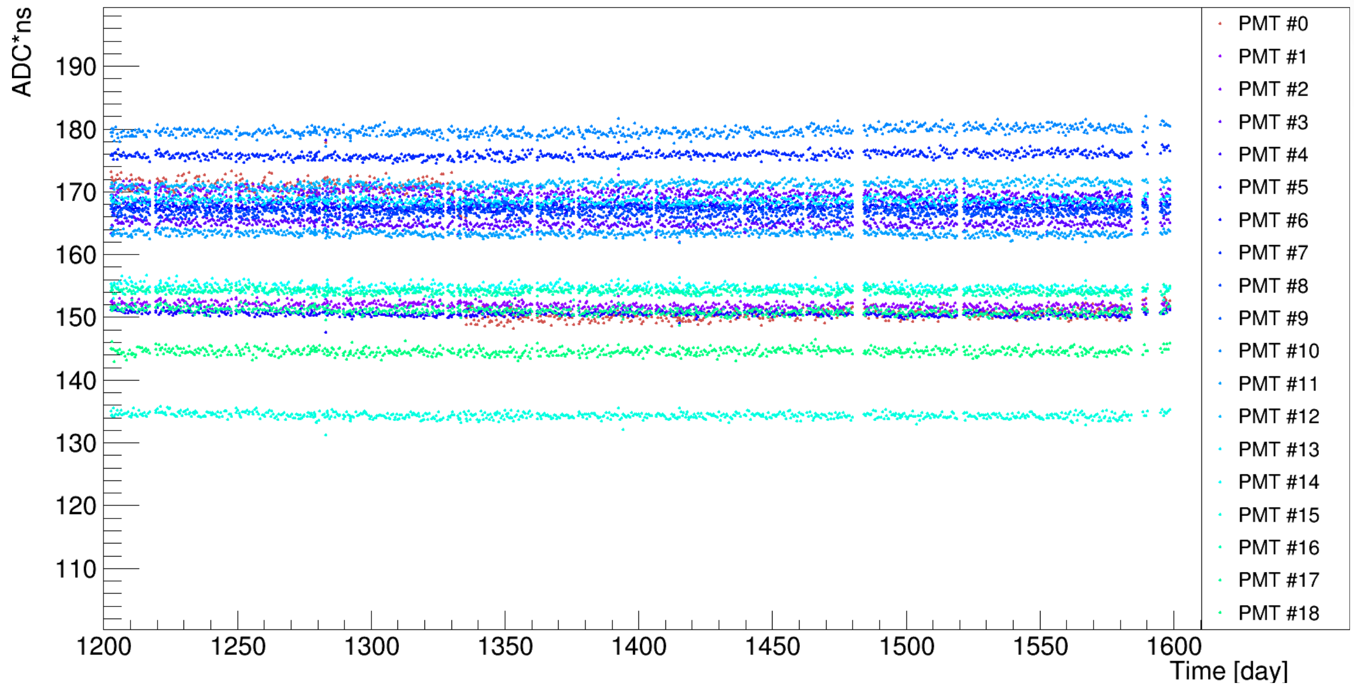
Prompt and delayed Veto signals

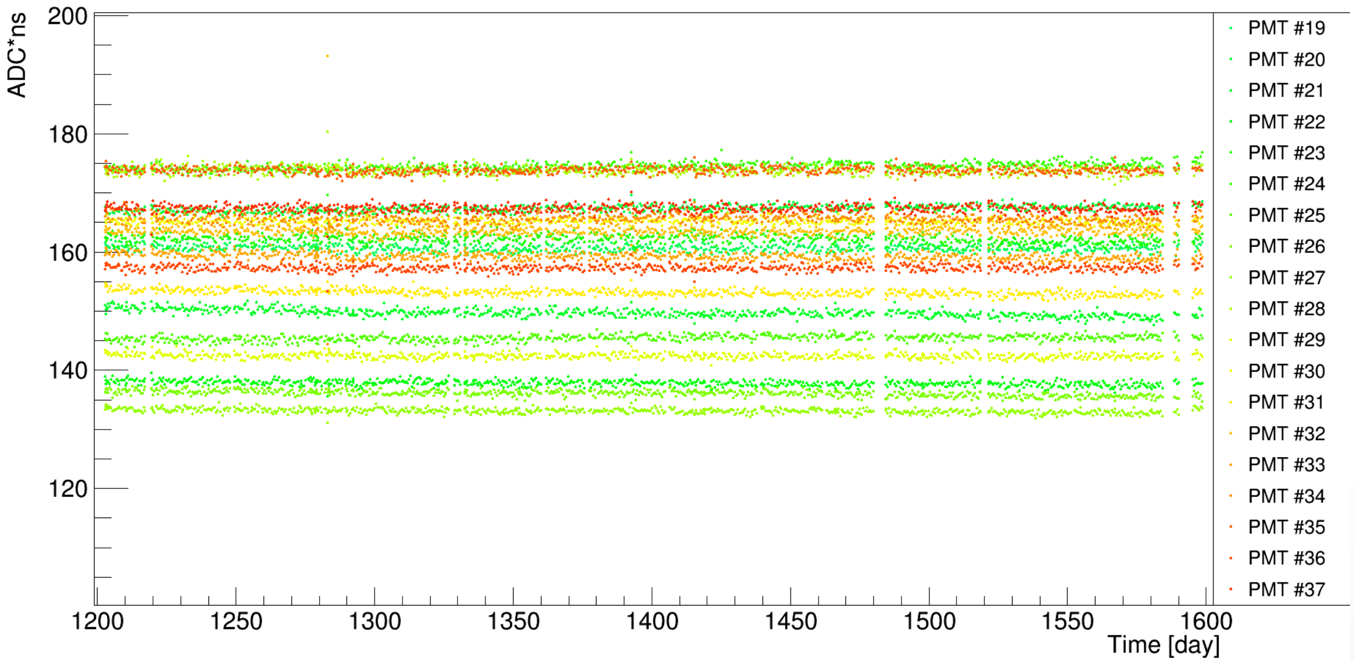
Borated-liquid-scintillator neutron veto

- (α,n) from PMT U and Th are the dominant neutron source.
- Separately detect both thermalization and capture signals from neutron.
- Rejection **measured** with AmC neutrons giving WIMP-like TPC signature.
- Rejection for radiogenic neutrons **~500**.
- Also effective for cosmogenic neutrons.



Single Electron Response





Fighting ER+Cherenkov

- 1 " thick PTFE coated with TPB WLS used as a reflector in DS50
- Cherenkov from electrons in Teflon produce visible light that can be seen in the TPC, dangerous bkg when a coincident ER recoil occurs
- For DS20k replace PTFE with a sandwich of thin acrylic transparent sheets and 3M enhanced specular reflector foils
- PTFE has high (α,n) cross due to Fluorine. Reduces also second largest radiogenic neutron source in the original Ds20k design

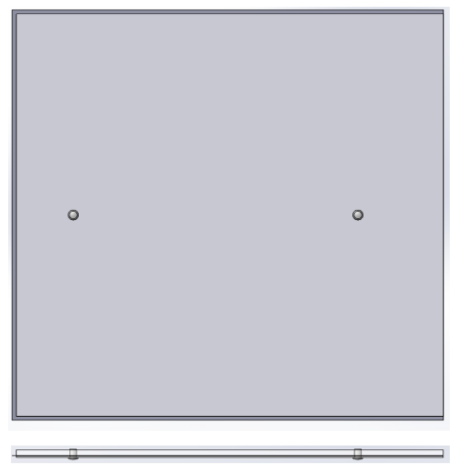


FIG. 15. 3D model of the individual acrylic and ERS panels.

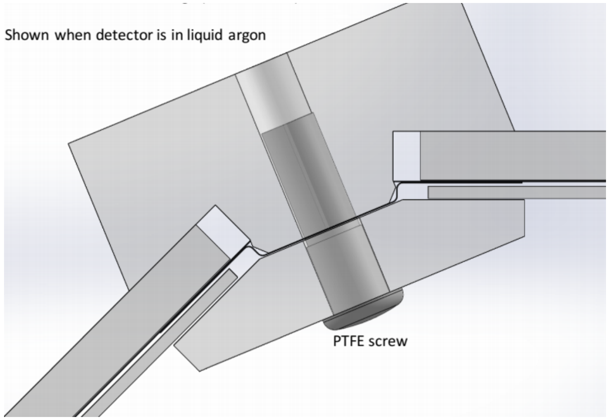


FIG. 16. Cross-sectional view of the reflector panel corner joints.

S2-only/ NR scale

arxiv:1802.06994