Darkside new results and prospects

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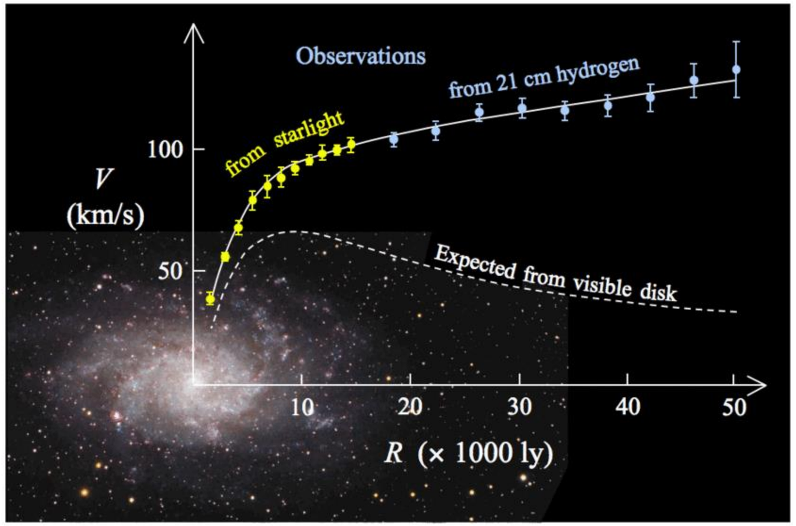
On behalf of the **DarkSide Collaboration**
La Thuile 2018, March 3rd

The Dark Matter paradigm

The evidence for the existence of Dark Matter (DM) is overwhelming, and comes from a wide variety of astrophysical measurements.

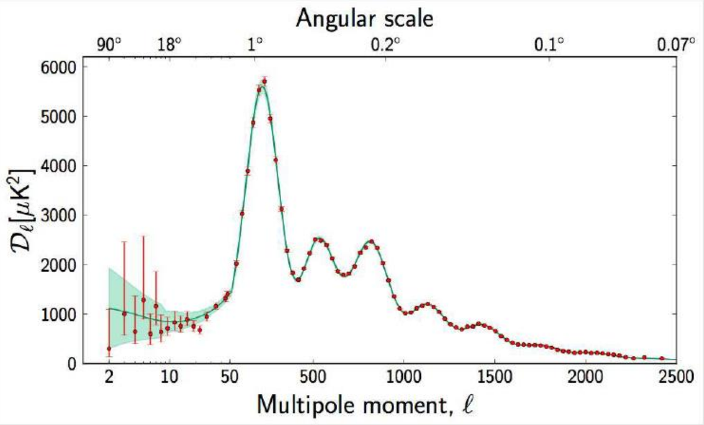
Velocity dispersion of spiral galaxies

In the 1970s, Ford and Rubin discovered that rotation curves of galaxies are flat. The simplest explanation is that **galaxies contain far more mass than can be explained by the bright stellar objects** in the galactic disks.



Cosmic Microwave Background

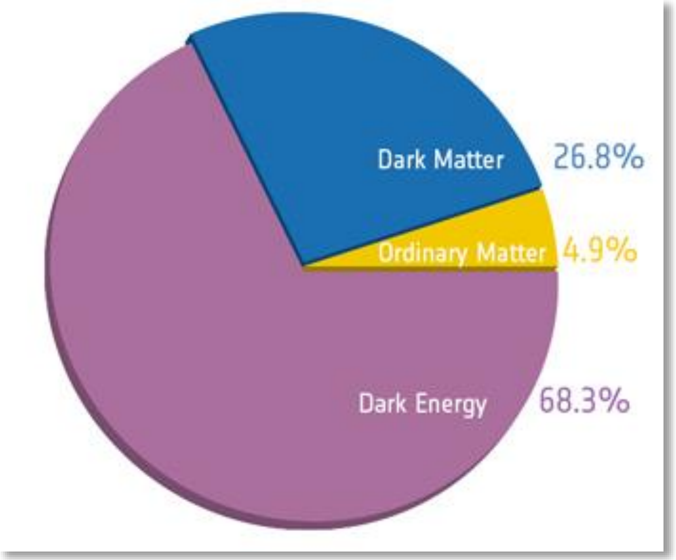
CMB temperature anisotropy angular power spectrum seen by Planck, with the predictions for the best fit of the standard cosmological model parameters



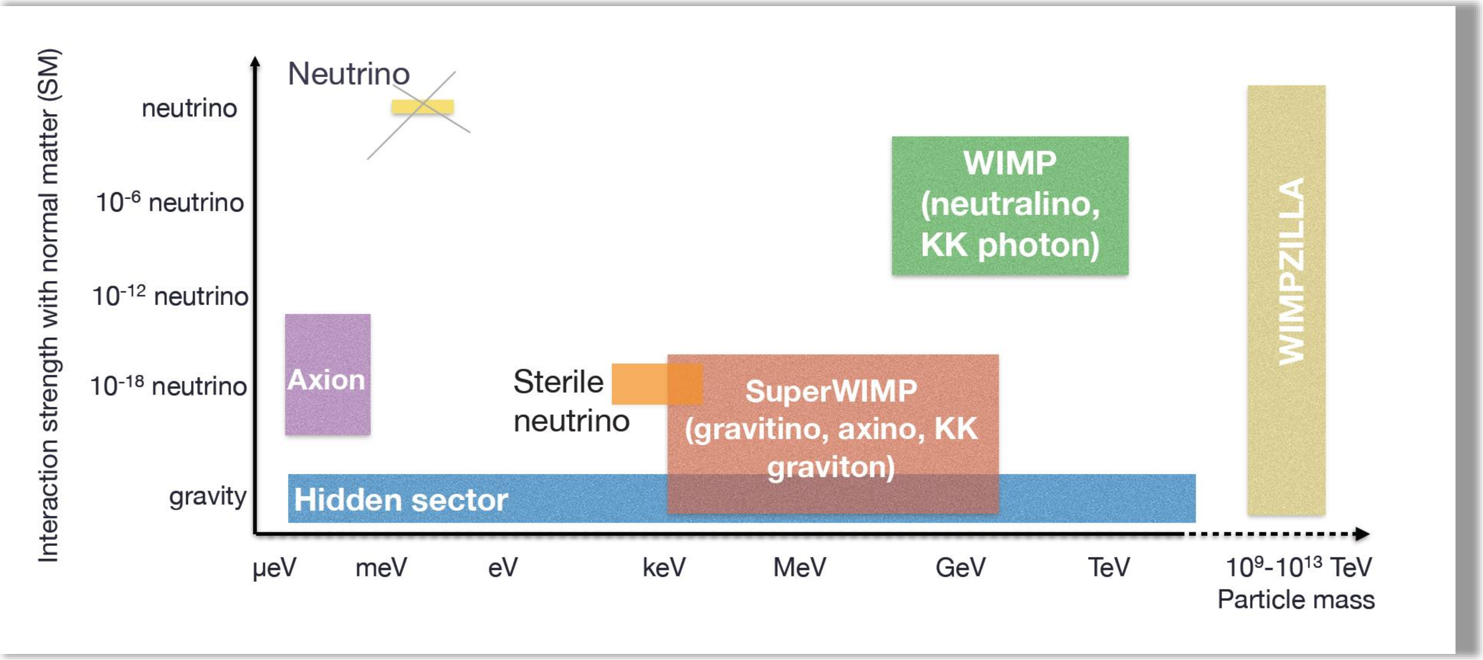
Bullet cluster and gravitational lensing

Lensing and optical observation of two galaxy clusters collision. The DM particles (blue) interacting only weakly could pass through each other more easily than the barionic matter (pink).

ΛCDM model



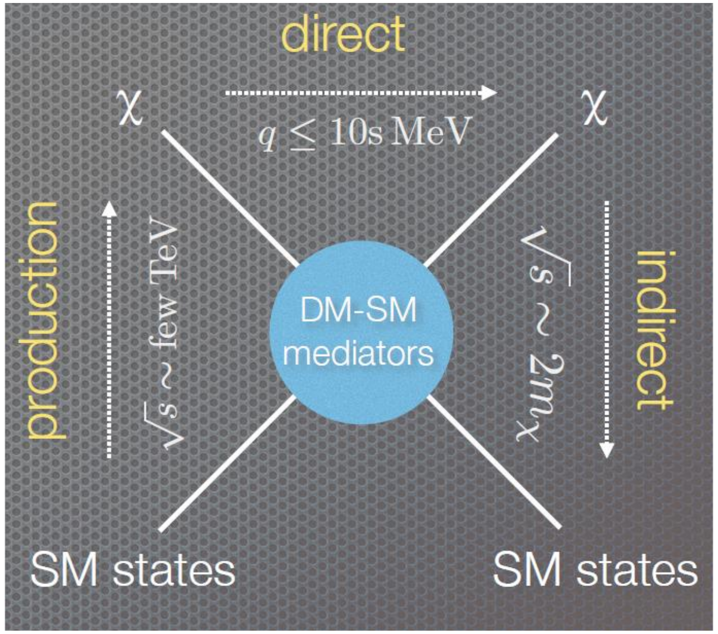
Detection of Dark Matter



The most searched candidate is a **Weakly Interacting Massive Particle (WIMP)** that decoupled when non relativistic and are provided by many theories beyond the SM like SUSY

Accelerator searches

Missing ET, mono-'objects', etc...
Can it establish that the new particle is the DM?



Indirect detection

High-energy neutrinos, gammas
look at over-dense regions in the sky.
Astrophysical backgrounds are difficult to model

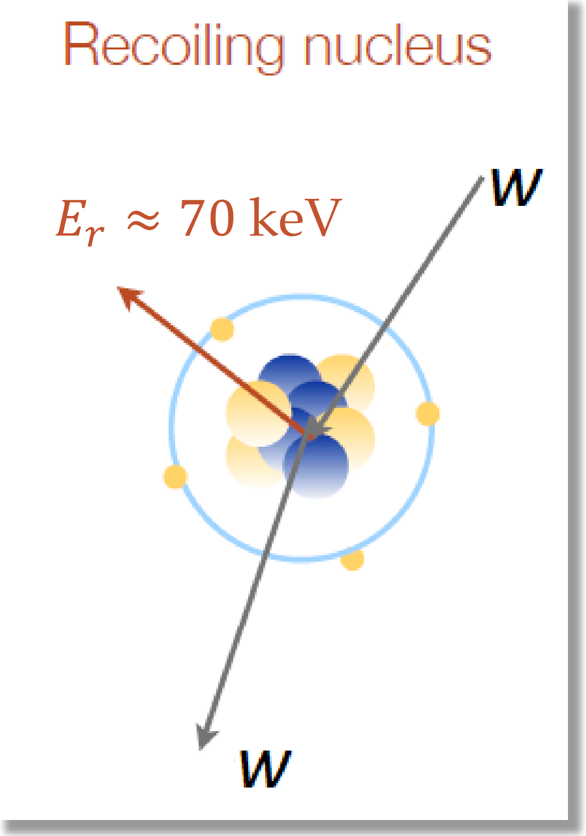
Direct detection

Nuclear recoils from elastic scattering
Dependence on A, J.
Local densitiy and v-distribution

The WIMP spectrum

Standard **recoil spectrum**, i.e. differential event rate **per unit detector** mass:

$$\frac{dR}{dE_r} \propto \frac{\sigma_{SI}^{p}}{2\,\mu_{\chi p}^{2} M_{\chi}} \quad A^2|F(E_r)|^2 \quad \rho_0 \int_{v_{min}}^{\infty} \frac{f_1(v)}{v}\, dv$$



Physics

σ_{SI}^{p} → WIMP-nucleon cross section

M_χ → WIMP mass

$\mu_{\chi p}$ → WIMP-nucleon reduced mass

$\mu_{\chi N}$ → WIMP-nucleus reduced mass

Target material

A → atomic mass of target material

$F(E_r)$ → The finite size of the nucleus is implemented with a nuclear **Helm form Factor**

E_{th} → Energy threshold

Astrophysics (DM halo properties)

ρ_0 → local WIMP mass density

$f(v)$ → WIMP velocity distribution

v_{min} → minimum WIMP speed required to transfer an energy E_r to the nucleus of mass m_n in the detector.

E_r → Recoiling nucleus energy

$$v_{min} = \sqrt{m_N E_r / (2\mu_{\chi N}^2)}$$

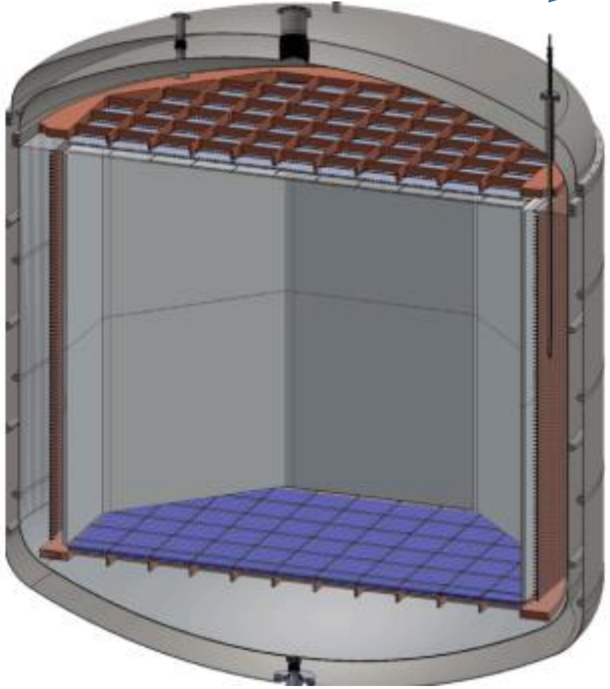
The DarkSide Program

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022

Past — Present — Future

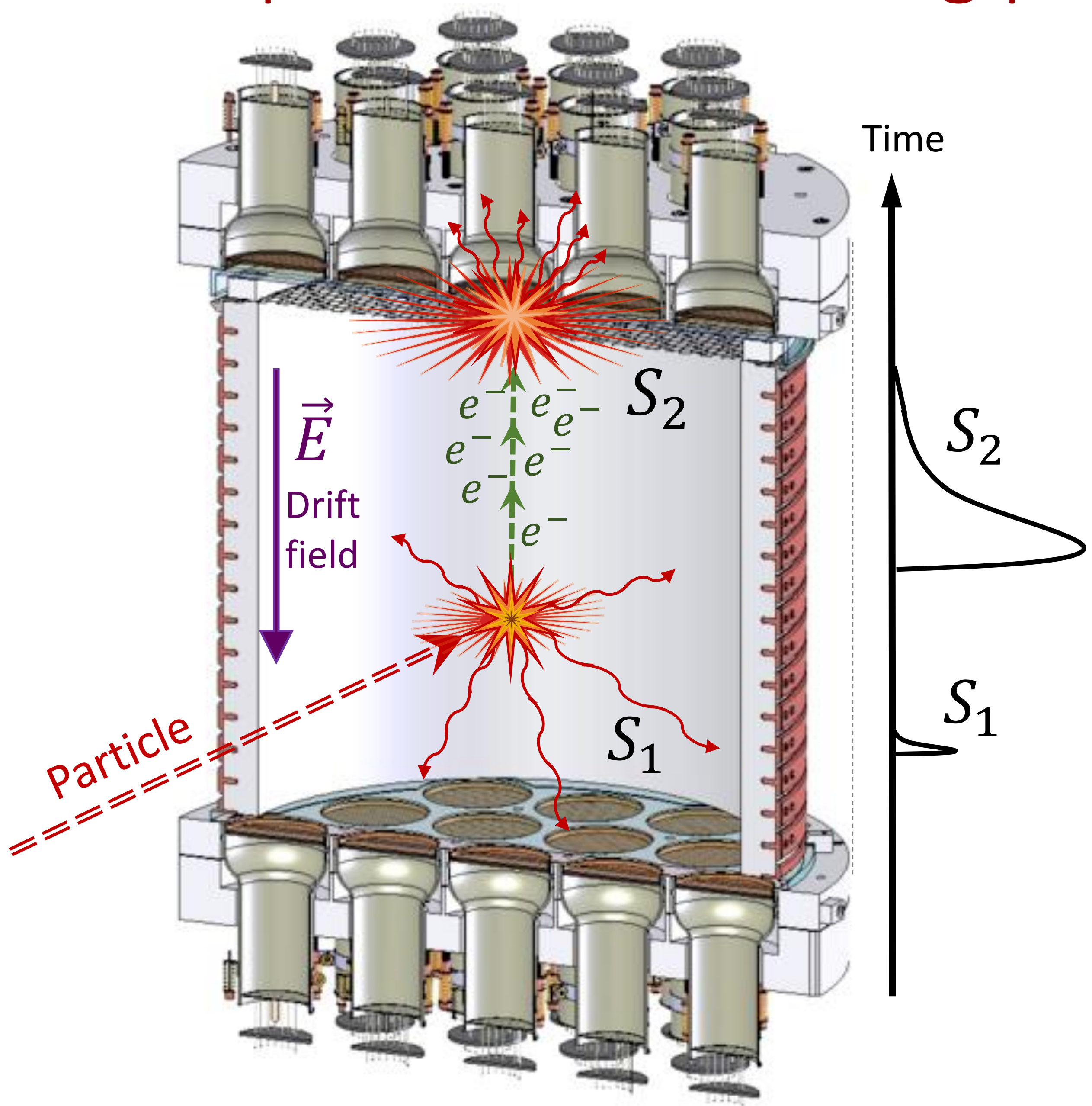
DarkSide-10
Technical prototype
No Dark Matter goal

DarkSide-50
Sensitivity to WIMP-nucleon cross section $10^{-44}\ cm^2$ for a WIMP mass of 100 GeV/c^2



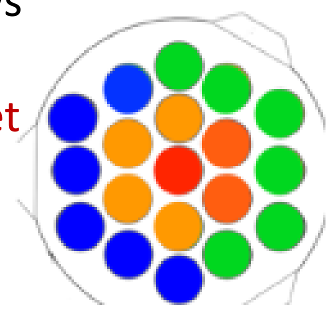
DarkSide-20k
Sensitivity to WIMP-nucleon cross section $10^{-48}\ cm^2$ ($10^{-47}\ cm^2$) for a WIMP mass of 100 GeV/c^2 (1 TeV/c^2)

Dual-phase TPC: working principle



Light collected by top and bottom PMT arrays

- S1 = Primary scintillation in liquid Ar
- S2 = Secondary scintillation in Ar gas pocket
- S1 & S2 -> full energy deposition
- Drift time -> vertical (z) position
- S2 Channel light pattern -> xy position



S2 pattern on top PMTs

Why Argon?

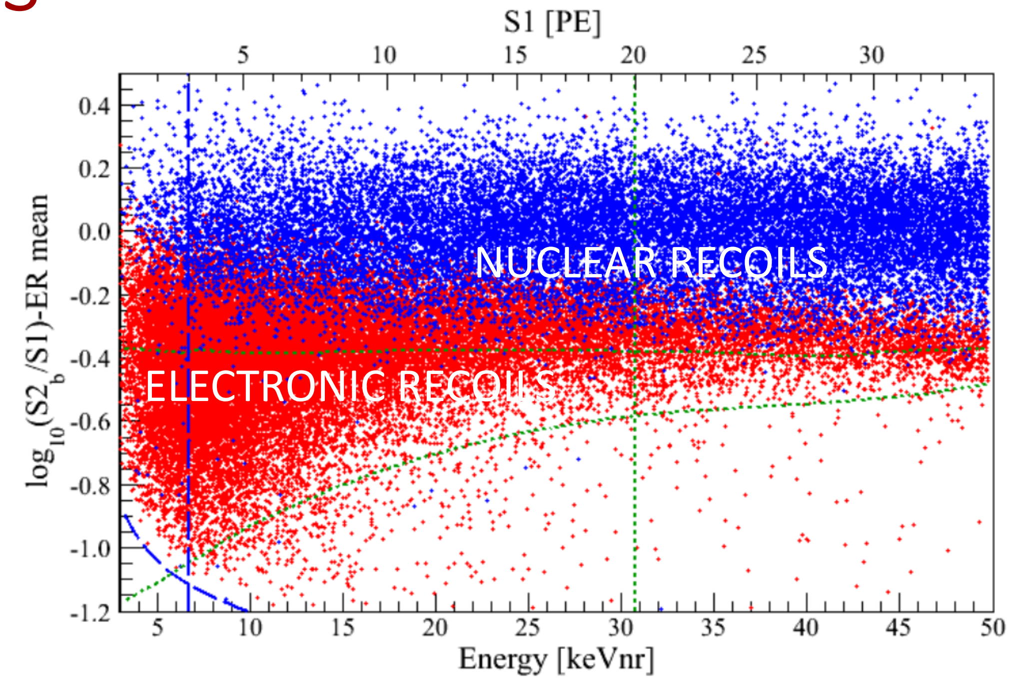
Discrimination: Pulse Shape Discrimination (PSD)

- Ar scintillation decays with 2 states, $\tau_{\text{singlet}} \sim 7$ ns and $\tau_{\text{triplet}} \sim 1600$ ns.
- NR produces more τ_{singlet} and less τ_{triplet} states than ER.
- f_{90} = the fraction of S1 light collected in the first 90 ns.
- f_{90} rejection $\sim 10^7$ for single scatter ER

Nuclear recoils VS electron recoils

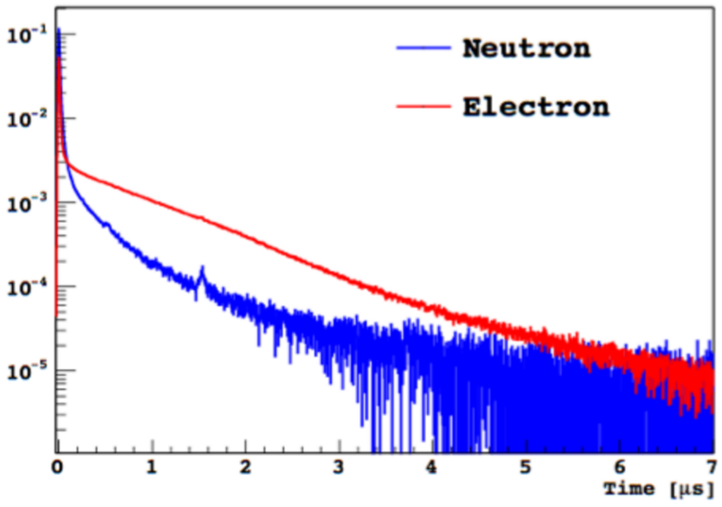
XENON: S2/S1

With the separation achieved by XENON100, it is found that a **99.5% Electronic Recoil discrimination** corresponds to a **50% acceptance of Nuclear Recoil events**, while 99.75% ER discrimination gives 40% Nuclear Recoil acceptance.



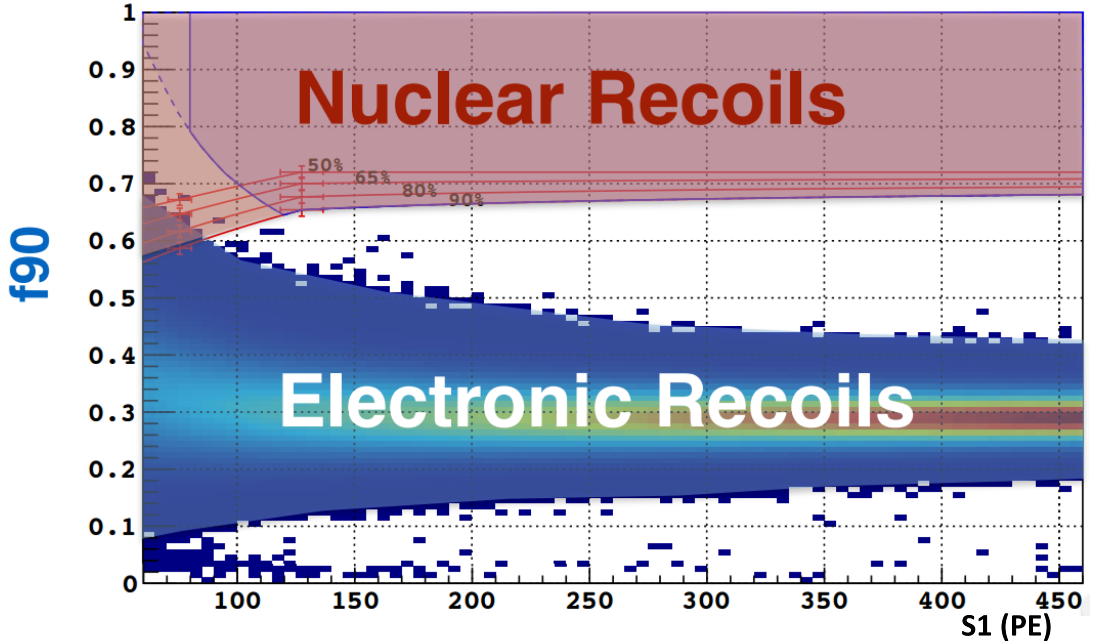
ARGON: S1 Pulse Shape Discrimination (PSD)

Argon has a fast component with a 7 ns decay time, or a slower component with 1.6 µs decay time depending on the nature of incident particle.



In DarkSide-50, we used the discrimination parameter f90, defined for each scintillation event as the fraction of primary scintillation light (S1) collected in the first 90 ns of the pulse.

Rejection power >10^7



The DarkSide-50 detector

- Current detector has ~50 kg active mass.
  - Challenge: intrinsic ^{39}Ar ß-decay

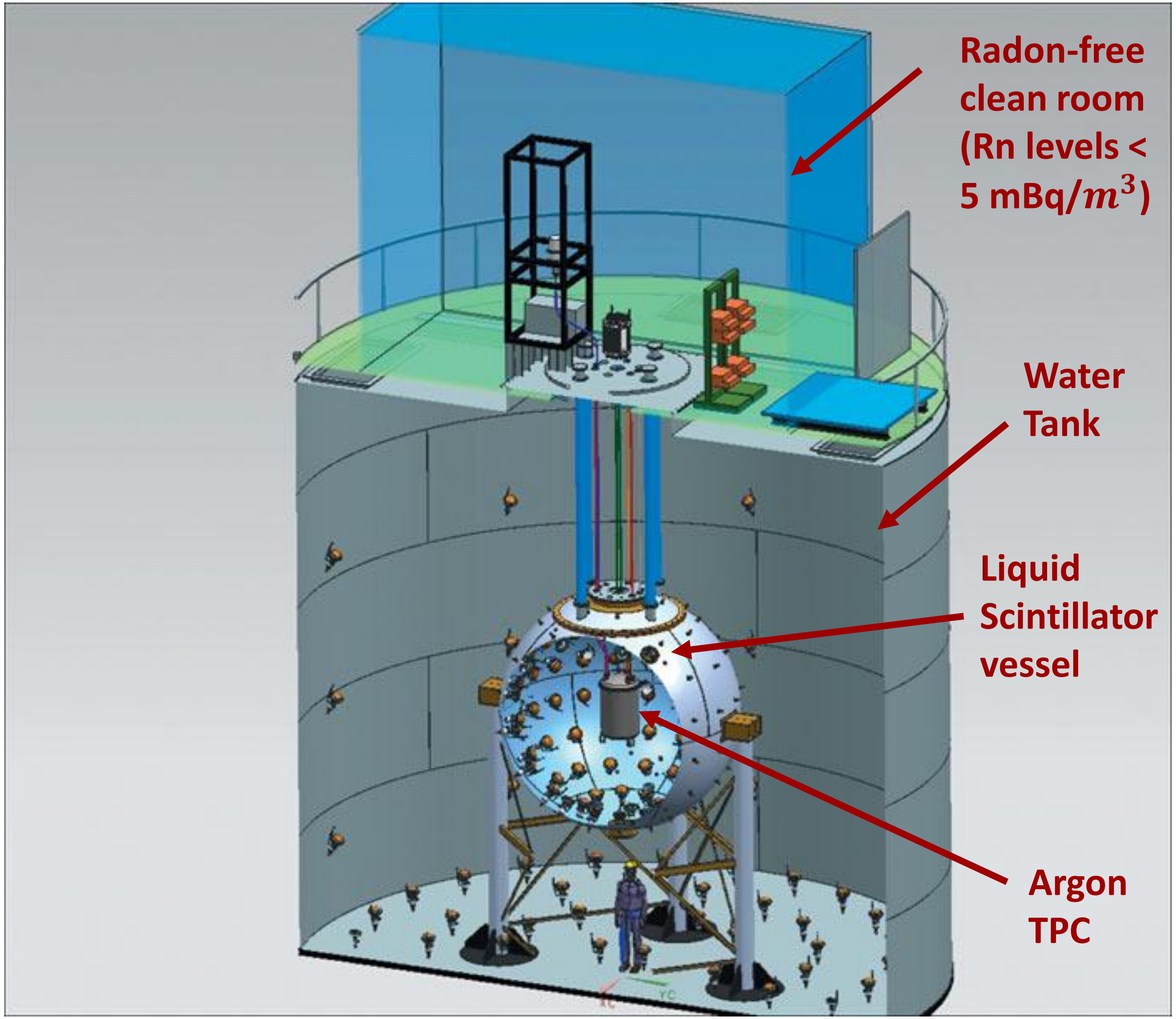
(T1/2: 269 yr, Q: 565 keV). ~1 Bq/kg in atmospheric argon.

Solution: extract low radioactivity argon from underground source (^{39}Ar depletion factor >1400)

TPC was previously loaded with atmospheric argon, now loaded with low radioactive underground argon

Active shielding:

- Neutron and $\gamma's$ Veto: 4 m diameter filled with 30-tonne boron-loaded liquid scintillator with veto efficiency above 99.8 %
- Muon Veto (Water Cherenkov Detector 1,000-tonne Cosmic Ray Veto) with veto efficiency above 99.5%
- Designed to be background-free (<0.1 background events in the nominal exposure) with various active techniques to reject backgrounds



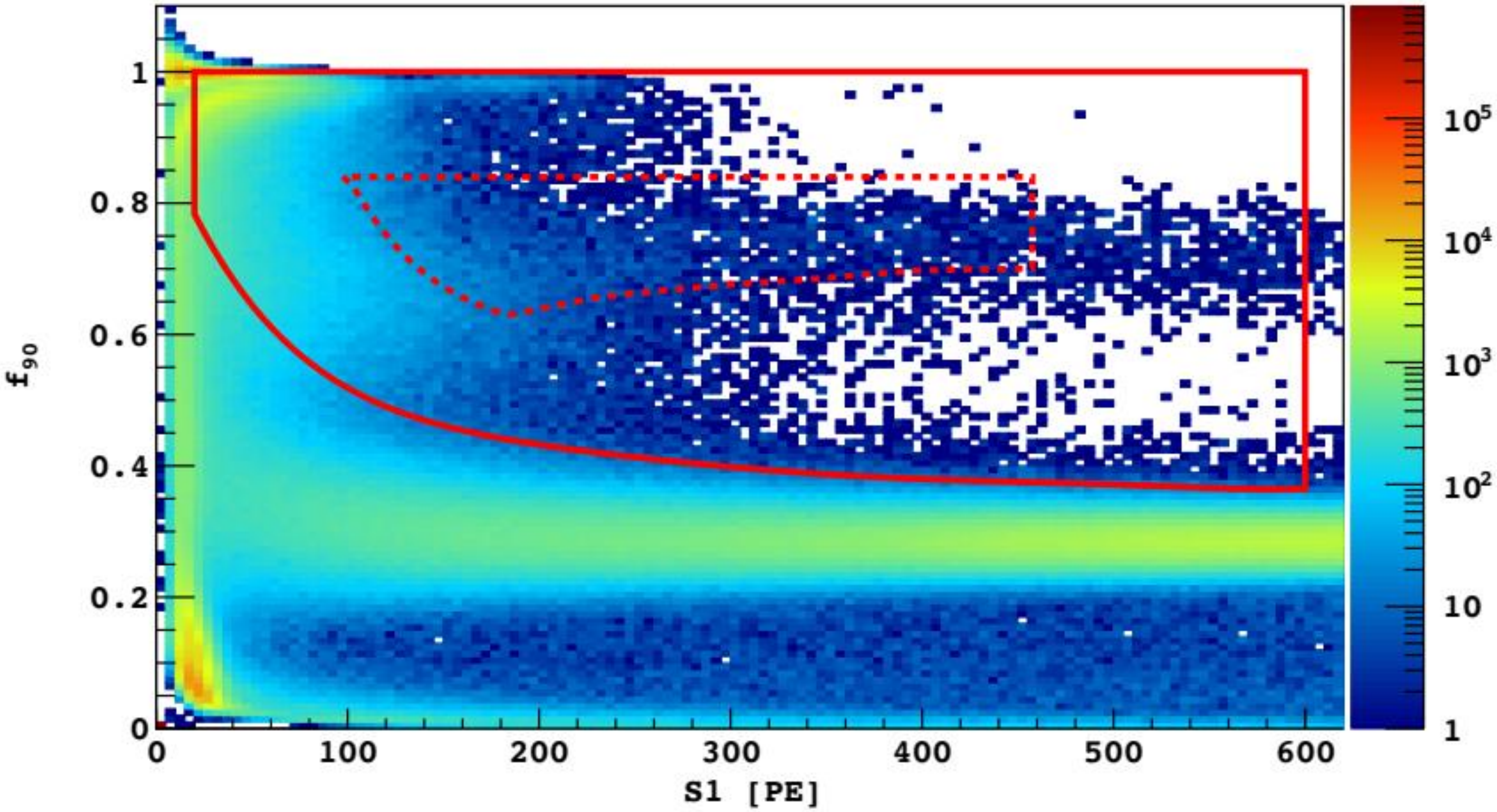
Menu of the day

NEW

On Arxiv the 20th of February 2018

High-Mass Search: A blind analysis of the 532 live-days of data

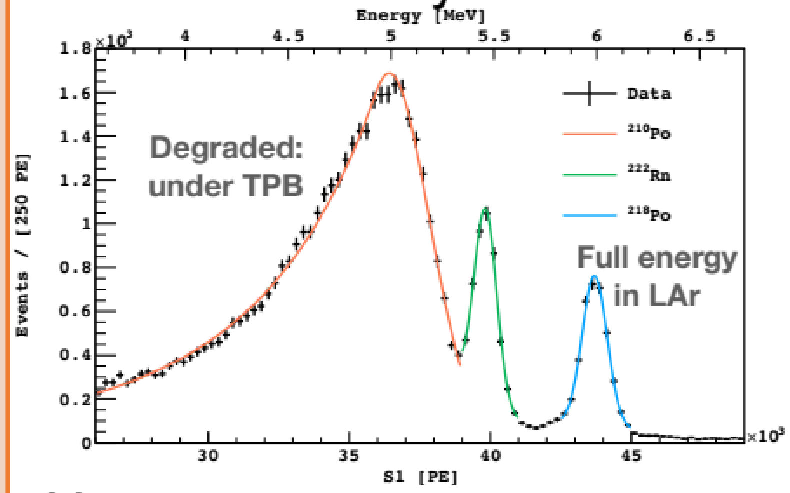
f_{90} = the fraction of S1 light collected in the first 90 ns



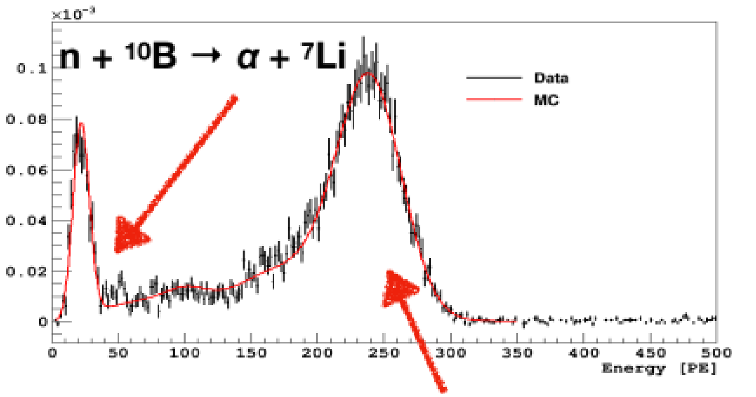
- Blinding box (red outline) shown with 71-day data: PRD 93, 081101 (2016)
- Goal: **design an analysis that will have <0.1 events of background** in the to be-designed search box. (Final box chosen: dashed red)

Nuclear and Electron recoil backgrounds

Surface α decays



Neutrons



n + ^{10}B → α + ^{7}Li + γ

Background rejection:

- S1 < 460
- Self-vetoing in DS-50!
  -Small or no S2
  -Long scintillation tail from TPB

Background rejection:

- TPC: multi-scatter
- LS Veto

Measured neutron efficiency with Am-C for TPC single-NR is 0.9964±0.0004

- Cosmogenics:

Water Cherenkov Veto

Electron Recoils: S1 + Cherenkov

γ-ray multiple-Compton scatters once in LAr and again in a nearby Cherenkov radiator.

Background rejection:

- Underground argon
- S1 fraction in max PMT
- PSD: f90 = S1 fraction in first 90 ns

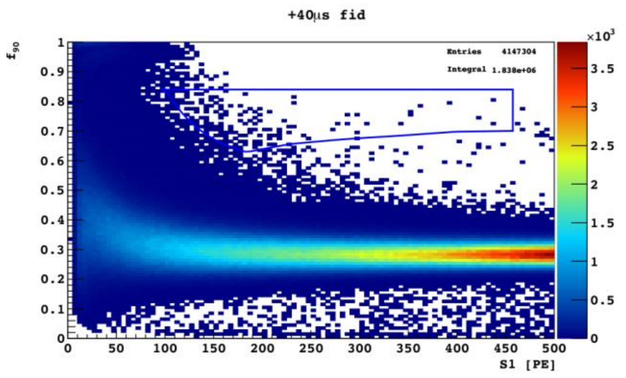
(*) Design cut to reduce ER to <0.08 event of background

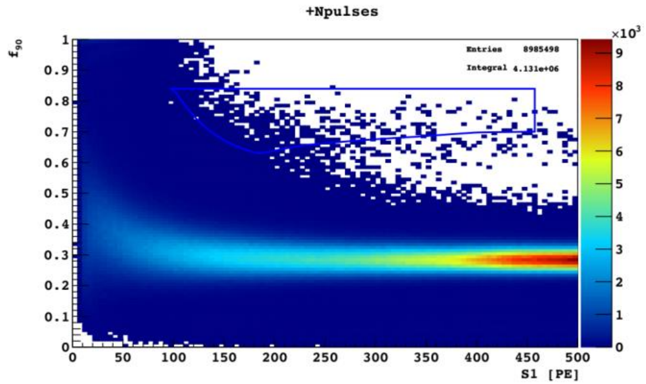
Summary of NR and ER backgrounds

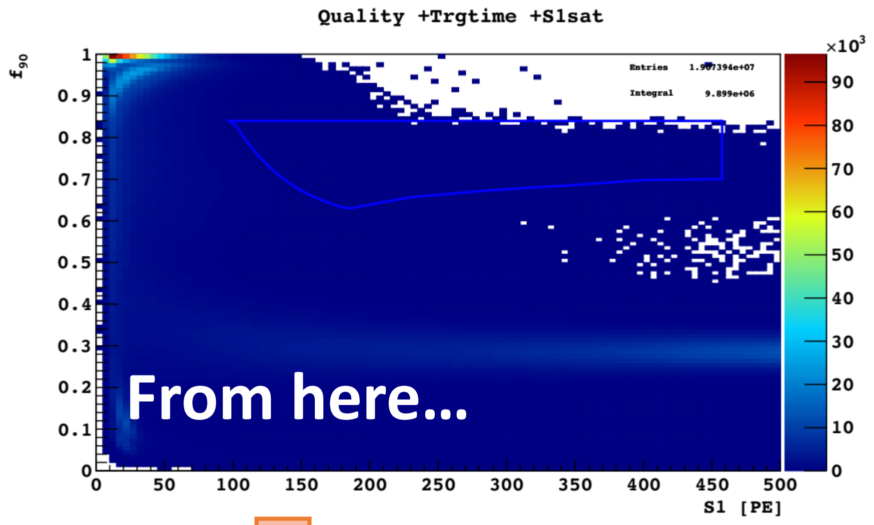
Background	Est. Survive
Surface a decays	0.001
Cosmogenic n	<0.0003
Radiogenic n	<0.005
ER S1+Cherenkov	0.08*
Total	**0.09±0.04**

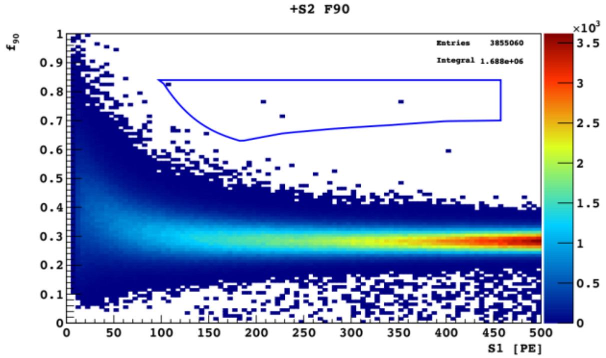
Goal achieved: open the box!

After unblinding: Step by step…

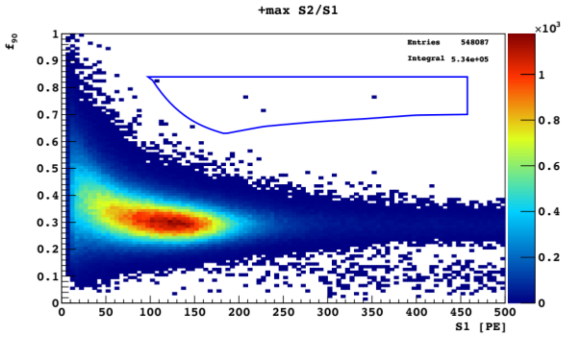


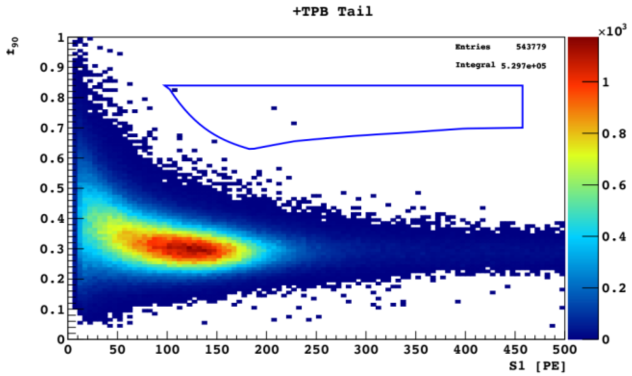




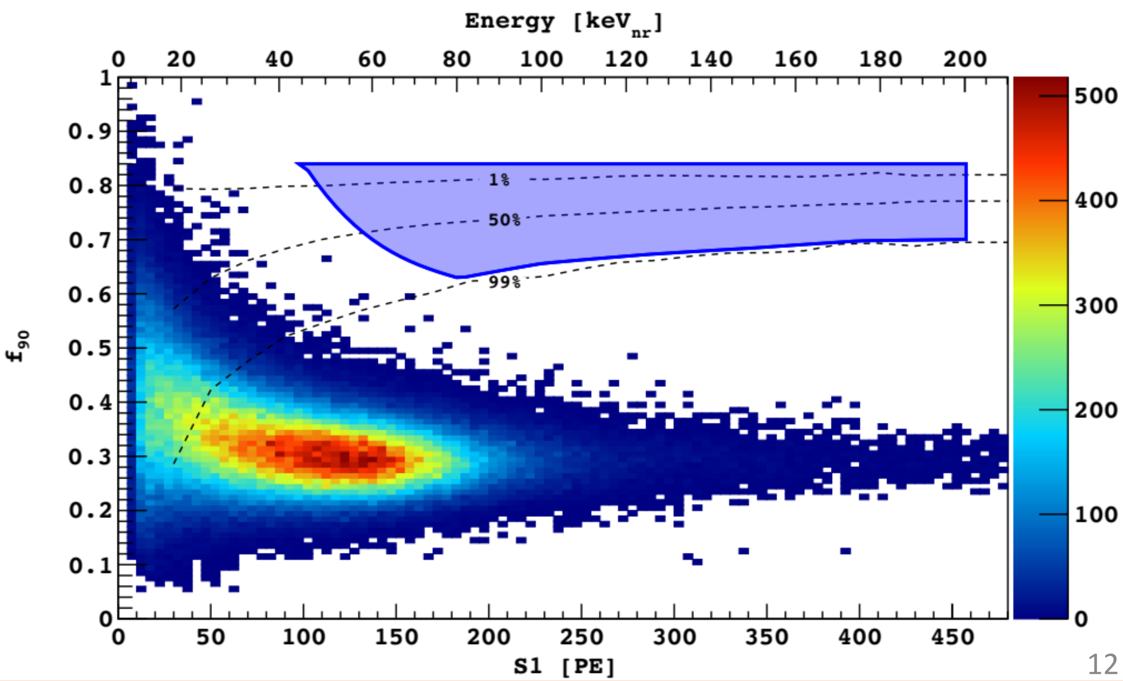


Cut over cut…



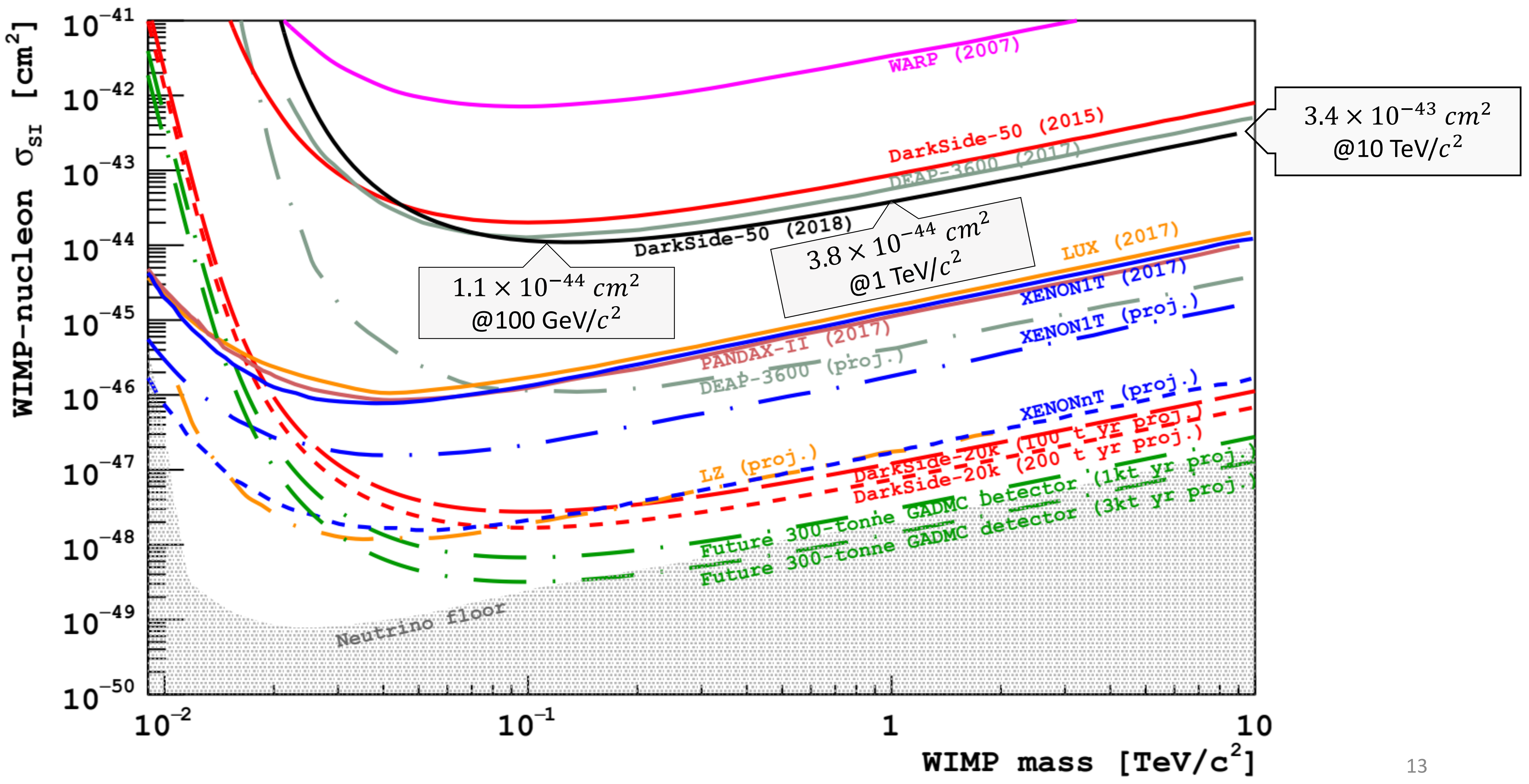


…to here: the final data set



The 90% C.L. exclusion limit

ArXiv:1802.07198 *DarkSide-50 532-day Dark Matter Search with Low-Radioactivity Argon*



Low-mass WIMP search with ionization only data

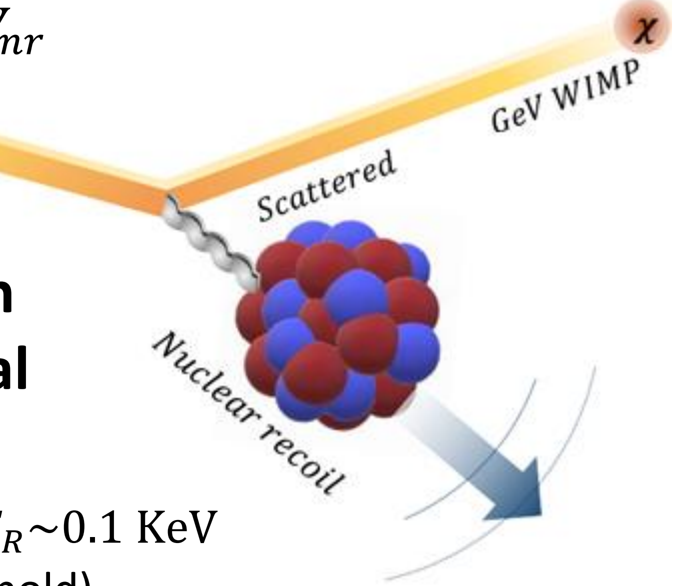
ArXiv:1802.06994 *Low-mass Dark Matter Search with the DarkSide-50 Experiment*

$$E_R = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v^2}{m_N} \simeq 50\ keV \left(\frac{m_\chi}{100\ GeV}\right)^2 \left(\frac{100\ GeV}{m_N}\right)$$

$m_N^{Ar} \sim 37$ GeV

For $m_\chi = 10$ GeV ➡ $E_R \sim 1.4$ KeV

Below threshold for S1 production ($\sim 6\ keV_{nr}$) but S2 has threshold $\sim 0.4\ keV_{nr}$



GeV DM-nucleus scattering causes an ionization (S2) signal

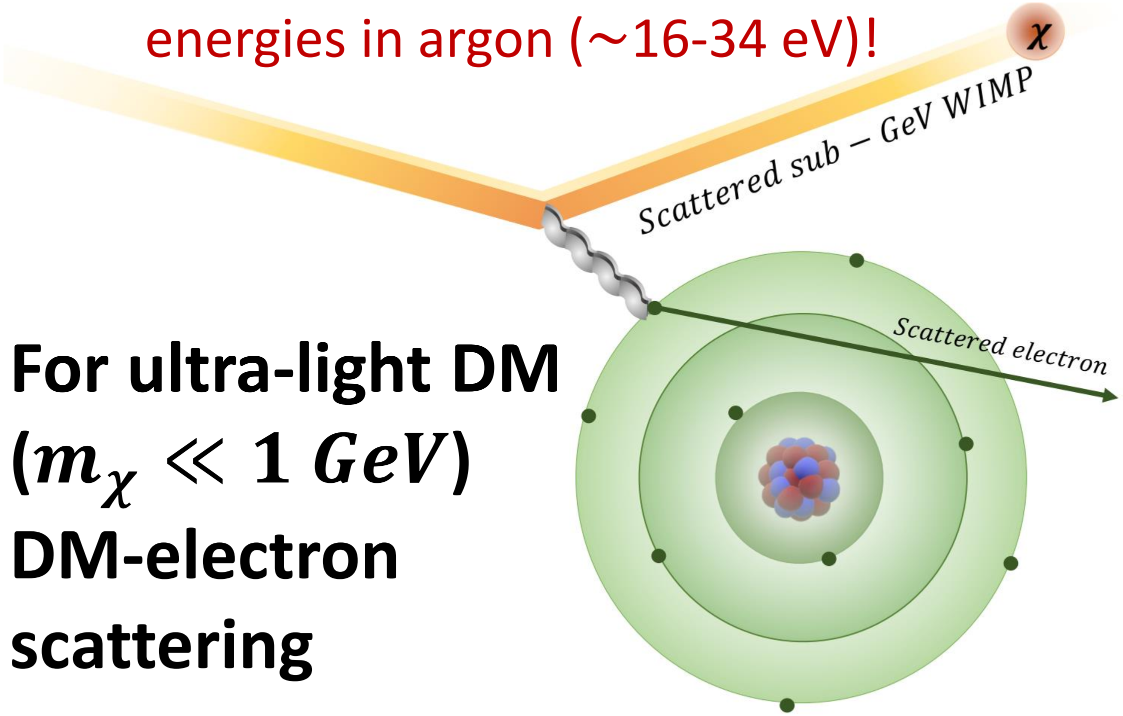
*(For $m_\chi = 100$ MeV -> $E_R \sim 0.1$ KeV below the ionization threshold)

ArXiv:1802.06998 *Constraints on Sub-GeV Dark Matter-Electron Scattering from the DarkSide-50 Experiment*

$$E_R = \vec{q} \cdot \vec{v} - \frac{q^2}{2\mu_{\chi N}} \sim \frac{1}{2}\ eV \times \left(\frac{m_\chi}{MeV}\right)$$

For $m_\chi = 100$ MeV ➡ $E_R \sim 50$ eV

Comparable with electron binding energies in argon (~16-34 eV)!



For ultra-light DM ($m_\chi \ll 1\ GeV$) DM-electron scattering

Ionization measurement

Scintillation signal (S1): threshold at $\sim 2\ keV_{ee}$ / $6keV_{nr}$ weak sensitivity to low mass WIMPs.

In DS-50, we easily detect single ionization electrons

Ionization signal (S2): threshold > $\sim 0.1\ keV_{ee}$ / $0.4keV_{nr}$
Sensitive to low mass WIMPs!!

We use Ionization (S2) only

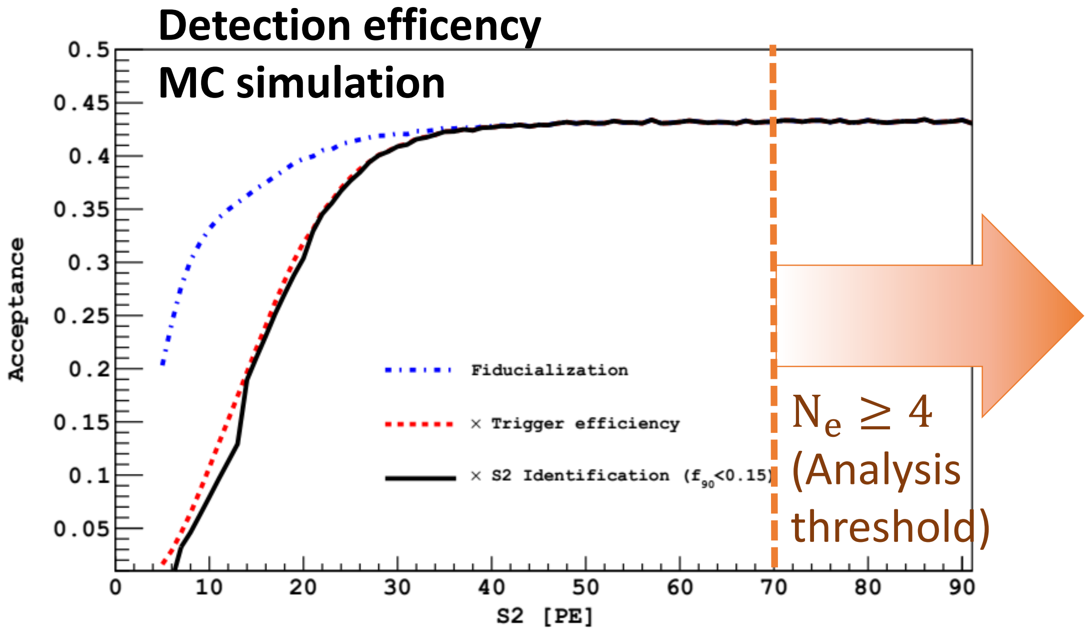
Detection efficiency: estimated from Data + MC

Fiducialization: use volume under 7 central PMTs

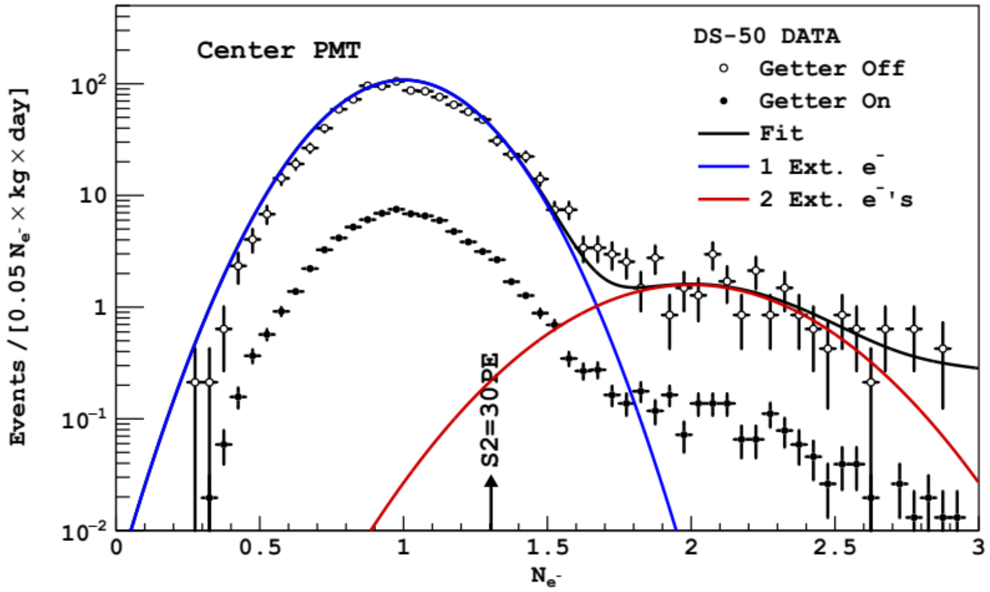
In DS-50, we can detect down to **single electron:**

Single-electron lineshape

One ionization electron ($N_e = 1$) under the center PMT creates 23 ±1 PE



The efficiency is flat above the analysis threshold of number of electrons >4

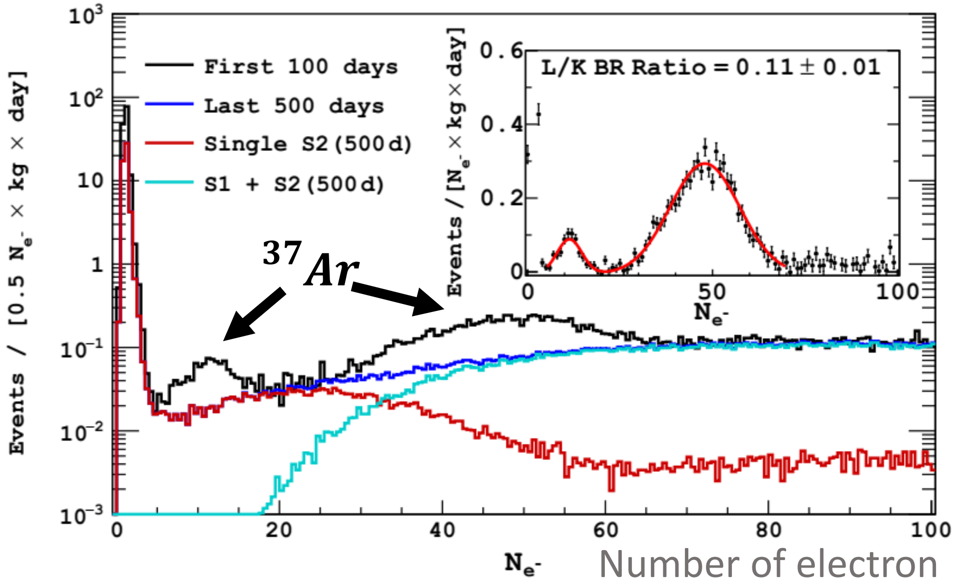


Energy scale for ER and NR

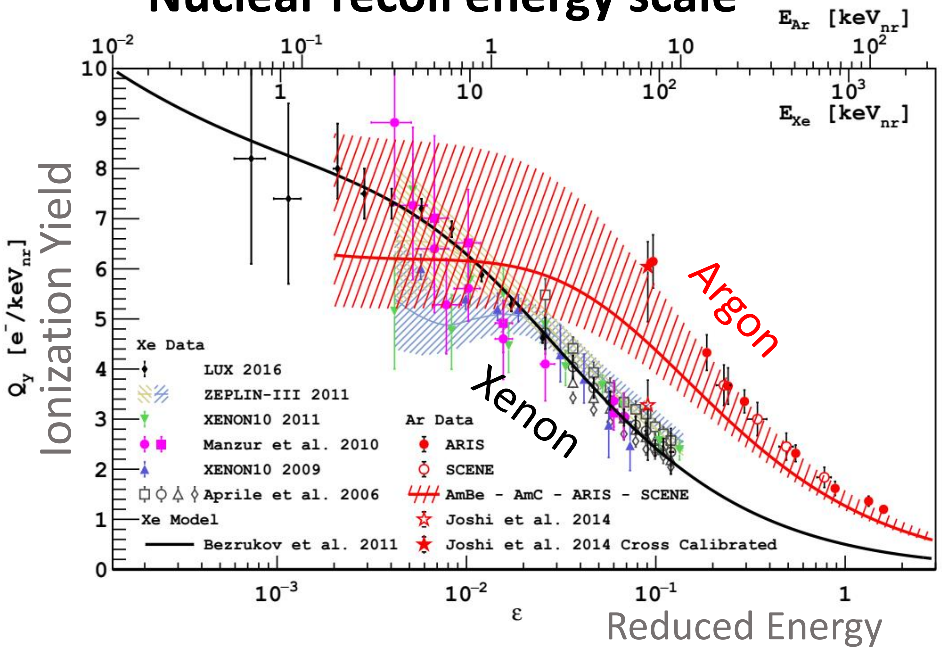
- ^{37}Ar provides two x-rays, 2.82 keV and 0.27 keV.
- ^{37}Ar Decayed out with 35 day half-life and not remain in the last 500-days data set.
- Good agreement of BR with measured value.
- AmBe and AmC neutron sources are used to extract ionization yield at ROI
- The difference between other measured points is take as systematics

NR ionization yield is obtained by fitting AmBe and AmC neutron calibration data

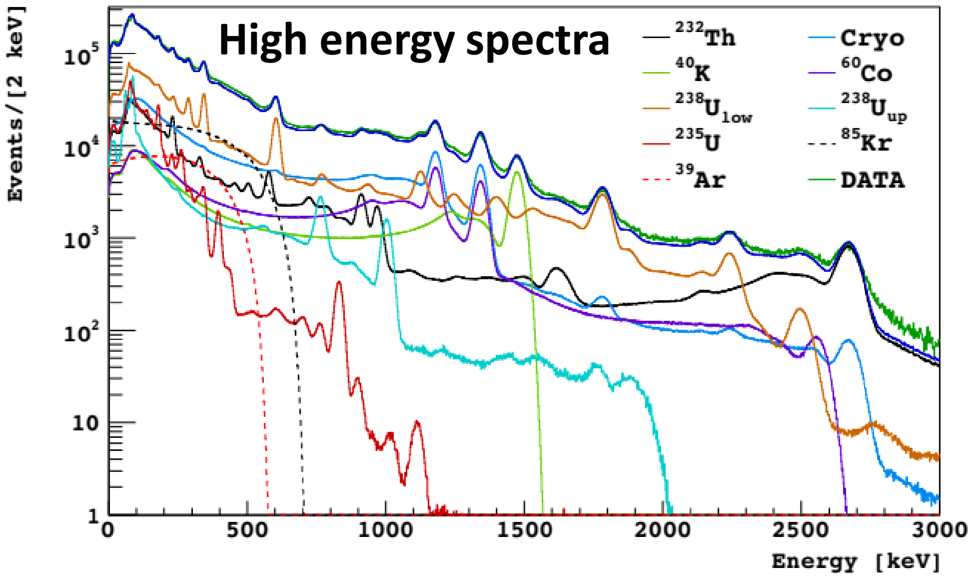
Electron recoil energy scale



Nuclear recoil energy scale



Background estimate and WIMP-nucleon signal

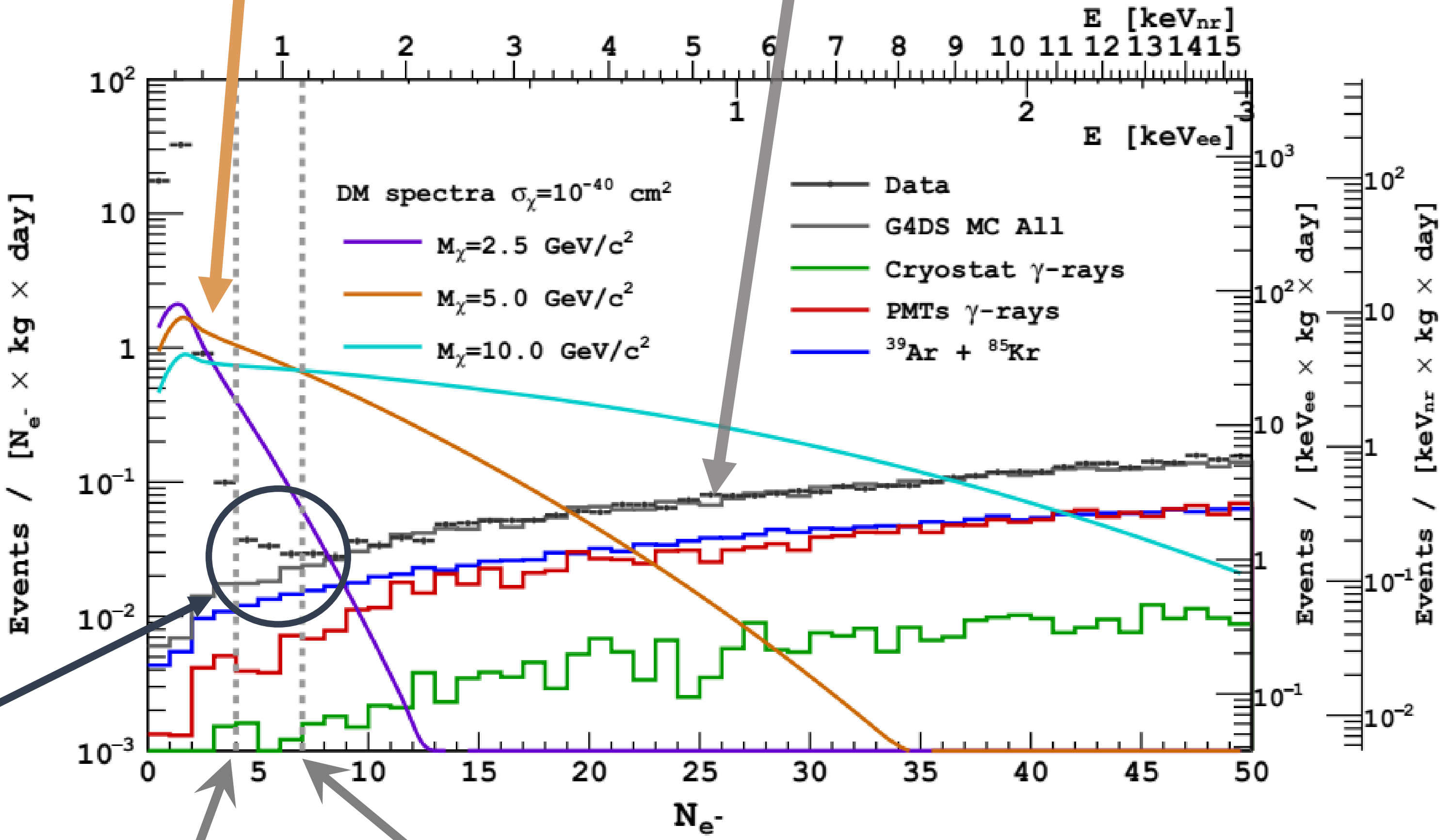


Detector activities from same analysis used for high-mass WIMP search

Extrapolation at low energy, OK within few %

WIMP spectra plotted with no "quenching fluctuations"

Data (points) and total MC background estimate (histogram)

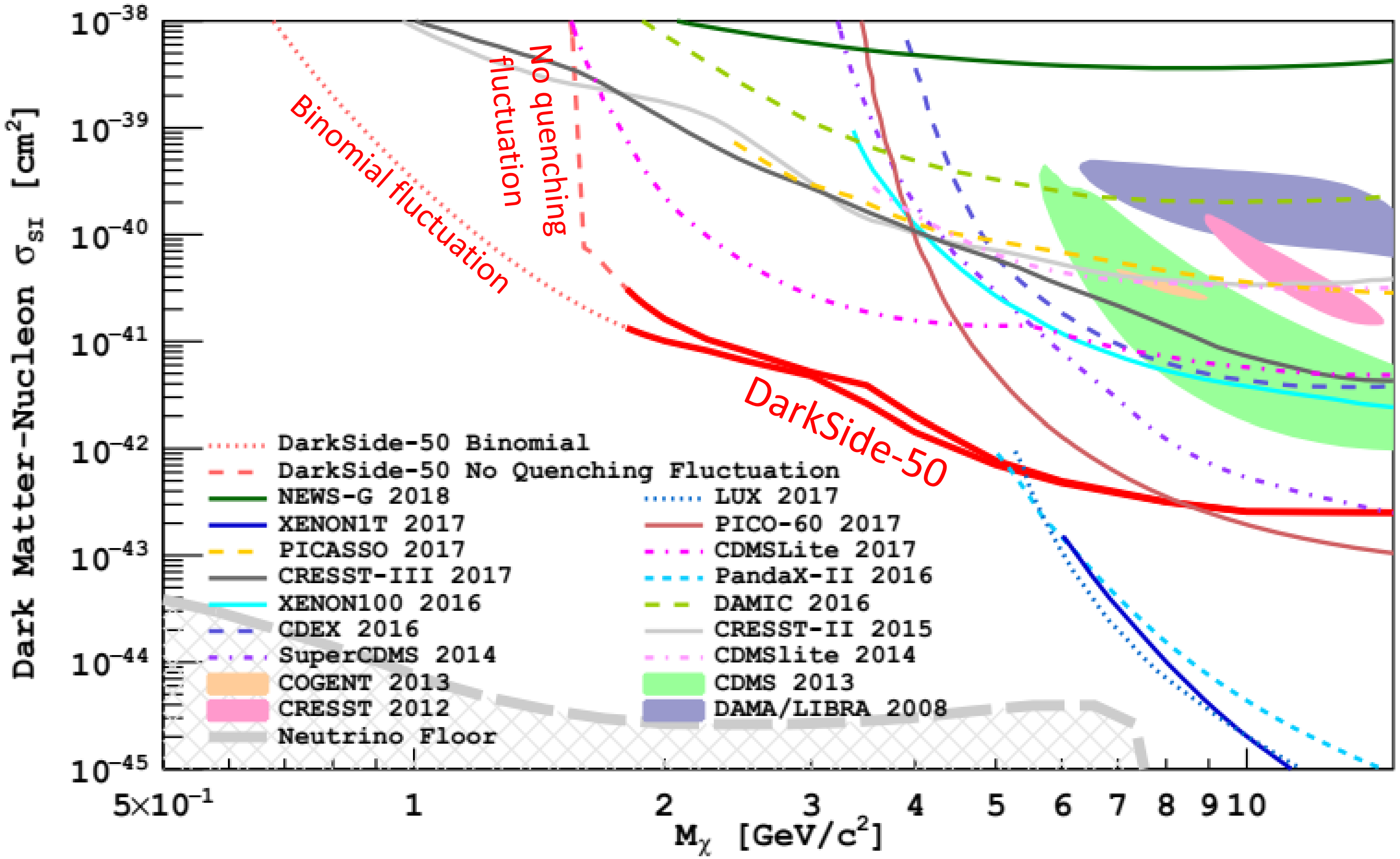


Excess of events due to tail of delayed electrons

Analysis threshold more sensitive for $M_\chi \geq 3.5$ GeV

Analysis threshold more sensitive for $M_\chi \leq 3.5$ GeV

The 90% C.L. exclusion limit



ArXiv:1802.06994

Profile Likelihood Method is used

- Uncertainties from both WIMP signals (NR ionization yield, single electron yields) and BG spectrum (rates, ER ionization yield)

Due to lack of knowledge about fluctuation at low recoil energy, two cases are considered.

- **Binomial fluctuation** for NR energy quenching, ionization, and recombination processes.
- **No Fluctuation** for NR energy quenching process. Corresponding to apply hard cut off in quenched energy ~0.6 keV_{nr}

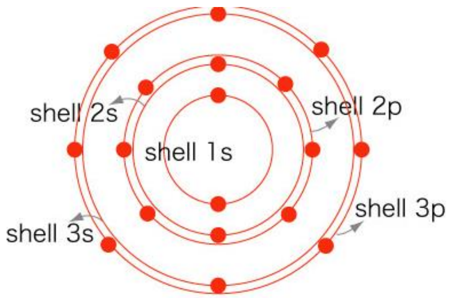
Interpretation for DM-electron scattering

DM-electron differential scattering rate

$$\frac{dR}{d\ln E_{\rm er}} = N_T \frac{\rho_\chi}{m_\chi} \frac{\overline{\sigma}_e}{8\,\mu_{\chi e}^2} \times \sum_{nl} \int dq\, q\, |f_{\rm ion}^{nl}(k',q)|^2 \, |F_{\rm DM}(q)|^2 \, \eta(v_{\min})$$

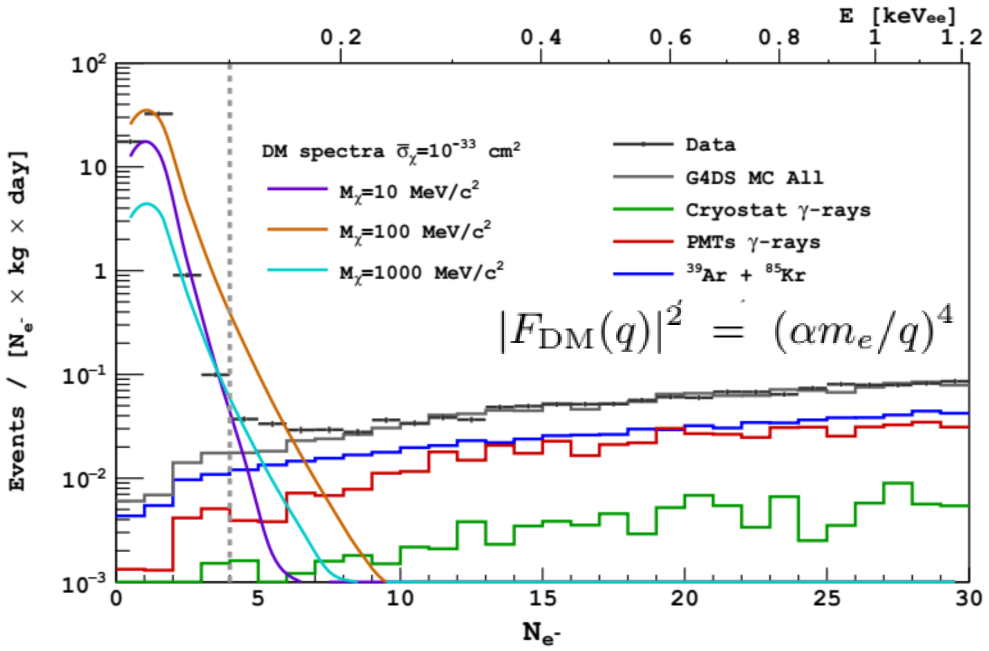
$$|F_{\rm DM}(q)|^2 = \begin{cases} 1, & m_{\rm med} \gg \alpha m_e \\ (\alpha m_e/q)^4, & m_{\rm med} \ll \alpha m_e, \end{cases}$$

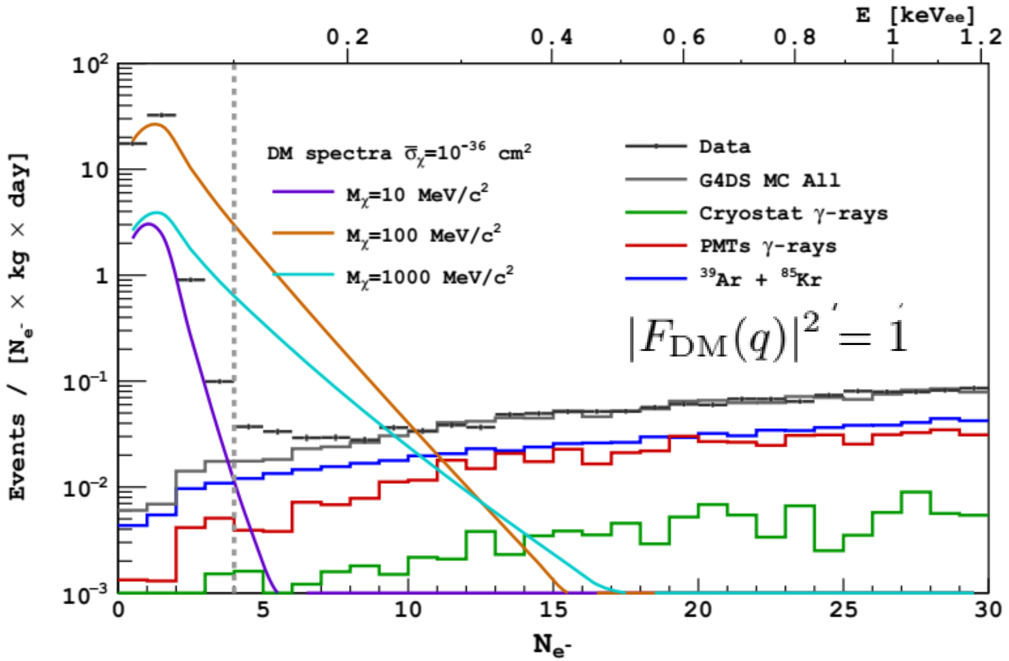
$$v_{\min} = \frac{|E_b^{nl}| + E_{\rm er}}{q} + \frac{q}{2m_\chi}.$$



$E_b^{3p} \sim 16.08$ eV, $E_b^{3s} \sim 34.76$ eV,
$E_b^{2p} \sim 260.45$ eV, $E_b^{2s} \sim 335.30$ eV, $E_b^{1s} \sim 3227.51$ eV

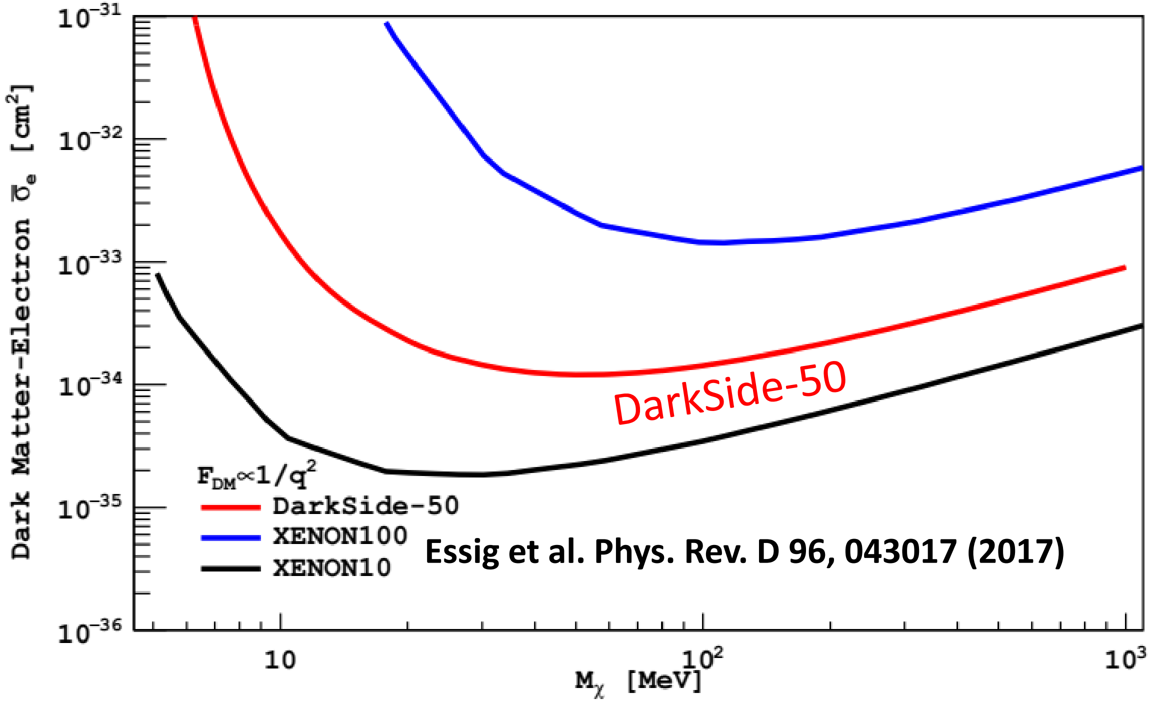
Ionization form factor: DM-e rate depends on the initial and final-state wavefunction of the electron. The outgoing wavefunction is obtained by solving the Schroedinger equation with a hydrogenic potential of some effective screened charge Zeff.



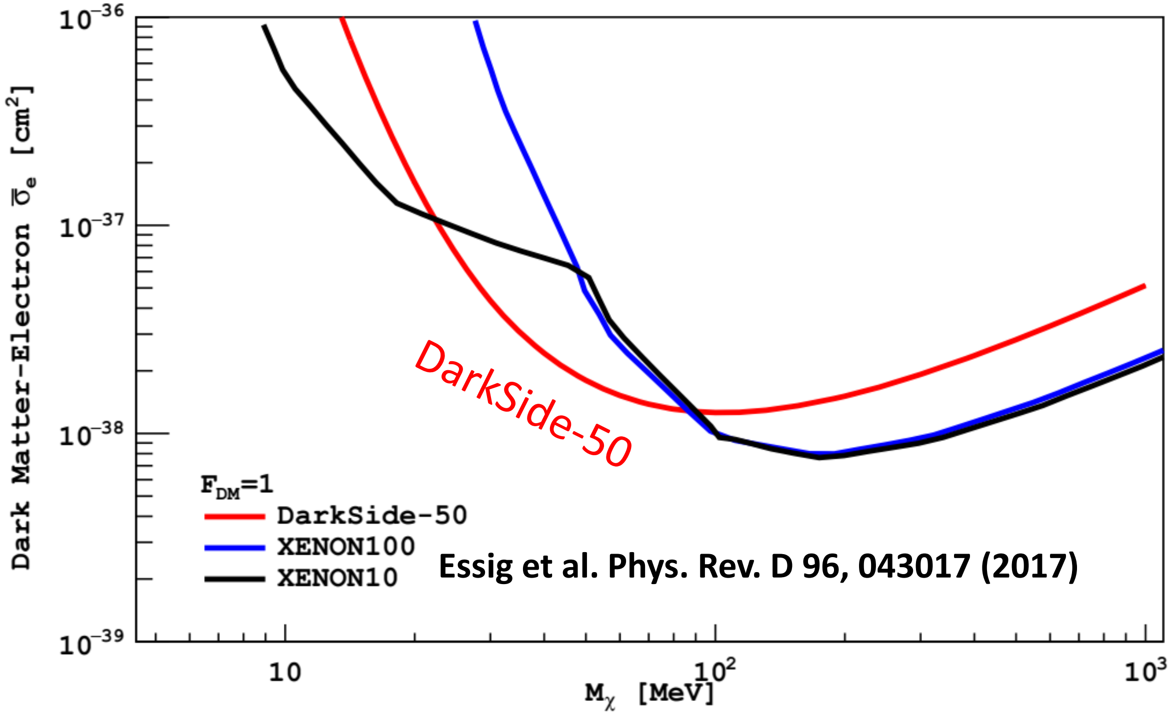


The 90% C.L. exclusion limit for DM-electron scattering cross section $(5 \leq M_{\chi}(MeV) \leq 1000)$

«Light mediator» regime (m_{med} is much lower than the typical momentum scale q_0)



«Heavy mediator» regime (m_{med} is much larger than the typical momentum scale q_0)



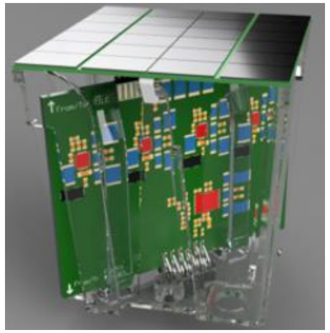
Profile Likelihood Method is used

- Uncertainties from ER ionization and single electron yields are included in both DM spectra and BG spectra
- In the case of a heavy mediator, F_{DM}= 1, **we improve the exclusion limit in the range from 20 MeV to 80 MeV.**

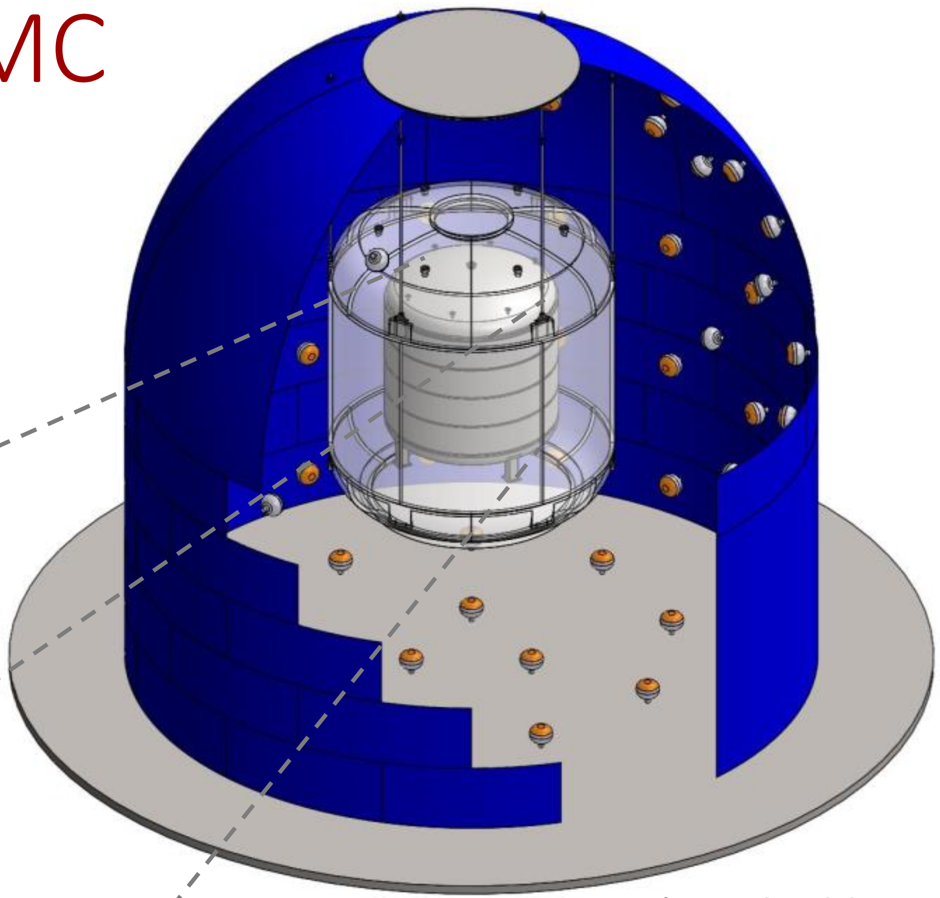
The future: DarkSide-20k and GADMC

Baseline design:

- 30 ton total, 20 ton fiducial, underground argon
- 15 m^2 SiPM sensors (low radioactivity)



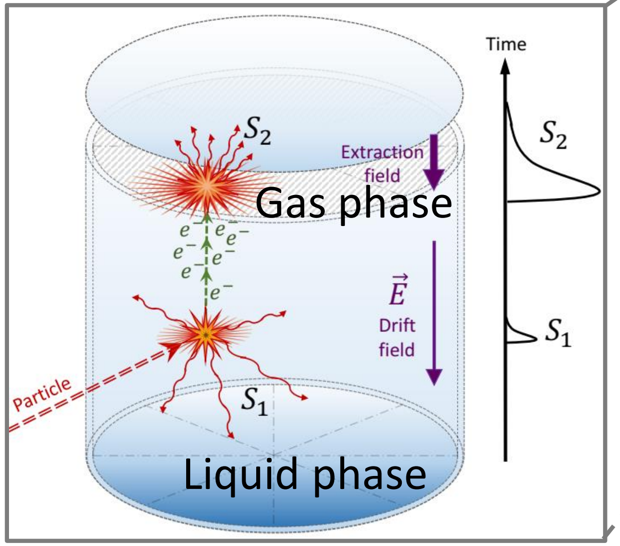
100 ton year background-free exposure (<0.1 events)



arXiv:1707.08145

Liquid argon target depleted in the radioactive ^{39}Ar

- **URANIA:** extraction of large quantities of underground argon
- **ARIA:** Isotopic separation via cryogenic distillation (distillation column to be installed in the Seruci mine in Sardinia)



Inner Liquid Scintillator (LS)
Outer Water Cherenkov (WC) Veto

- LSV targets events induced by internally- and externally-generated neutrons and γ-induced events
- WCV provides tagging of cosmic rays and shielding from radioactivity in the laboratory

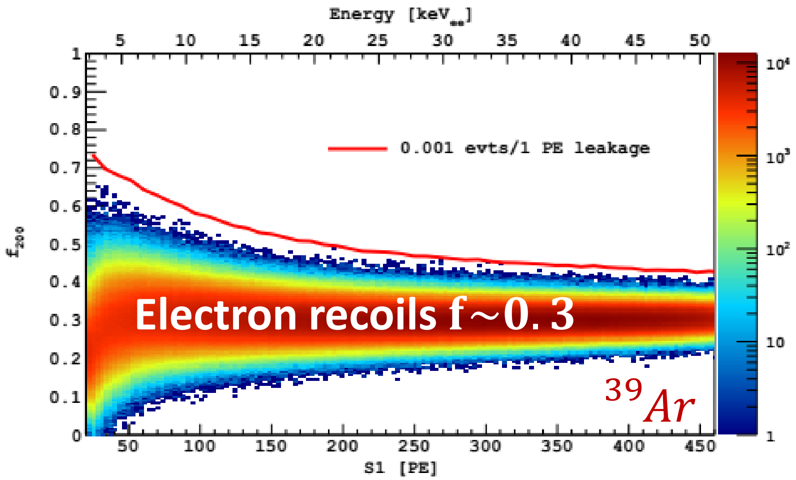
Backgrounds and nuclear recoil acceptance

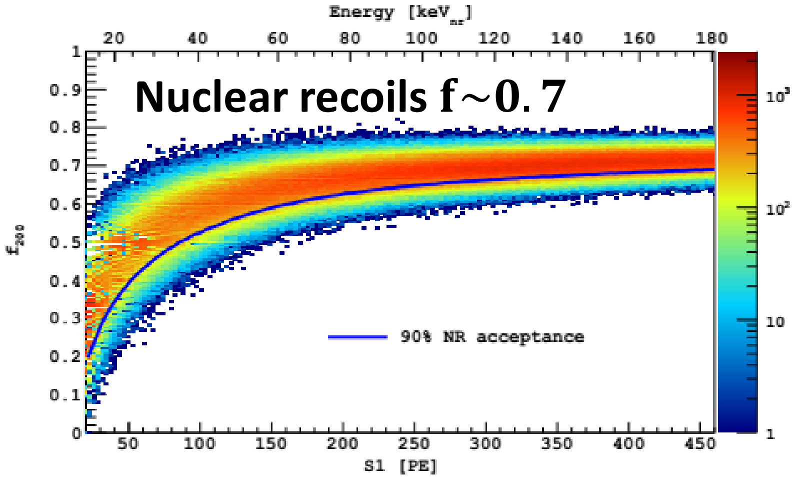
Being dark matter interactions very rare it is of utmost importance to contain the number of **instrumental background interactions to <0.1 events**, so that a positive claim can be made with few events as possible

PSD incorporated in the f_{200} parameter (the fraction of S1 detected in the first 200 ns of the pulse)

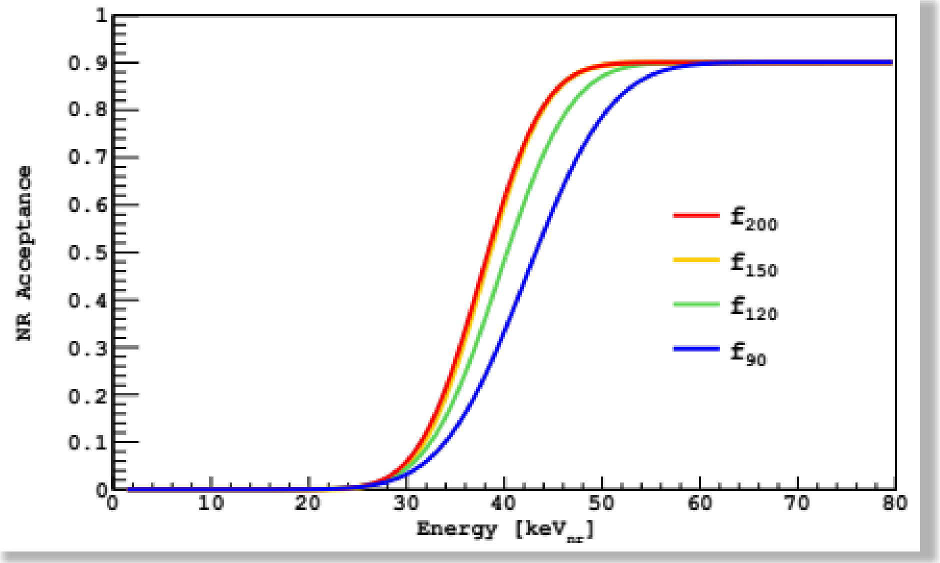
NR acceptance region defined by requiring < 0.005 ER events/(5-PE bin) (< 0.1 events in the WIMP search region) .

The resulting ER reduction factor is $> 3 \times 10^9$





Background	Events in ROI $[100\,\mathrm{t\,yr}]^{-1}$	Background $[100\,\mathrm{t\,yr}]^{-1}$
Internal β/γ's	1.8×10^8	0.06
Internal NRs	negligible	negligible
e^--ν_{pp} scatters	2.0×10^4	negligible
External β/γ's	10^7	<0.05
External NRs	<81	<0.15
Cosmogenic β/γ's	3×10^5	≪0.01
Cosmogenic NRs	–	<0.1
ν-Induced NR	1.33±0.26	1.33±0.26



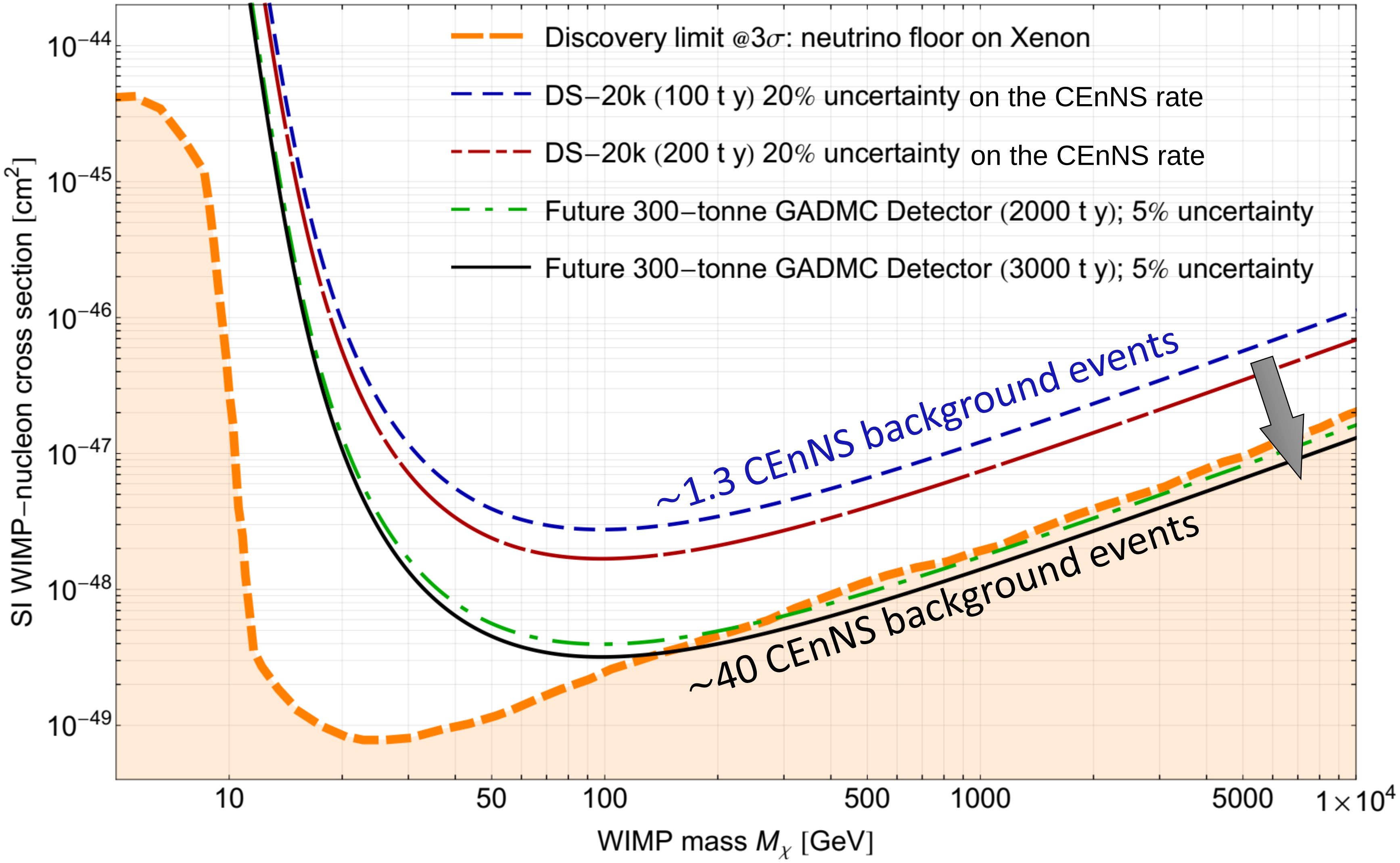
DarkSide-20k (GADMC) sensitivity

C. E. Aalseth et al., "DarkSide-20k: A 20 Tonne Two-Phase LAr TPC for Direct Dark Matter Detection at LNGS," Arxiv:1707.08145

(2021-) DarkSide-20k approved by INFN and LNGS in April 2017 and by NSF in October 2017
Officially supported by LNGS, LSC, and SNOLab.

(2027-) The argon community (ArDM, DarkSide, DEAP, MiniCLEAN) has coalesced into a Global Argon Dark Matter Collaboration (**GADMC**), to construct a **300 tonne** argon detector allowing a kilotonne-year exposure which will follow the DarkSide-20k experiment at LNGS.

90% CL WIMP-nucleon cross section in cm^2 sensitivity



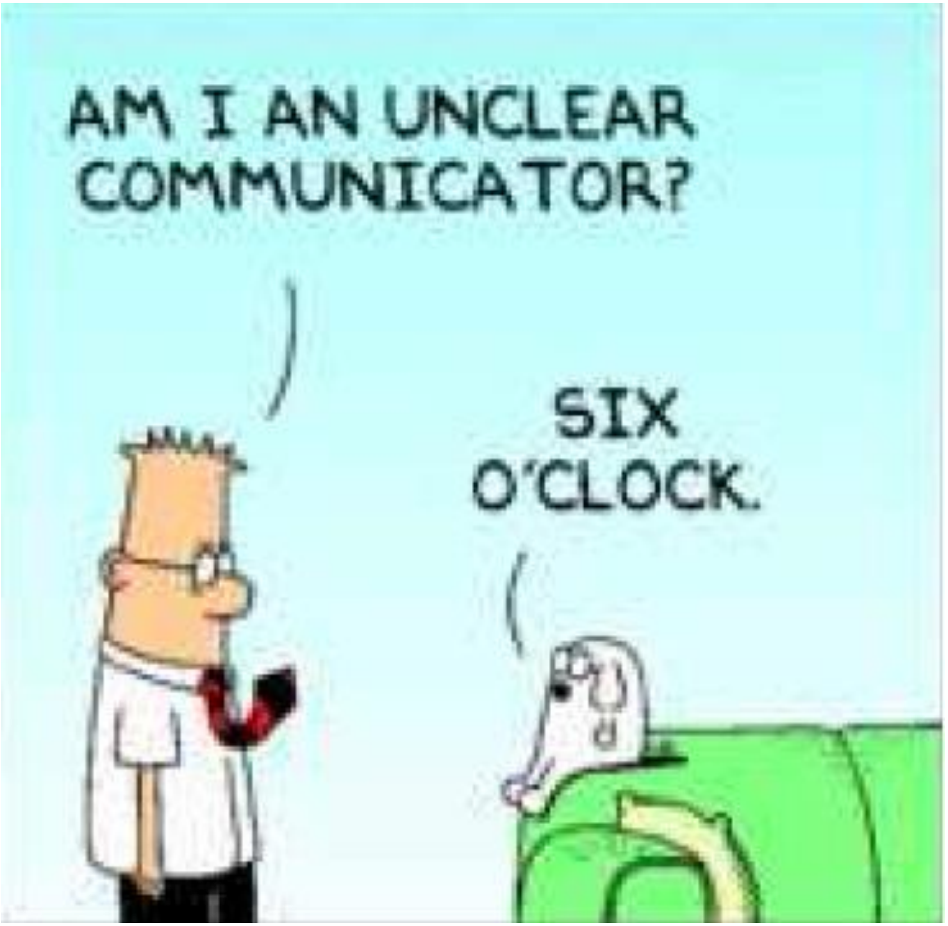
DS-20k (100 ty) will be able to exclude cross sections down to $2.8 \times 10^{-48}\ cm^2$ @100 GeV. For the same WIMP mass GADMC (3000 ty) $\sigma_{\chi p} = 3 \times 10^{-49}\ cm^2$

Conclusions

- Blind Analysis is successfully done with 532 live-days of data.
- Pulse Shape Discrimination (f90) is strong discriminator and necessary for “background free” WIMP search at high mass.
- Liquid Argon is also sensitive to low mass WIMPs and sub-GeV DM.
- Next generation DarkSide-20k is coming!
- Stay tuned for new results!!

Thanks for your attention

BACKUP



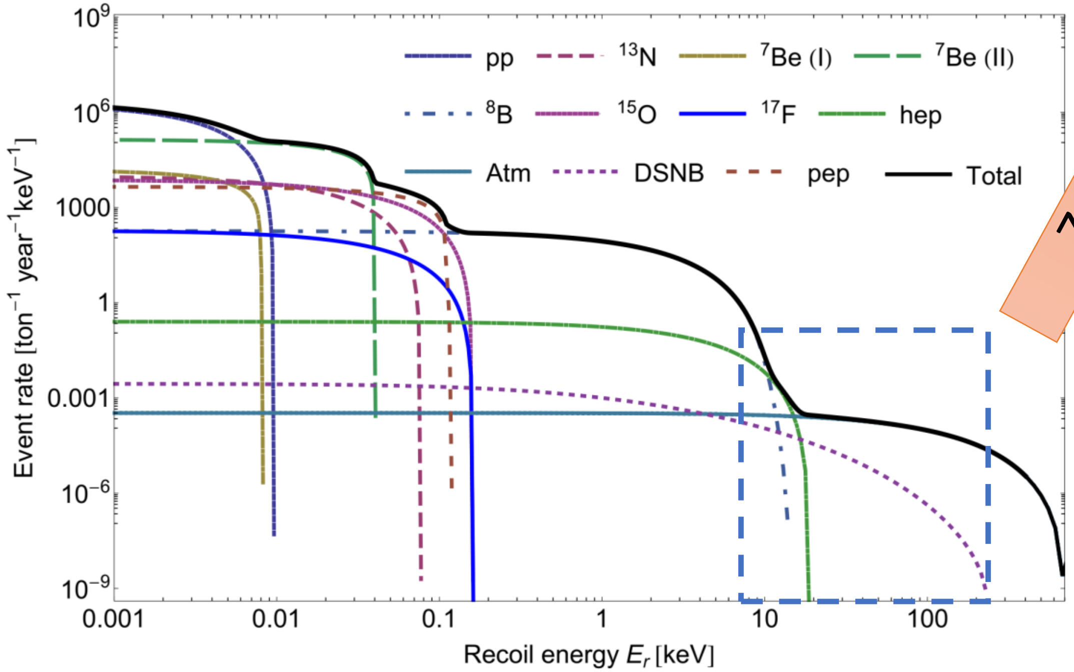
Coherent elastic neutrino nucleus scattering

CEnNS will induce nuclear recoils almost indistinguishable from those potentially induced by WIMPs.

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) |F(E_r)|^2$$

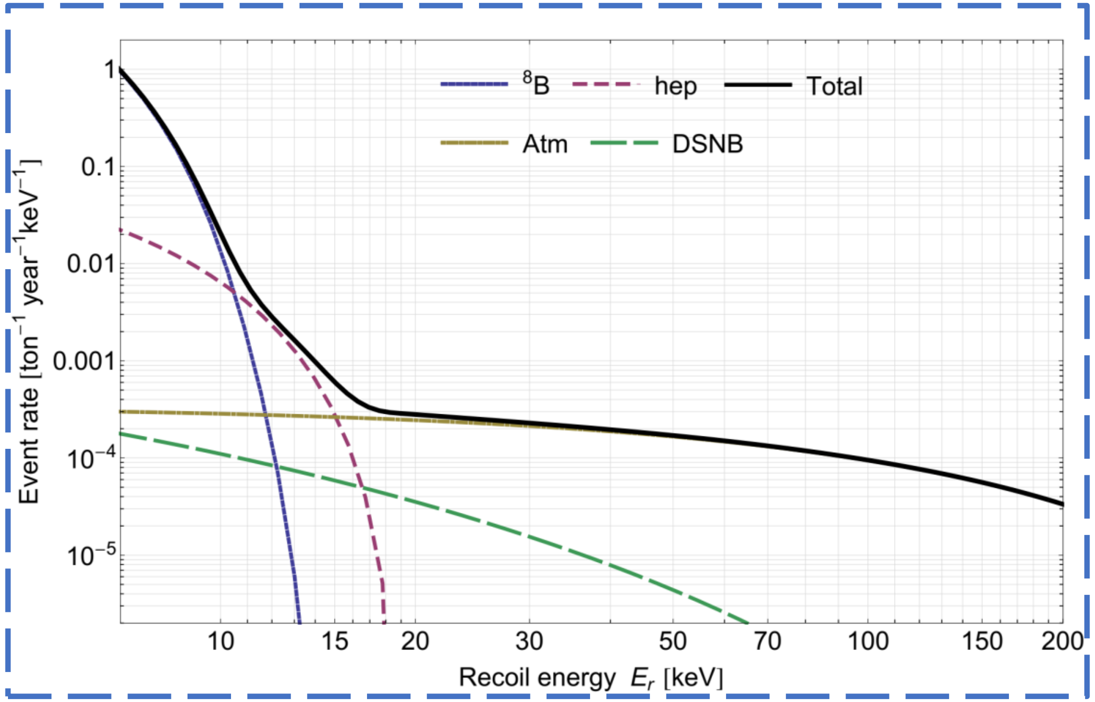
$$\frac{dR_\nu(E_r)}{dE_r} = \eta \times \int_{E_{\nu_{min}}} \frac{dN}{dE_\nu} \times \frac{d\sigma(E_\nu, E_r)}{dE_r} dE_\nu$$

Neutrino fluxes @Earth



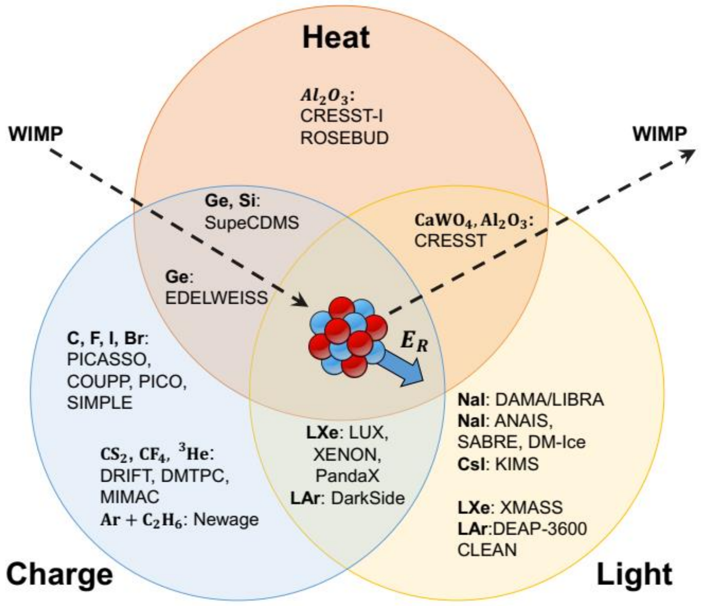
Zoom

Region of interest $1\ \text{keV} \lesssim E_r \lesssim 200\ \text{keV}$



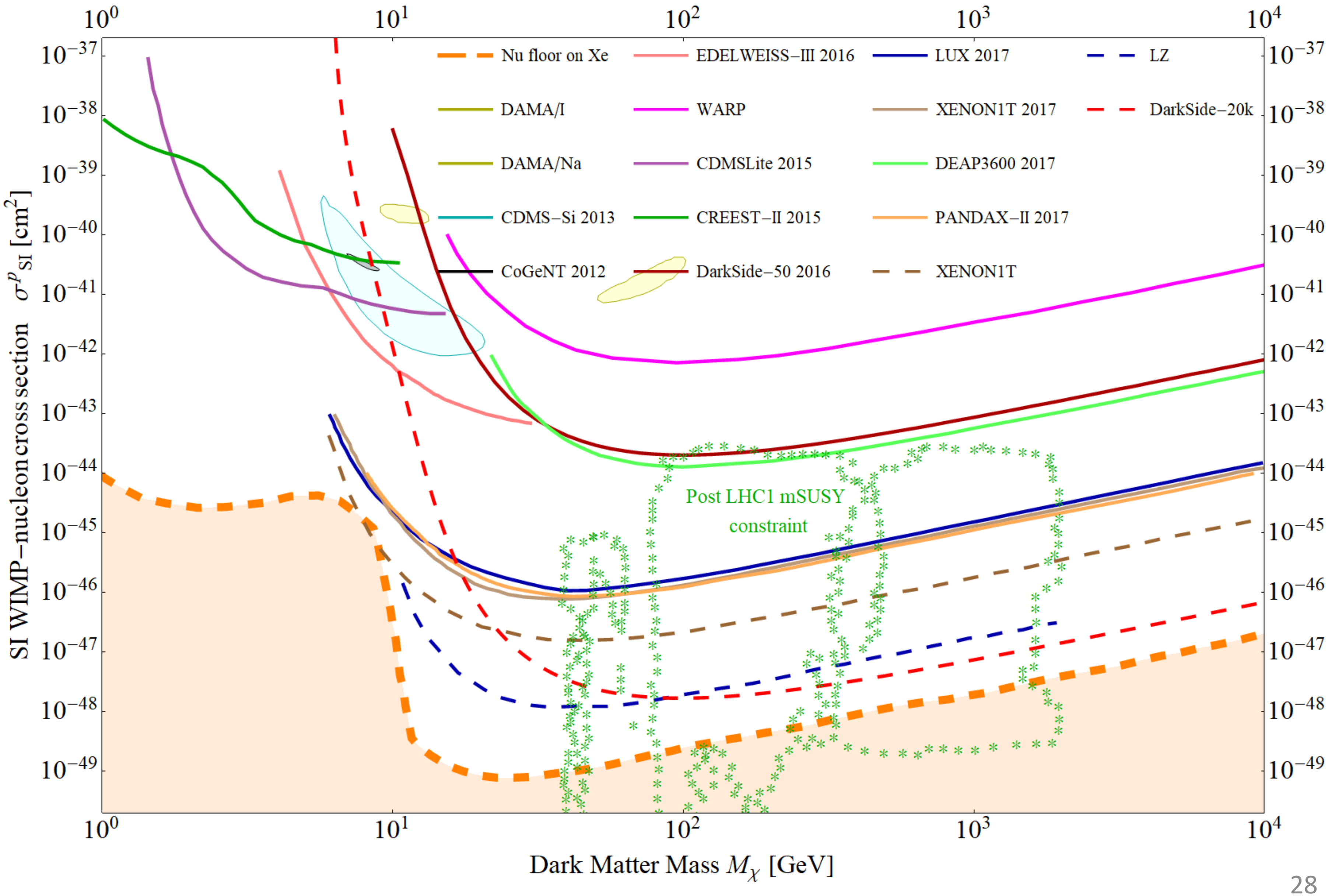
Atmospheric neutrinos are the dominant component for DarkSide-20k in the high-mass search region!

Current experimental results



Scatterings of DM particles off nuclei can be detected via subsequently produced

- **light** (scintillation photons from excitation and later de-excitation of nuclei)
- **charge** (ionization of atoms in a target material)
- **heat** (phonons in crystal detectors)



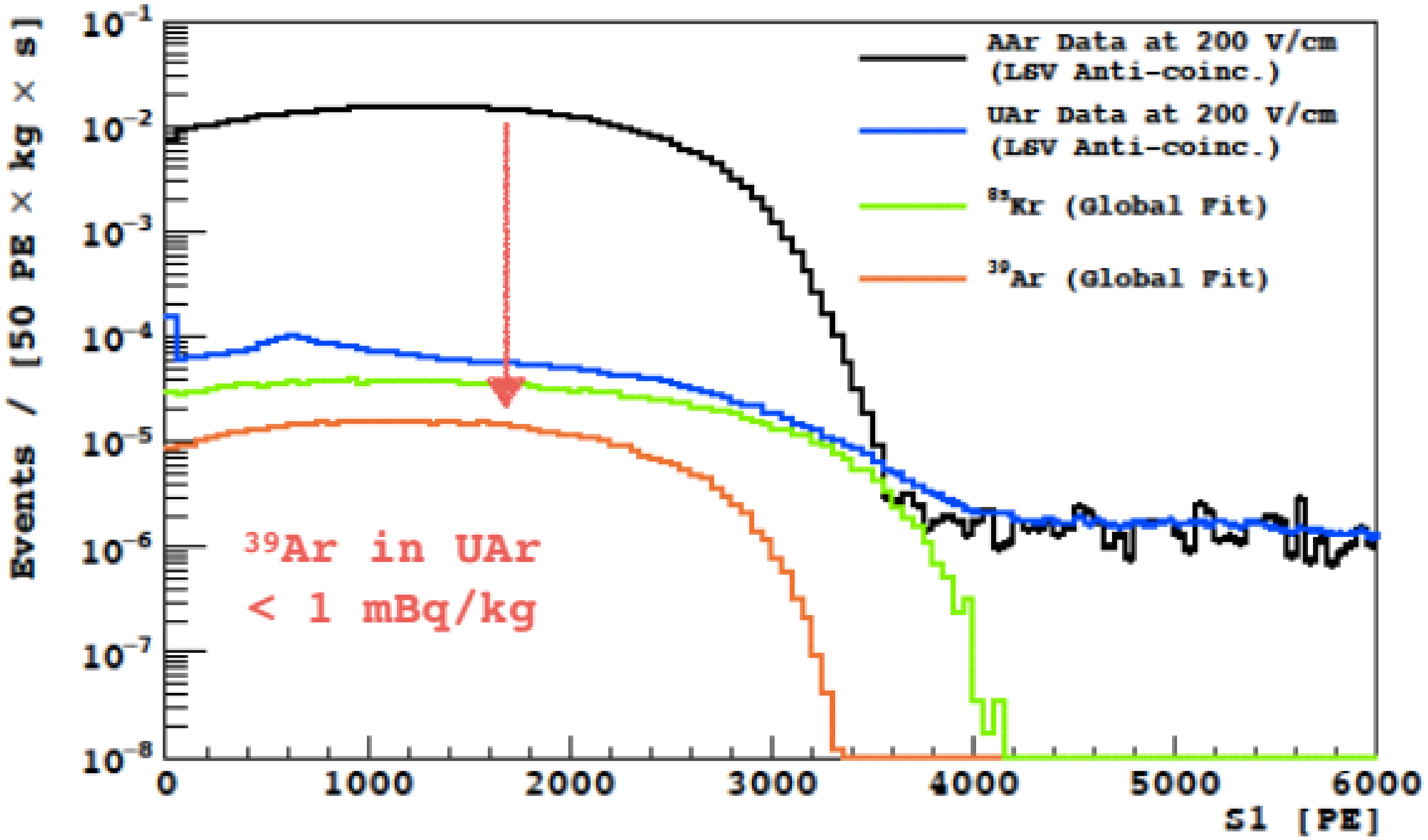
Suppression: AAr Vs UAr

Suppression: AAr Vs Uar

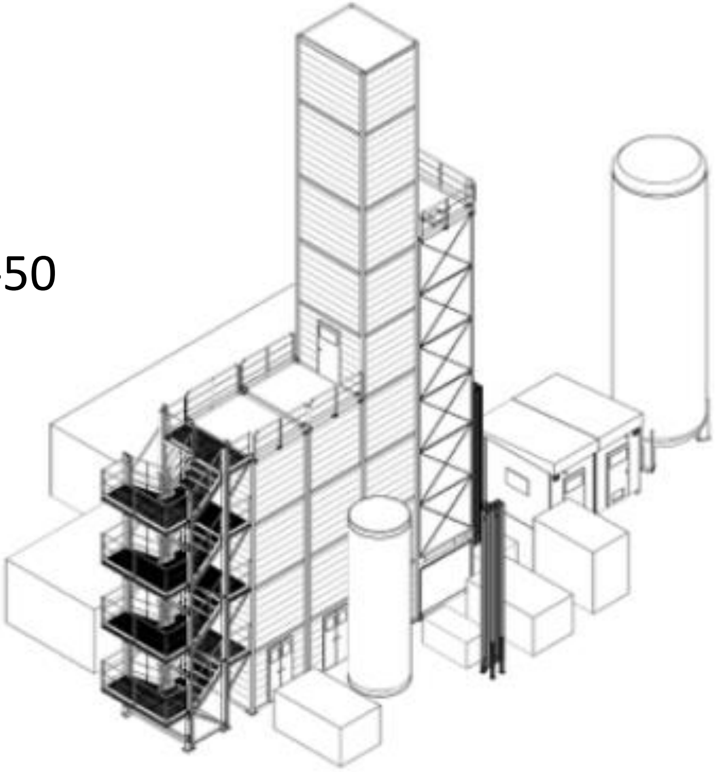
- Underground argon (UAr): 150 kg successfully extracted from a CO_2 well in Colorado

- ^{39}Ar **depletion factor >1400**

PRD, 93 (2016): 081101(R)

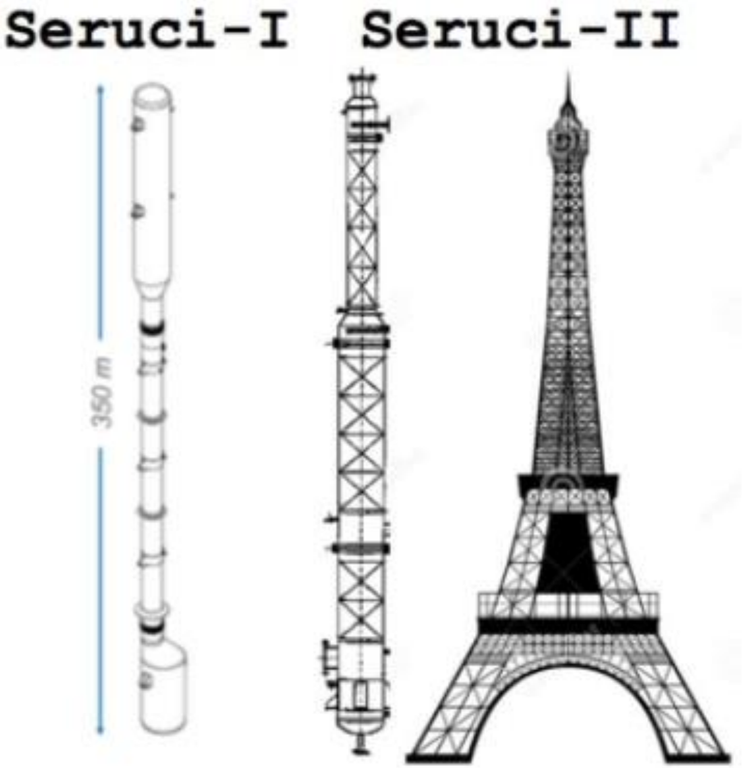


URANIA and ARIA



URANIA

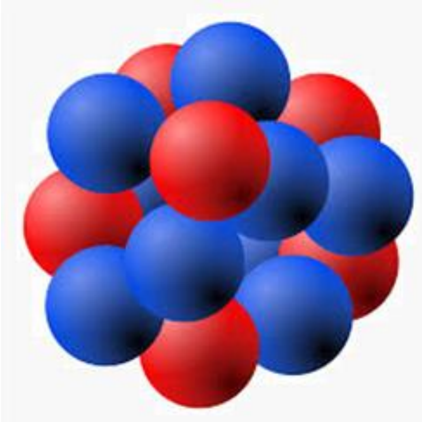
- Procurement of 50 tonnes of UAr from same Colorado source as for DS-50
- Extraction of 100 kg/day, with 99.9% purity
- UAr transported to Sardinia for final chemical purification at ARIA



ARIA

- Big cryogenic distillation column in Seruci, Sardinia
- Final chemical purification of the UAr
- Can process O(1 tonne/day) with 10^3 reduction of all chemical impurities
- Ultimate goal is to isotopically separate ^{39}Ar from ^{40}Ar

The Helm Nuclear Form factor



- The nuclear form factor, F(q), is taken to be the **Fourier transform** of a spherically symmetric ground state **mass distribution** normalized so that F(0) = 1:

$$F(q) = \frac{1}{M}\int \rho_{\rm mass}(r) e^{-i\mathbf{q}\cdot\mathbf{r}} d^3r = \frac{1}{M}\int_0^\infty \rho_{\rm mass}(r)\,\frac{\sin qr}{qr}\,4\pi r^2 dr.$$

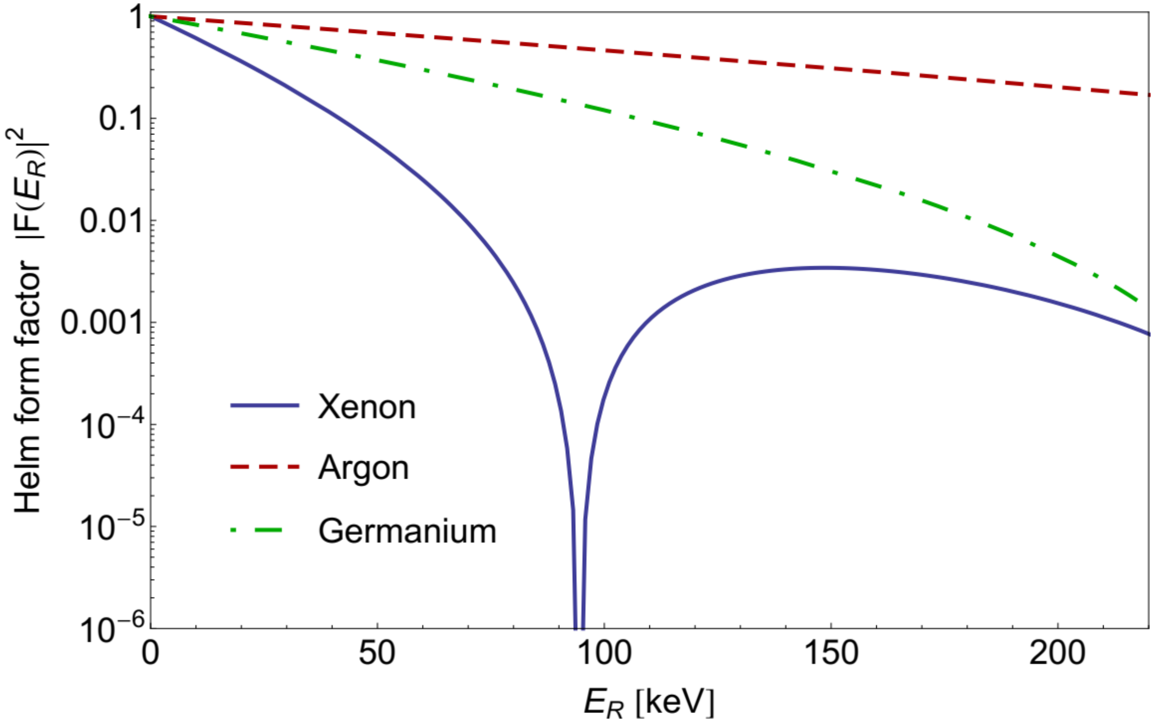
Since the mass distribution in the nucleus is difficult to probe, it is generally assumed that mass and charge densities are proportional so that charge densities, determined through **elastic electron scattering**, can be utilized instead.

$$\rho_{\rm mass}(r) = \frac{m_N}{Ze}\rho_{\rm charge}(r)$$

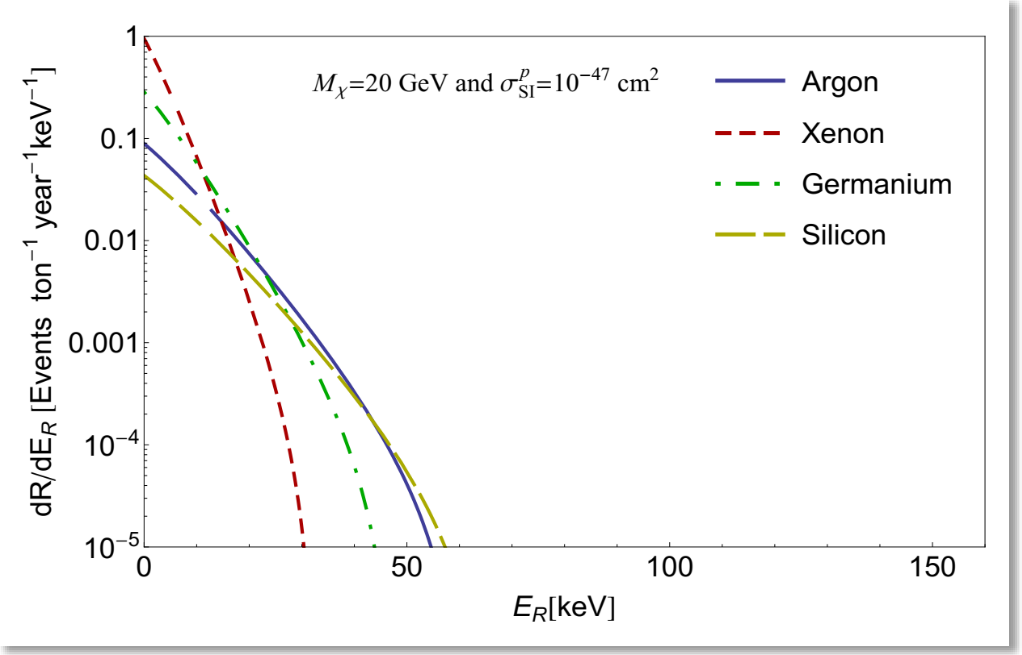
It is convenient to have an analytic expression. This expression has been provided by the **Helm form factor**, given by

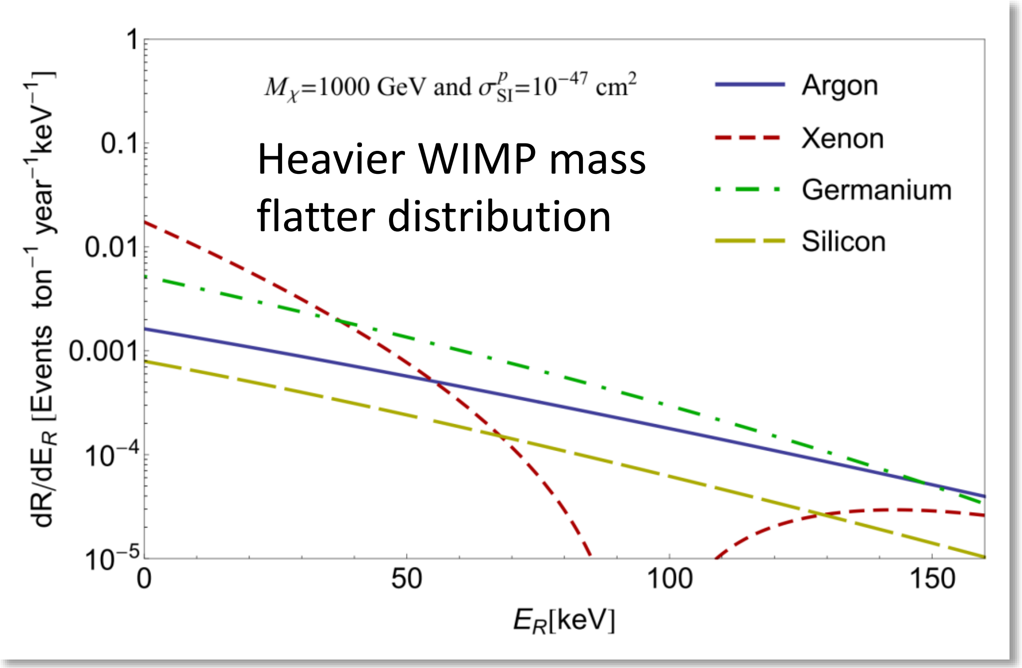
$$|F^{SI}(q)|^2 = \left(\frac{3j_1(qR_1)}{qR_1}\right)^2 e^{-q^2s^2}$$

Where j_1 is the spherical Bessel function of the first kind and R_1 is an effective nuclear radius and s is the nuclear skin thickness, parameters that need to be fit separately for each nucleus



Final WIMP spectra





In a real experiment there will be also a **nuclear recoil acceptance function**, $A(E_R)$, which takes into account all the backgrounds cuts, the WIMP signal selection efficiency and the experimental resolution.

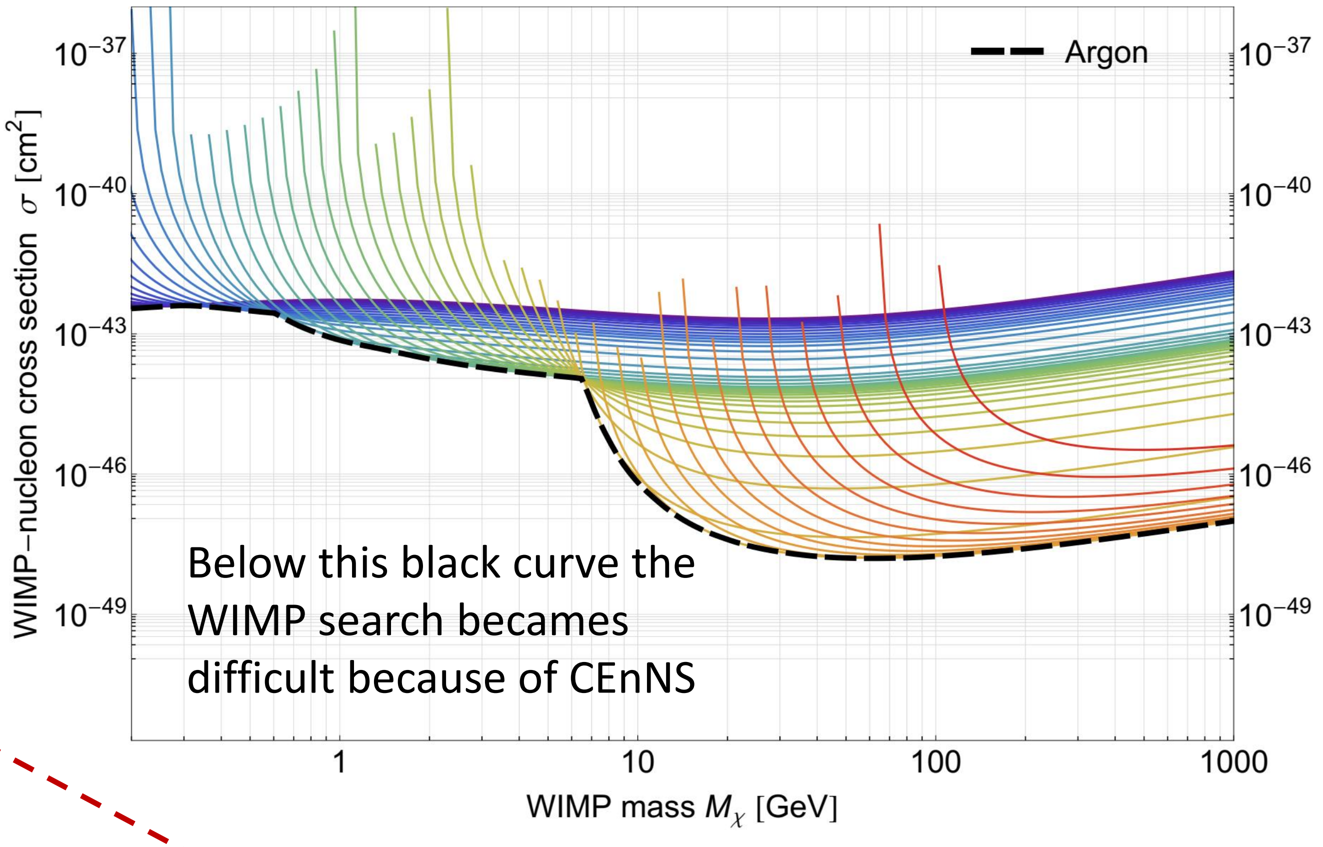
The total number of WIMP events is then given by

$$N_\chi = M\,T \int_{E_{th}}^{E_{up}} A(E_R) \frac{dR}{dE_R}\, dE_R$$

Experiment exposure [tonne x year]

Best WIMP sensitivity in the presence of CEnNS (Neutrino floor)

1000 background-free exclusion limits, isovalues of WIMP events (2.3 at 90% C.L.), as a function of the WIMP mass, with varying thresholds (E_{th}) from **0.001 to 200 keV** and adjusted each curve's exposure (MT) such that each experiment expects a neutrino background of one event.



$$\hat{\sigma}_{90\%}(E_{th}, M_\chi) = \frac{2.3}{(MT)_{1\,neutr} \times \int_{E_{th}}^{E_{up}} \frac{dR_\chi}{dE_r} dE_r}$$

Coherent elastic neutrino nucleus background

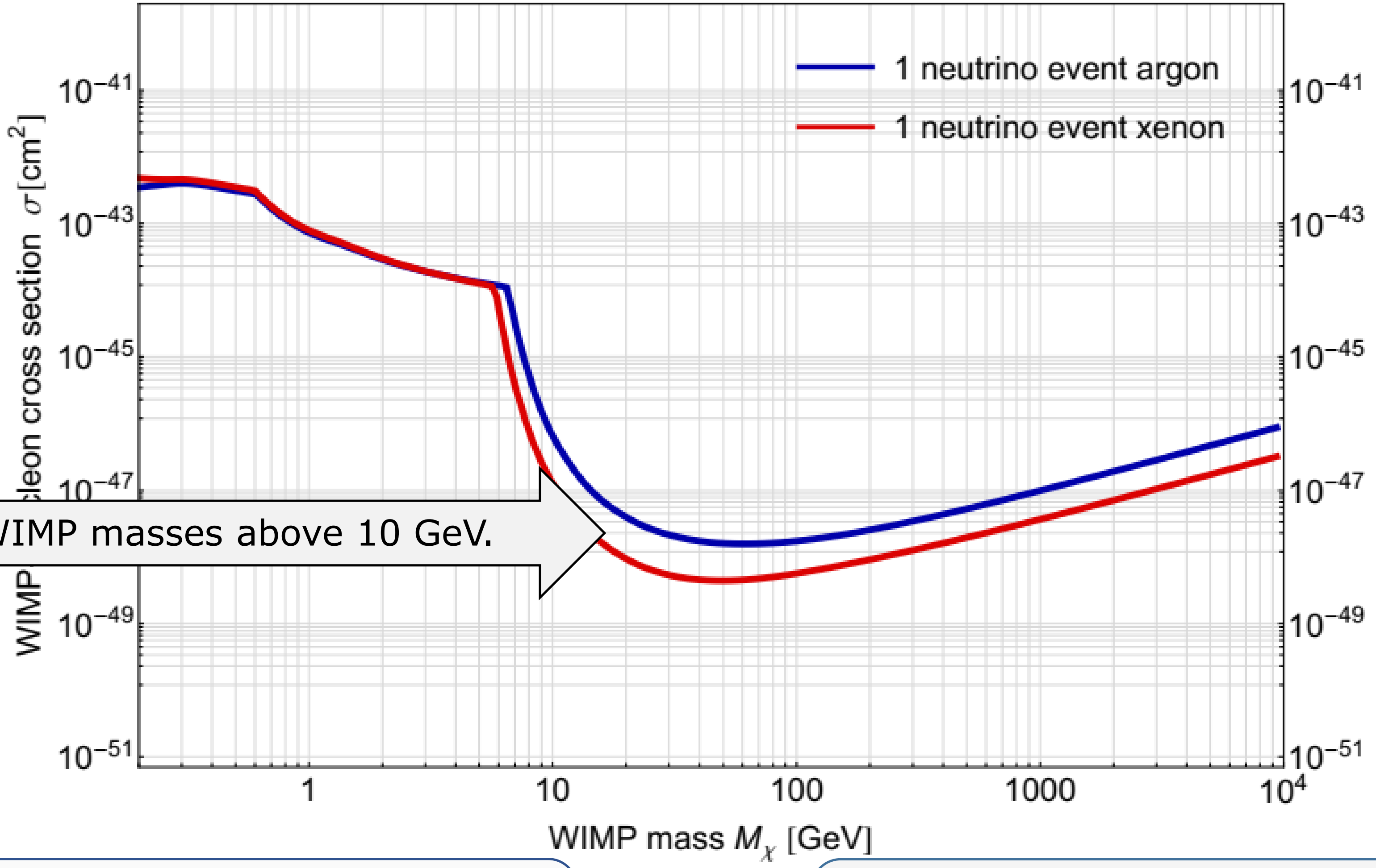
$$\frac{dR_\nu(E_r)}{dE_r} = \eta \times \int_{E_{\nu_{min}}} \frac{dN}{dE_\nu} \times \frac{d\sigma^{CNS}(E_\nu, E_r)}{dE_r} dE_\nu$$

$$(MT)_{1\,neutr} = \frac{1\ \nu\ events}{\int_{E_{th}}^{E_{up}} \frac{dR_\nu}{dE_r} dE_r\ [\nu\ events\ ton^{-1} year^{-1}]}$$

WIMP-nucleus recoil spectrum

$$\frac{dR_\chi}{dE_r} = \frac{\sigma_{w-n}}{2M_w\,\mu_n^2} A^2 F^2(E_r)\,\rho_0 \int \frac{f_1(v)}{v} dv$$

Comparison between argon and xenon isoevents curve



Differences for WIMP masses above 10 GeV.

Xenon

$\sigma_{\chi-n}(M_\chi = 100 \text{ GeV}) = 5.6 \cdot 10^{-49} \text{ cm}^2$

Argon

$\sigma_{\chi-n}(M_\chi = 100 \text{ GeV}) = 1.7 \cdot 10^{-48} \text{ cm}^2$