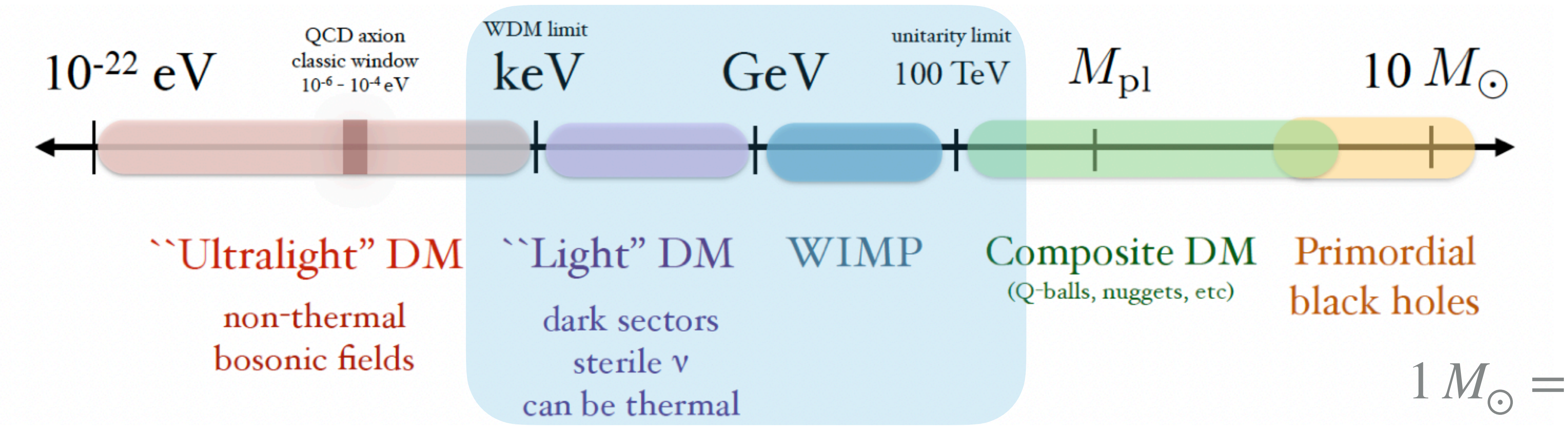
The DarkSide-20k Experiment

Giuliana Fiorillo

What is dark matter?

A spectrum spanning 80 orders of magnitude

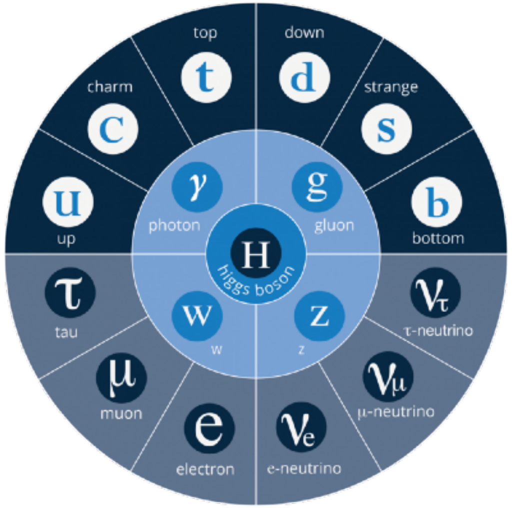


$1\,M_{\odot} = 10^{57}$ GeV

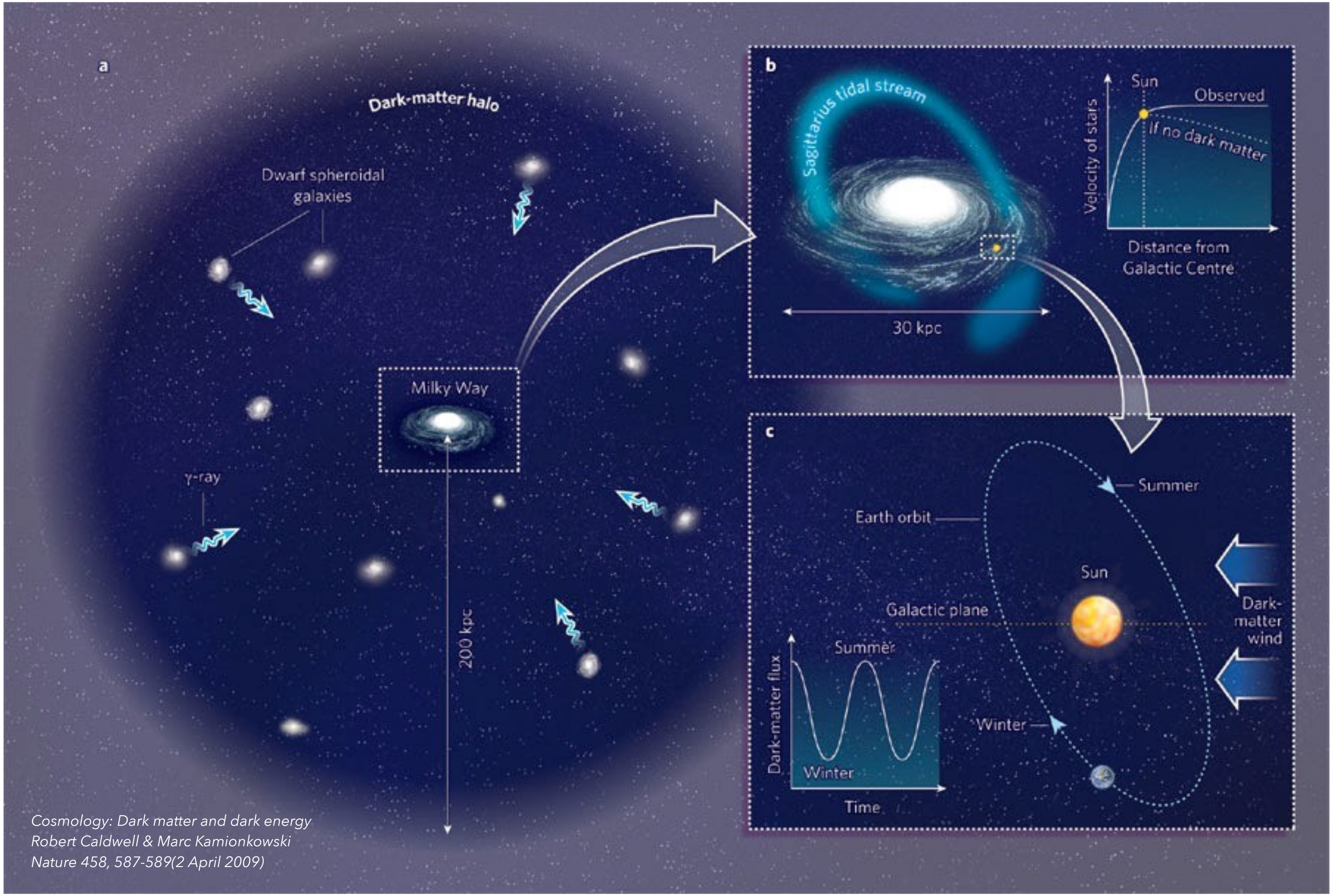
WIMP paradigm: a good place to start looking

The Minimal WIMP Model Basic Assumptions:

- Single particle that does not interact with itself
- Interacts weakly with Standard Model
- 2→2 annihilations primarily in s-wave
- Annihilations set thermal abundance today



Direct detection



Cosmology: Dark matter and dark energy
Robert Caldwell & Marc Kamionkowski
Nature 458, 587-589(2 April 2009)

WIMP wind on Earth

Goodman & Witten (1985):

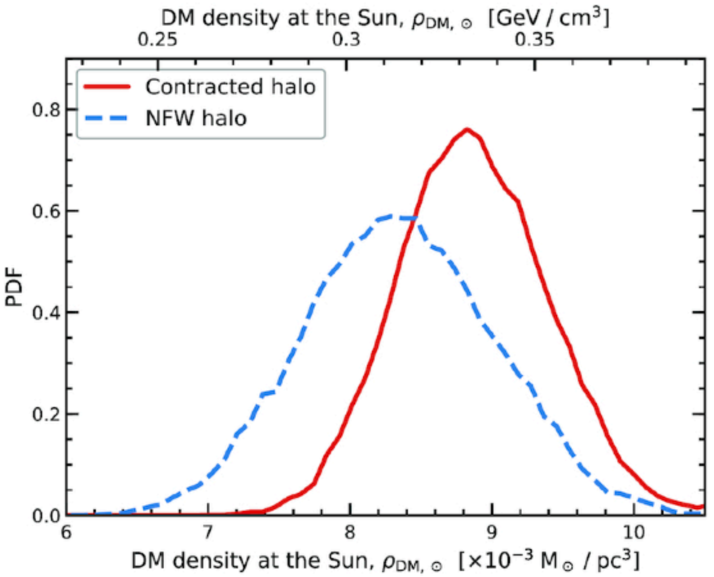
“Detectability of certain dark matter candidates”

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \times \int dv\, f(v)\, v \frac{d\sigma_\chi}{dE_R}$$

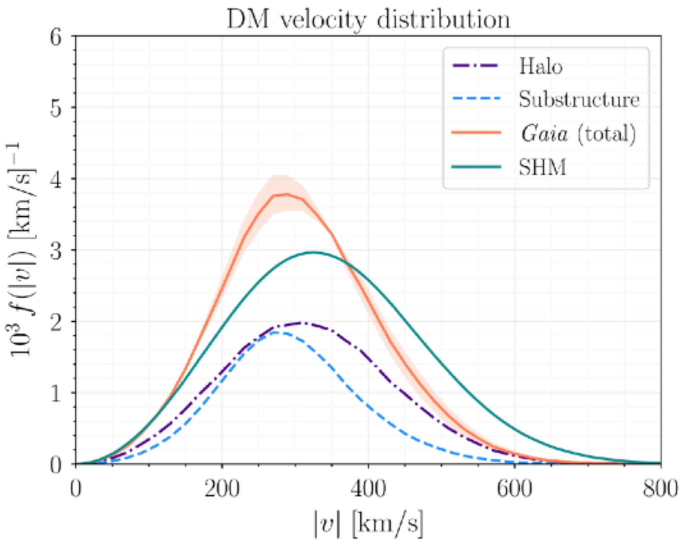
- ρ_χ galactic dark matter halo local density
- v relative velocity wrt terrestrial detector
- σ_χ elastic scattering off target nuclei

$$\Phi \simeq \frac{10^5}{\mathrm{s\ cm^2}} \times \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)$$

M. Cautun et al, MNRAS 2020

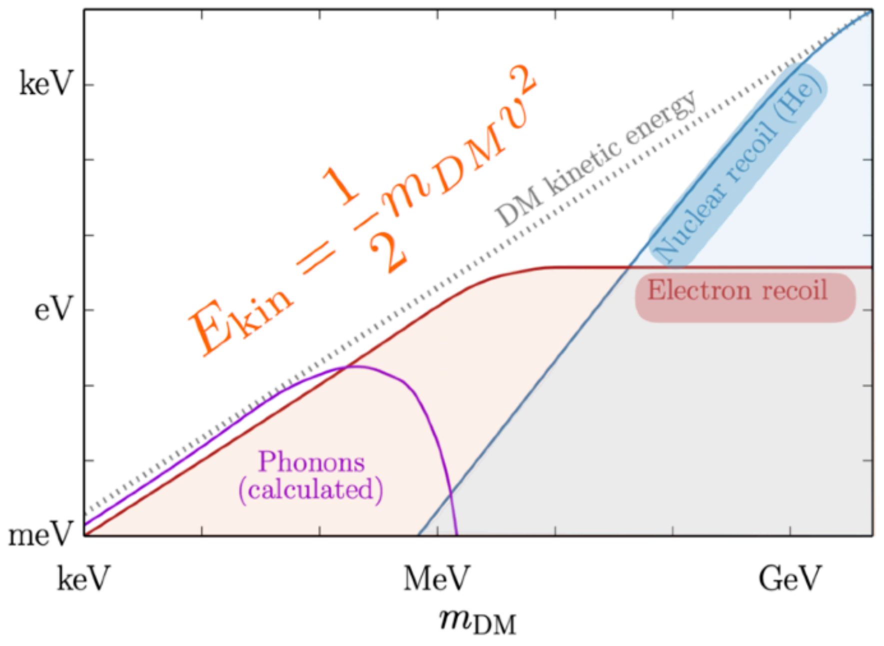


Buch et al, PRD101, 2020



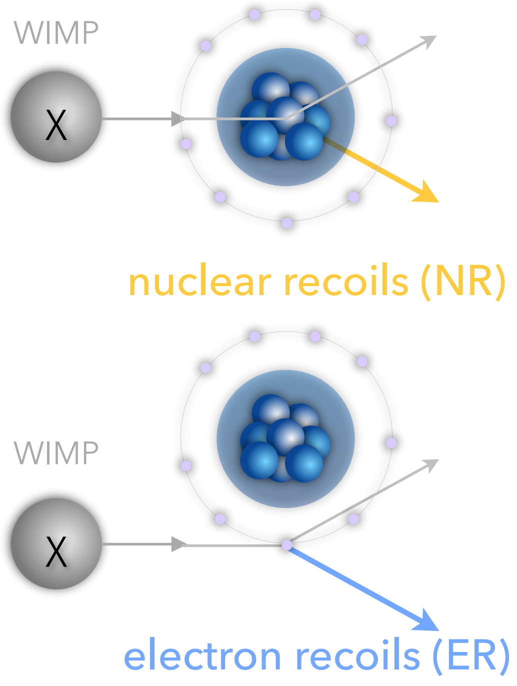
Dark Matter scattering kinematics

- DM mass kinematically accessible through inelastic interactions extracting substantial fraction of the DM kinetic energy:
  - DM-N scattering w/ Migdal
  - DM-e scattering
  - DM scattering w/ collective modes (e.g. phonons, magnons)

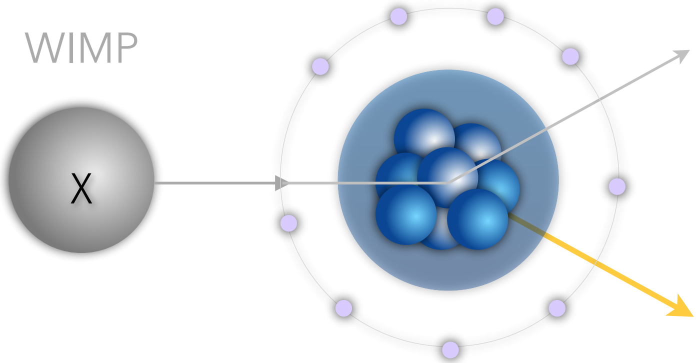


arXiv:1904.07915

$$E_{\rm kin} = \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 1 \text{ eV} \left(\frac{m_{\rm DM}}{1 \text{ MeV}} \right)$$



WIMP-nucleon scattering



$$E_0 = \frac{1}{2} m_\chi v^2; \quad r = \frac{4 m_\chi m_N}{(m_\chi + m_N)^2}$$

$$E_R = E_0 r \frac{(1 - \cos\theta)}{2}$$

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} \exp\left(-\frac{E_R}{E_0 r}\right) \times [S(E_R) F^2(q^2) I$$

$F^2(q^2)$ Form factor

$S(E_R)$ seasonal modulation

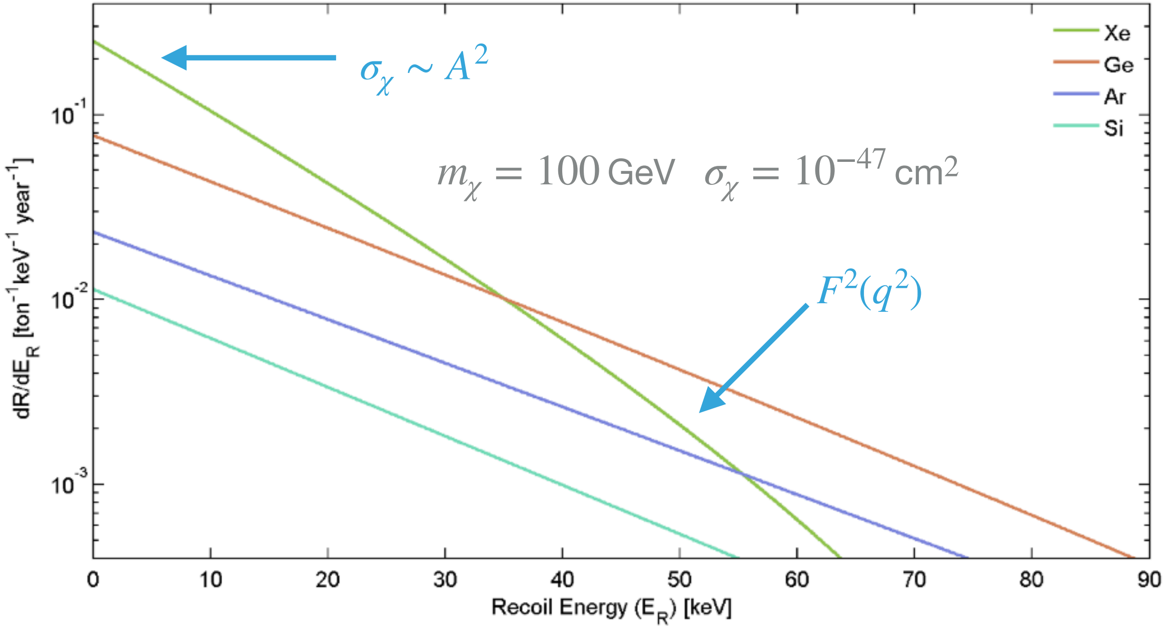
I Interaction type

- Coherent elastic scattering on a nucleus
  - ➡ standard SI/SD description
  - ➡ nuclear form factors generally included

$$\frac{d\sigma(E_{\rm nr})}{dE_{\rm nr}} = \frac{m_N}{2v^2\mu^2}\left[\sigma_{\rm SI} F^2_{\rm SI}(E_{\rm nr}) + \sigma_{\rm SD} F^2_{\rm SD}(E_{\rm nr})\right]$$

$$\sigma_{\rm SI} = \sigma_n \frac{\mu^2}{\mu_n^2} \frac{(f_p Z + f_n (A - Z))^2}{f_n^2} = \sigma_n \frac{\mu^2}{\mu_n^2} A^2$$

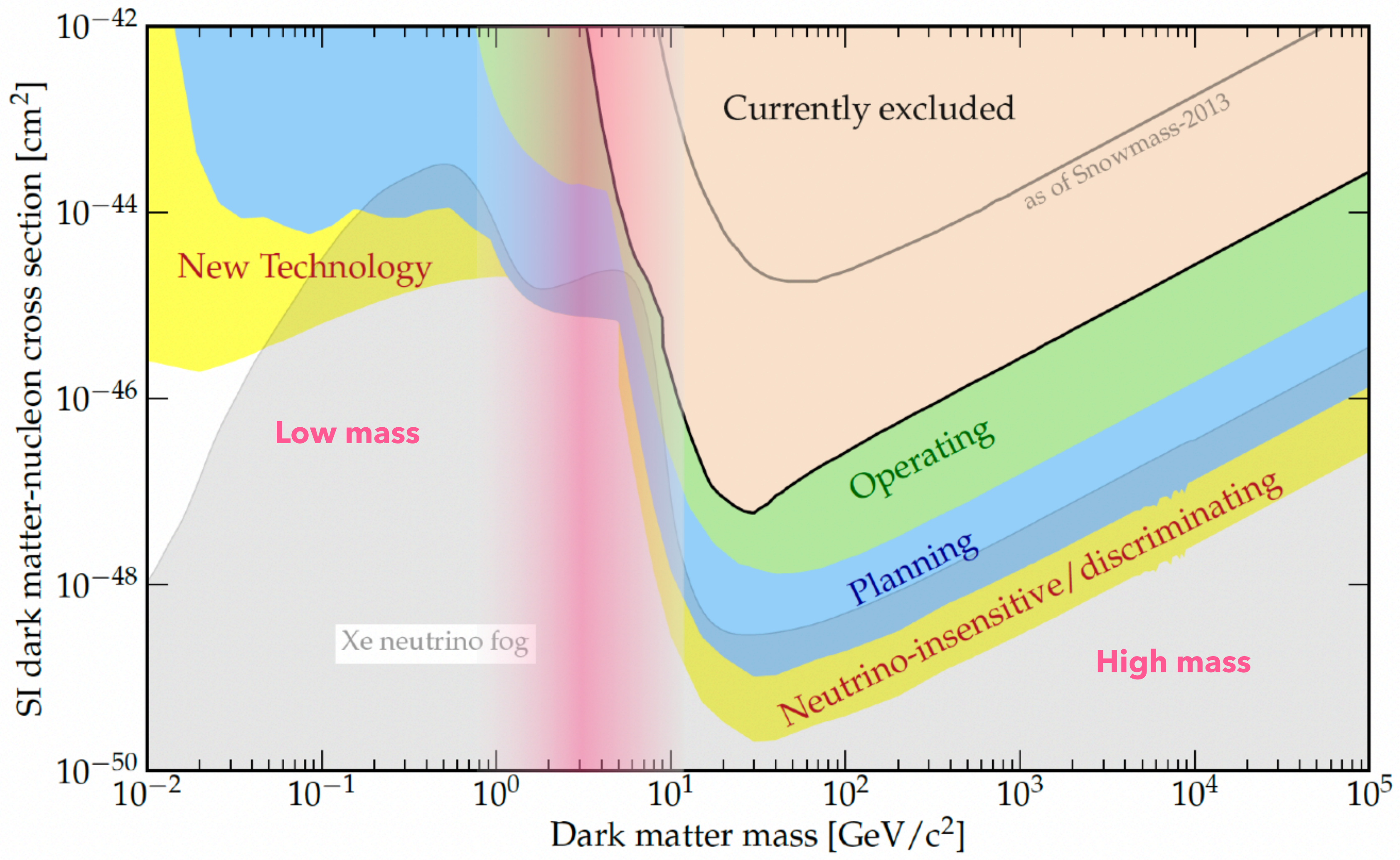
$$\frac{d\sigma_{\rm SD}}{d|\vec{q}|^2} = \frac{8 G_F^2}{\pi v^2} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]^2 \frac{J+1}{J} \frac{S(|\vec{q}|)}{S(0)}$$



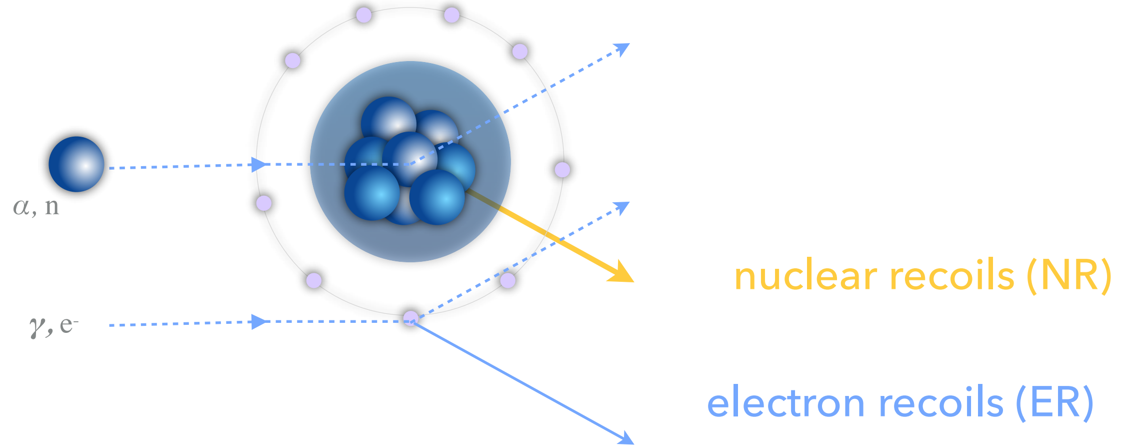
WIMP nucleon SI interaction exclusion limits lanscape

- To improve sensitivity:
  - larger exposure M × T and lower background
- To extend sensitivity at low mass WIMPs:
  - lower energy threshold
- Minimum of the curve:
  - depends on target nuclei

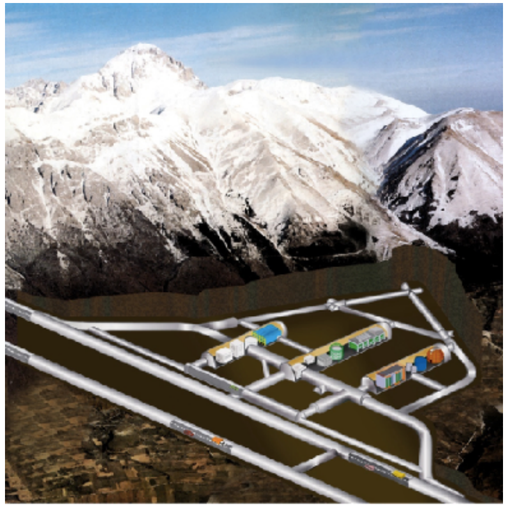
2021 Snowmass Cosmic Frontier Report, arXiv:2211.09978



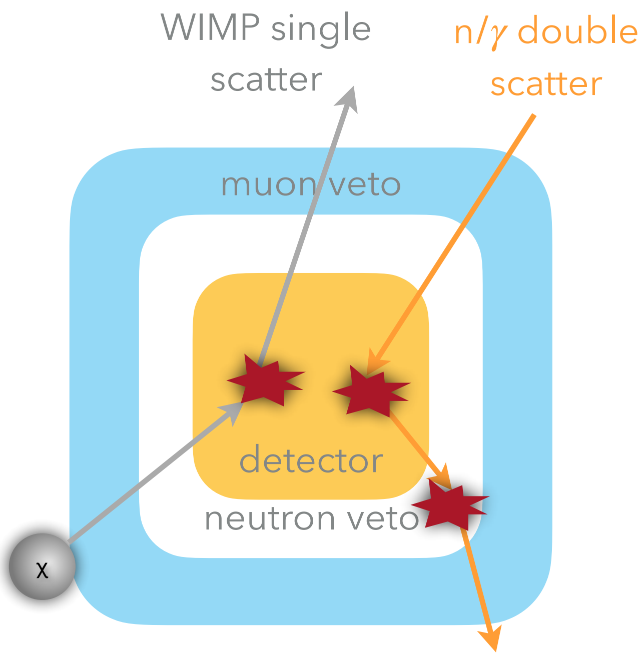
Experimental challenge



- To observe a signal which is:
  - very small: low recoil energies < 100 keV
  - very rare: <1 event/(kg y) at low masses and < 1 event/(t y) at high masses
  - buried in backgrounds with > 10^6 higher rates:
    - Muon-induced neutrons: NRs
    - Cosmogenic activation of materials/targets: ERs
    - Radioactivity of detector materials: NRs and ERs
    - Target intrinsic isotopes: ERs



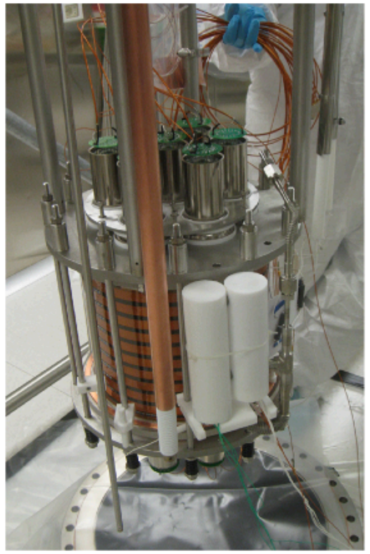
Deep Underground Laboratory



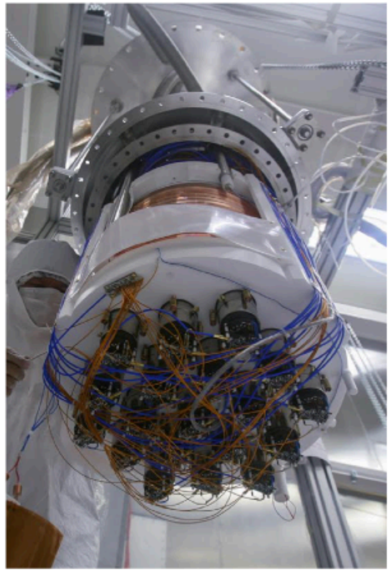
Active veto shield

The DarkSide Program

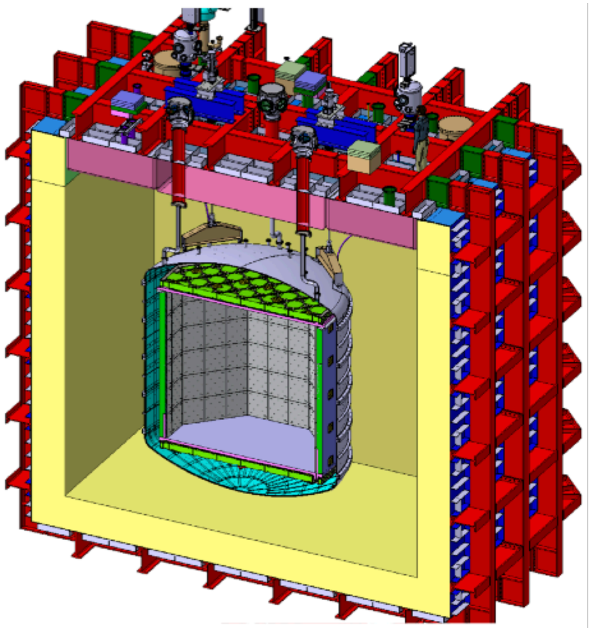
- Direct detection of WIMP dark matter
- Based on a two-phase argon time projection chamber (TPC) - Light/charge detection combined to obtain Particle ID
- Design philosophy based on having very low background levels that can be further reduced through active rejection, for background-free operation from both neutrons and $\beta/\gamma's$
- DarkSide-20k follows the successful operation of its predecessors, installed deep underground at LNGS



DarkSide-10
(2010)

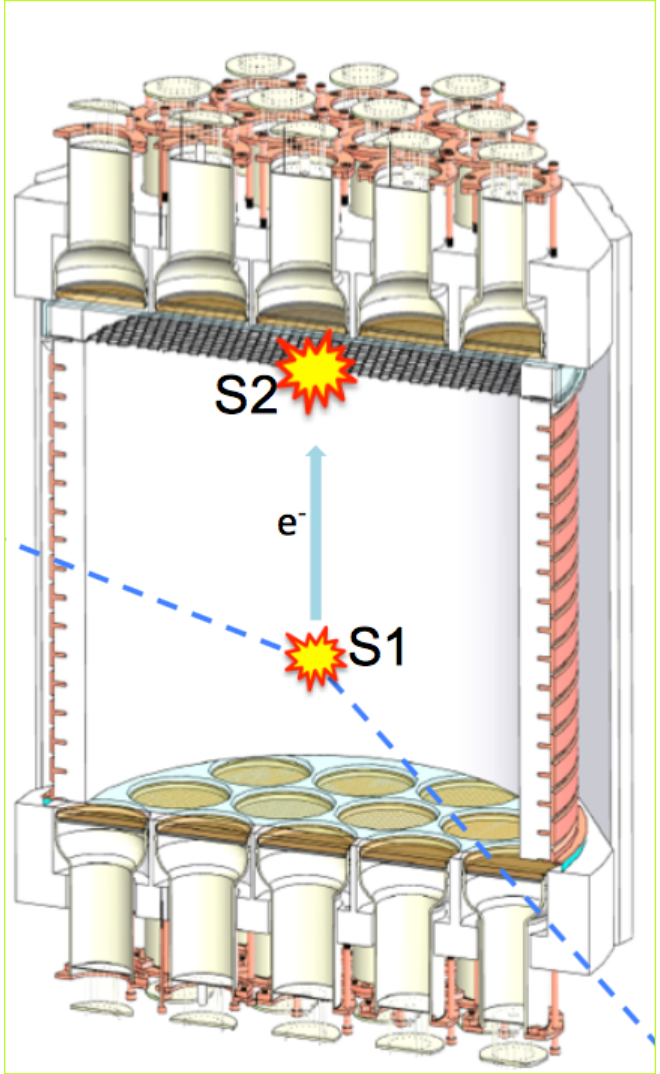


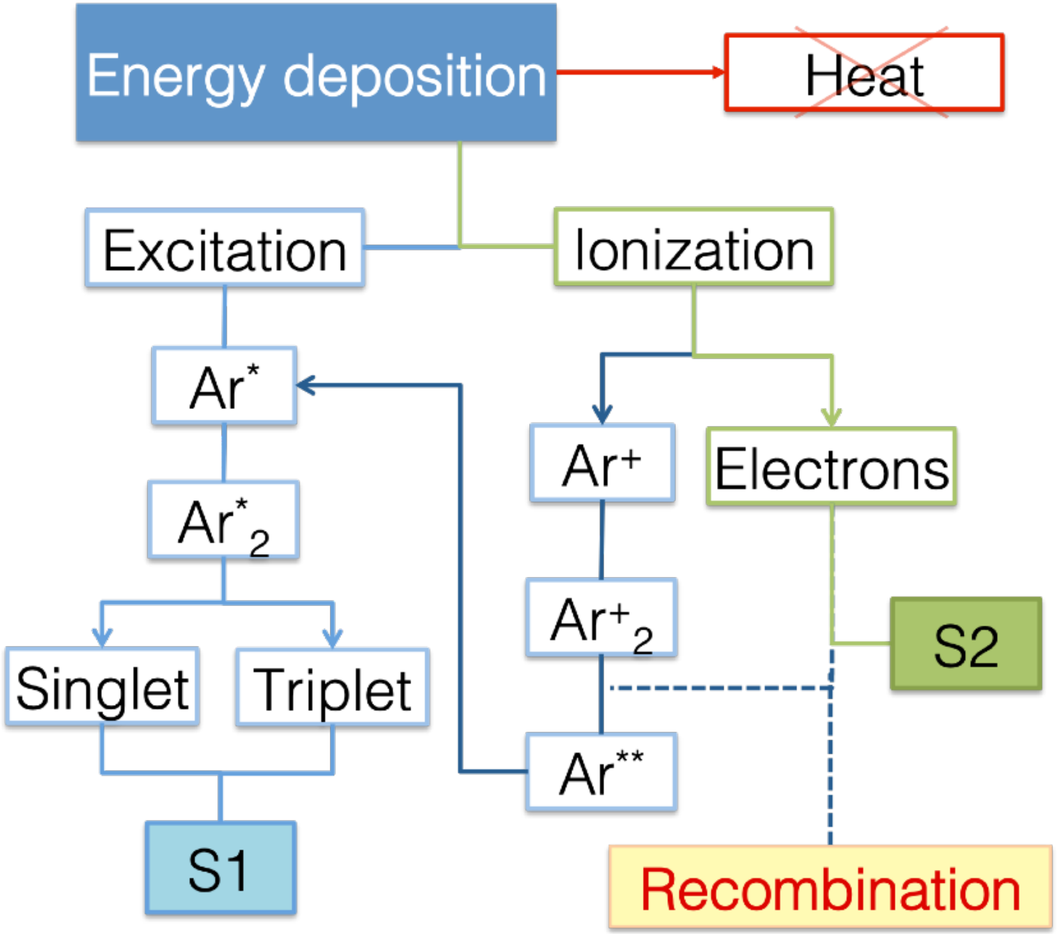
DarkSide-50
(2013-2020)



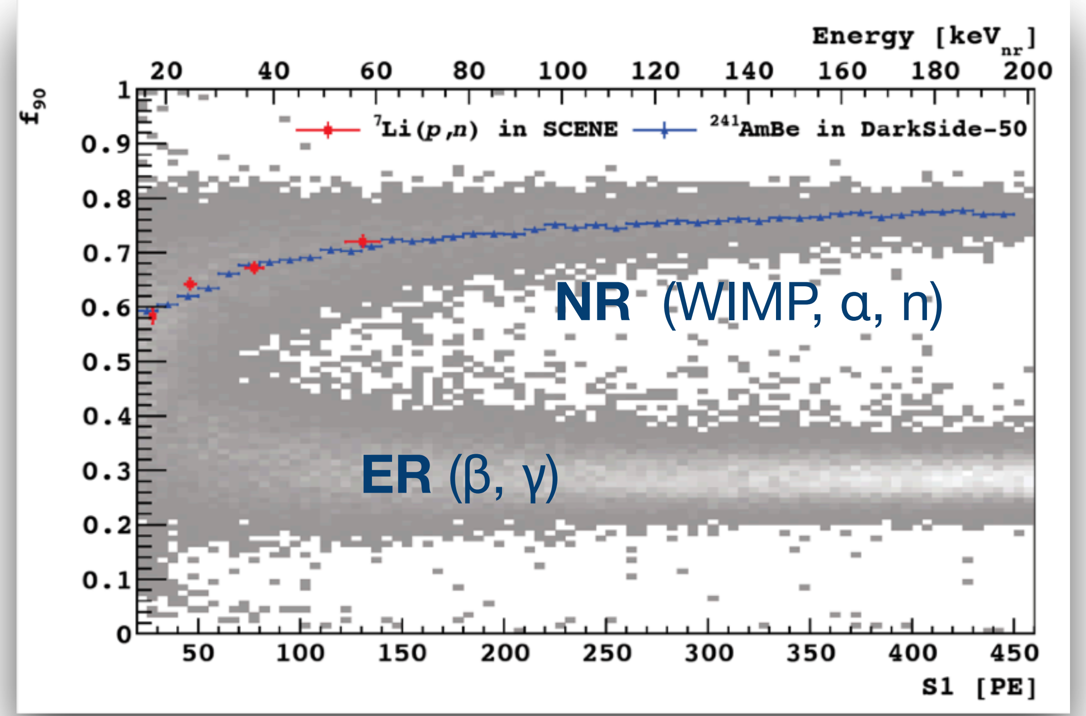
DarkSide-20k
In construction at LNGS

Dual phase Time Projection Chamber with Argon





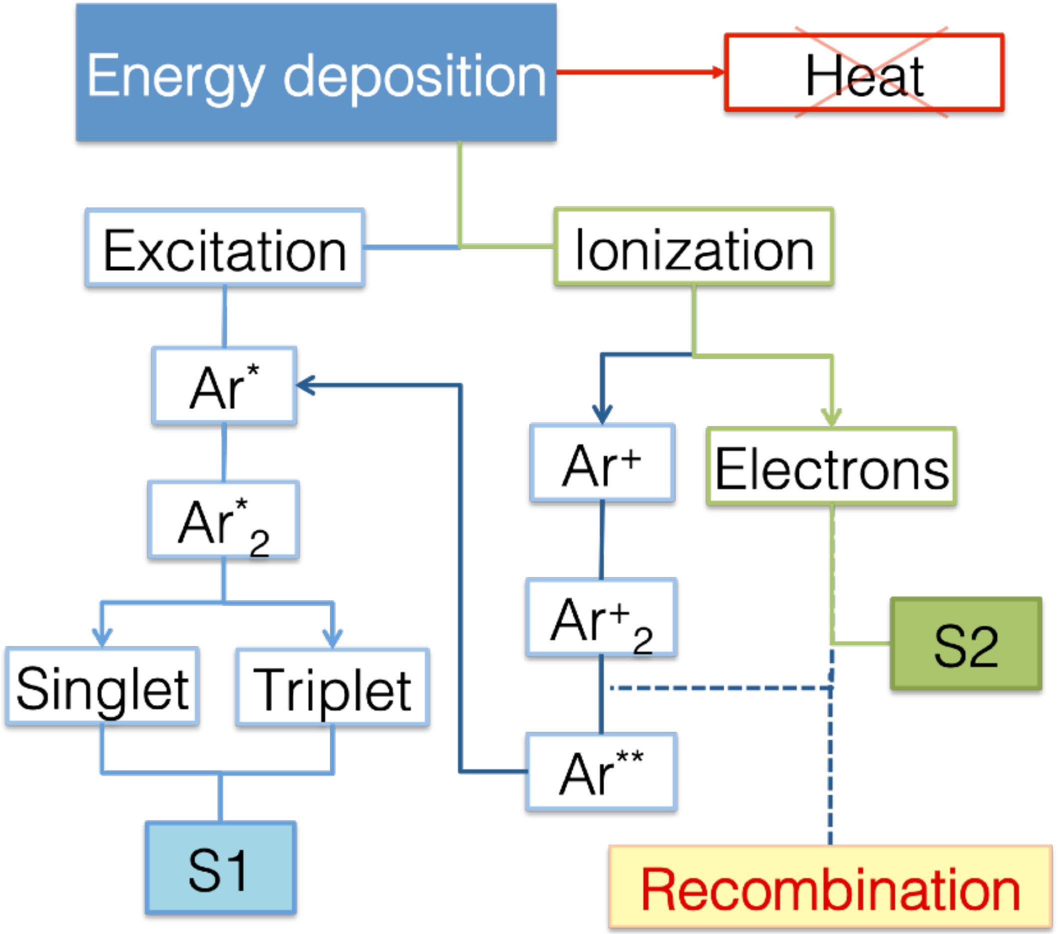
Pulse Shape Discrimination in Liquid Argon



ER Rejection factor: ~ 10^8 in LAr

t_{fast} ~ 6 ns, t_{slow} ~ 1.6 ms

DEAP-3600: Phys. Rev. D 100, 022004



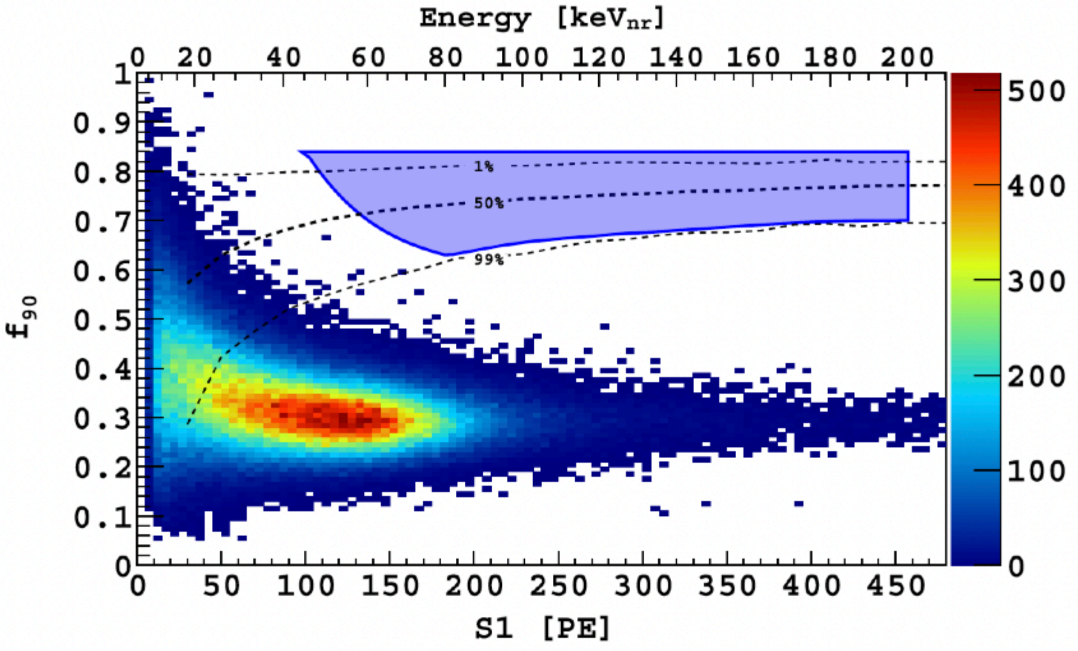
DarkSide-50

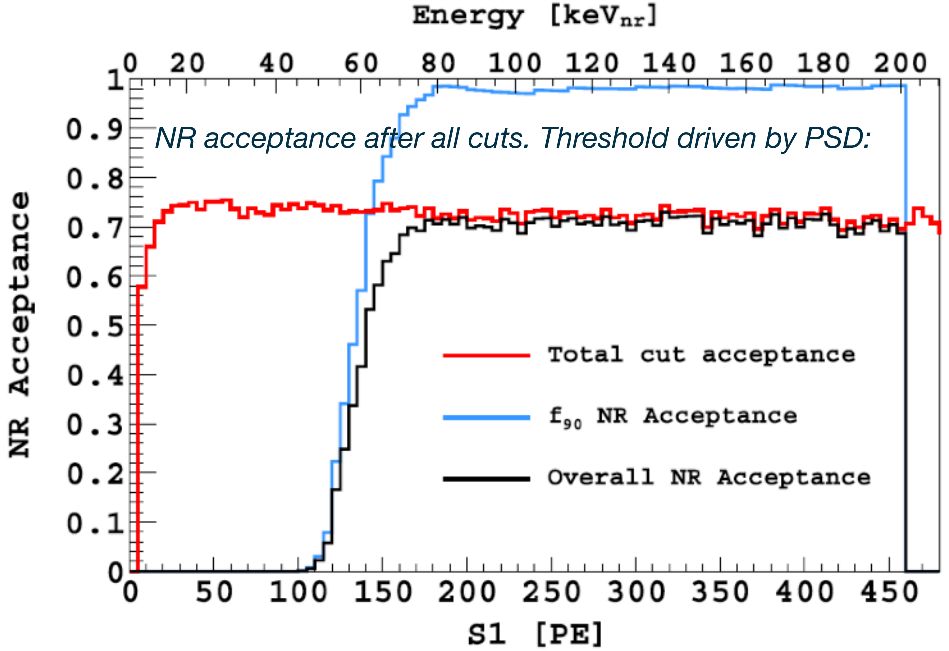
Blind analysis published in 2018

- 532 live-days
- Use first 70 days of UAr dataset to tune cuts
- **Minimise backgrounds** while maximising acceptance to NR

Expected backgrounds in ROI, before opening box

NR	surface alphas	0.001
NR	cosmogenic neutrons	<0.00035
NR	radiogenic neutrons	<0.005
ER	electron recoil	0.08
		0.09±0.04

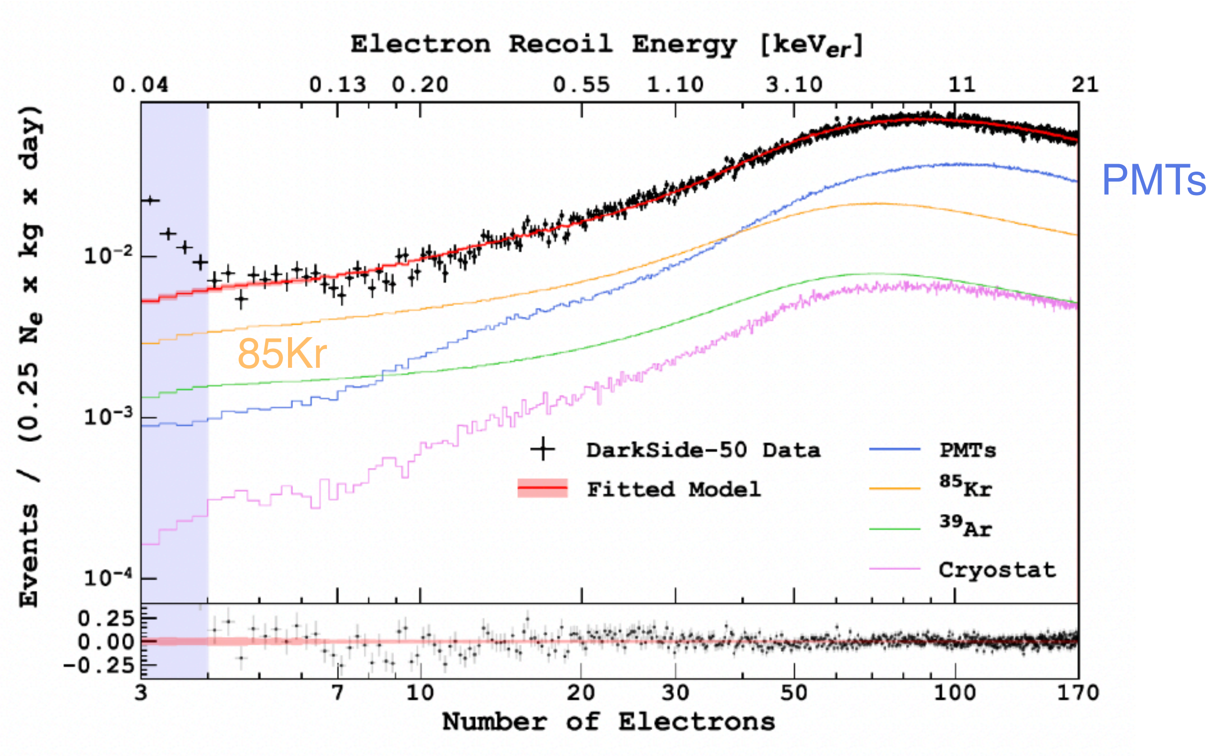


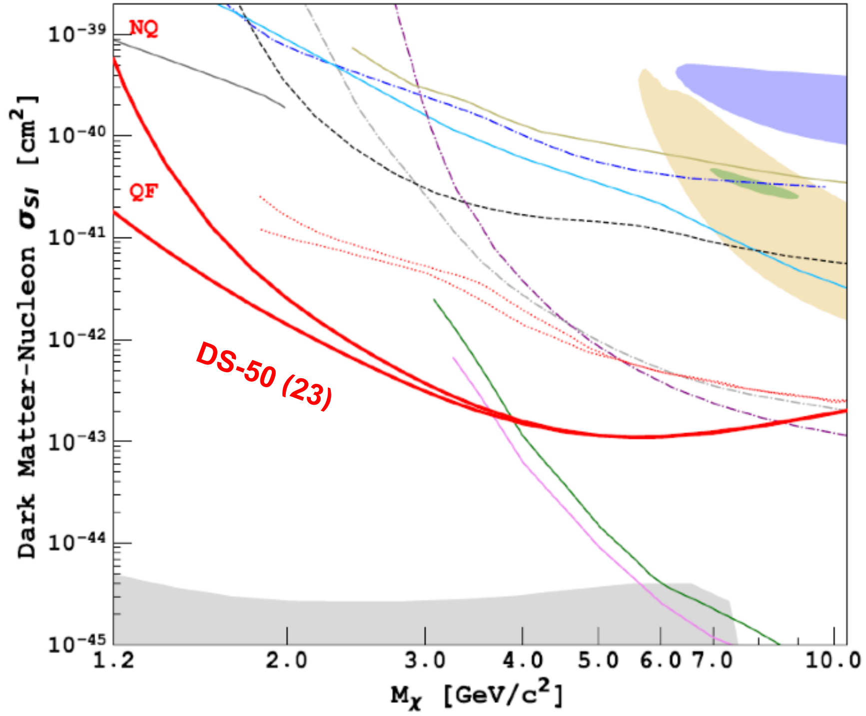


PHYS. REV. D 98, 102006 (2018)

DarkSide-50 highlights

- Exploit single electron sensitivity to lower analysis threshold down to 100 eV
- Low energy calibration with internal ER sources, AmBe for NRs
- No PSD, no vertical fiducialization
  → backgorund model
- Most stringent exclusion for GeV scale dark matter (world best limits below 3.6 GeV)



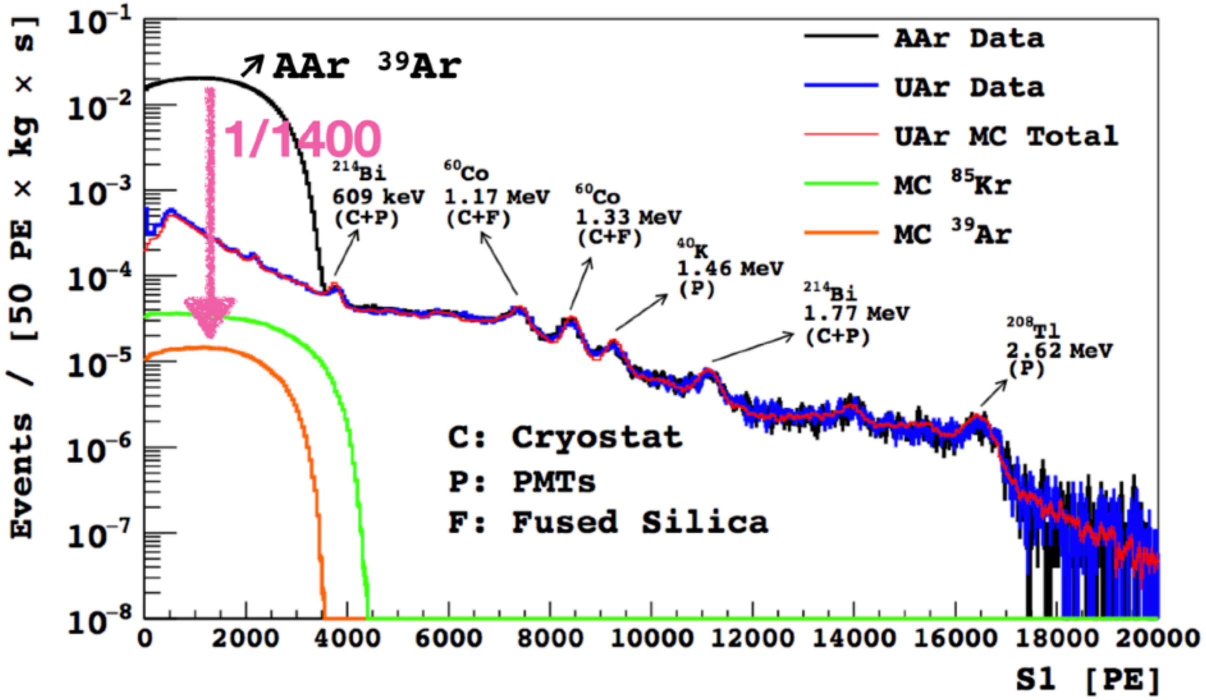


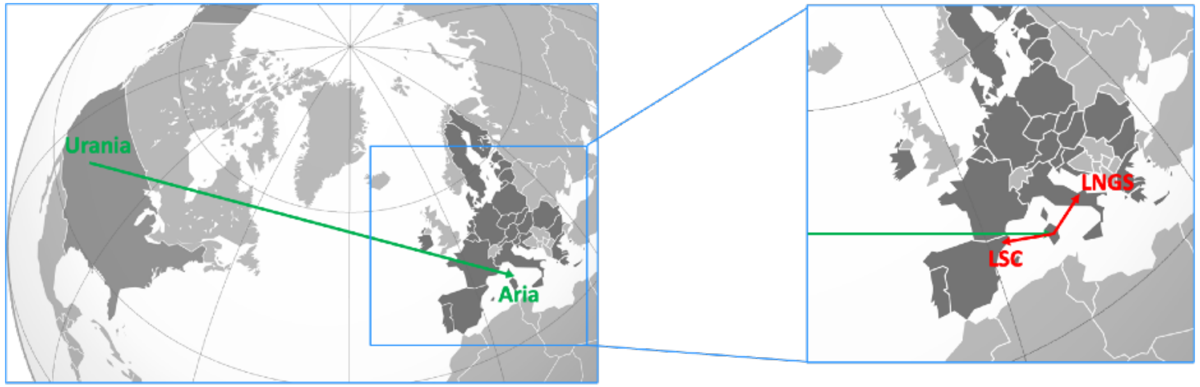
Phys. Rev. D 107, 063001 (2023)

Underground Argon

Phys. Rev. D 93, 081101(R)

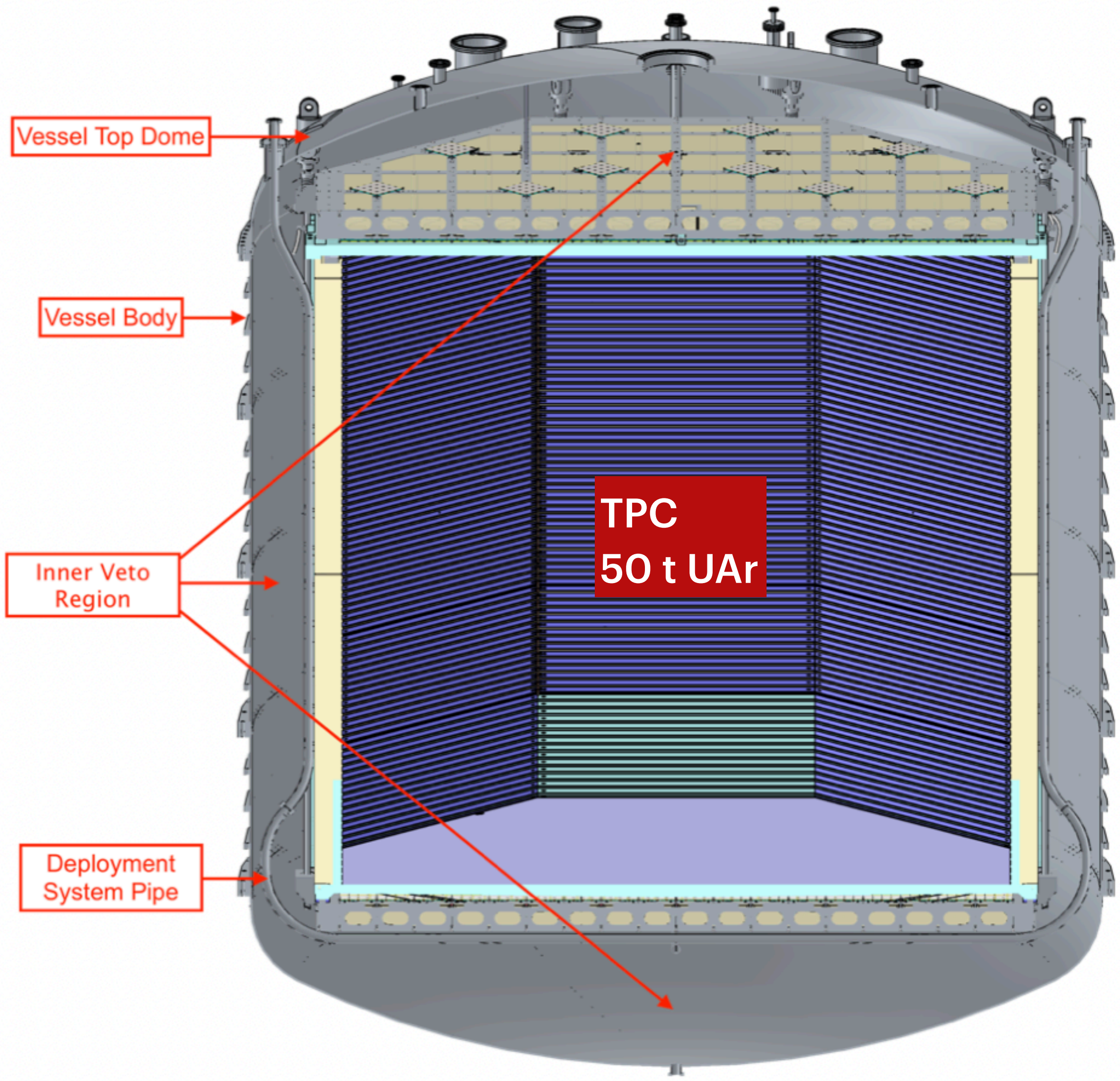
- Intrinsic ^{39}Ar radioactivity in atmospheric argon is the primary background for argon-based detectors
  - endpoint 565 keV
  - ~269 years half life
  - ~ 1Bq/kg in AAr
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where pulse shape discrimination is less effective)
- ^{39}Ar is a limiting factor due to pile-up of events
- ^{39}Ar is a cosmogenic isotope and the activity in argon from underground sources can be significantly lower compared to atmospheric argon
- We deployed 157 kg of underground argon (UAr) in DS-50 in 2015
- UAr has a ^{39}Ar reduction factor of 1400!
- DS-20k UAr will be extracted in Urania (Colorado) and further purified in Aria (Sardinia)
- UAr batches characterized in Canfranc (LSC) with the DarT detector



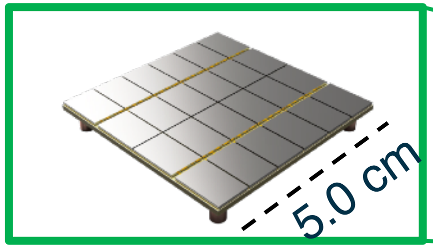


DarkSide-20k TPC

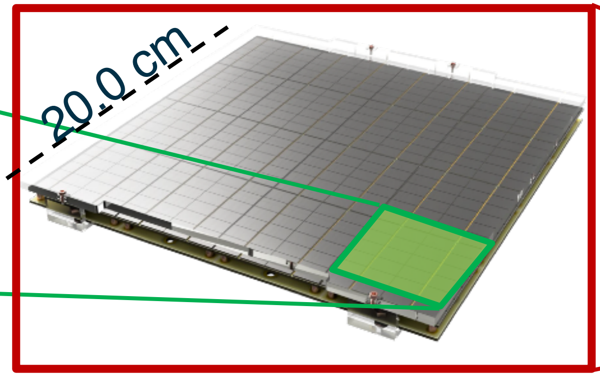
- Octagonal shape dual-phase argon TPC, structurally made in pure PMMA
- 3.5 m tall, 3.5 m diameter
- Active (fiducial) UAr mass: 49.7 (20.2) t
- Inner neutron veto Active UAr mass: 32 t
- Two optical planes (OP) watching the main TPC volume (524 photon detector units, PDUs)
- Inner veto: 120 PDUs installed on the barrel looking at the Inner Veto volume



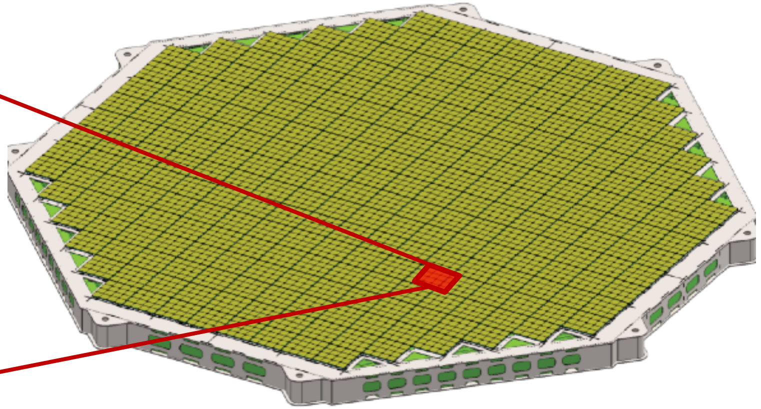
The PDU



Tile: 5x5 cm^2
24 SiPMs directly mounted on a FEB
SiPM: NUV-HD-CRYO developed by FBK
and produced by LFoundry

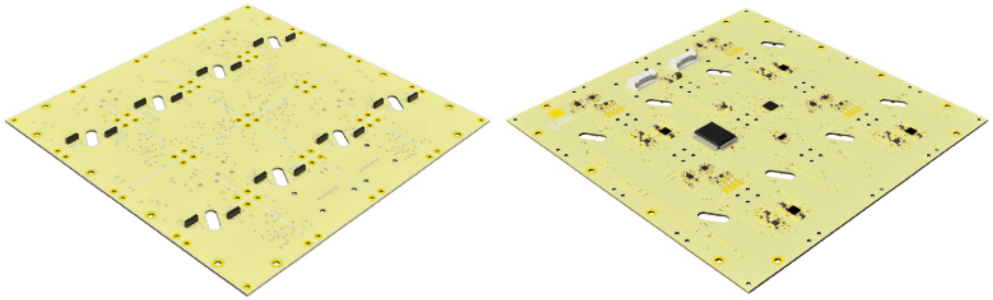


PDU: 20x20 cm^2
16 Tiles Assembled on a Motherboard
4 readout Channel



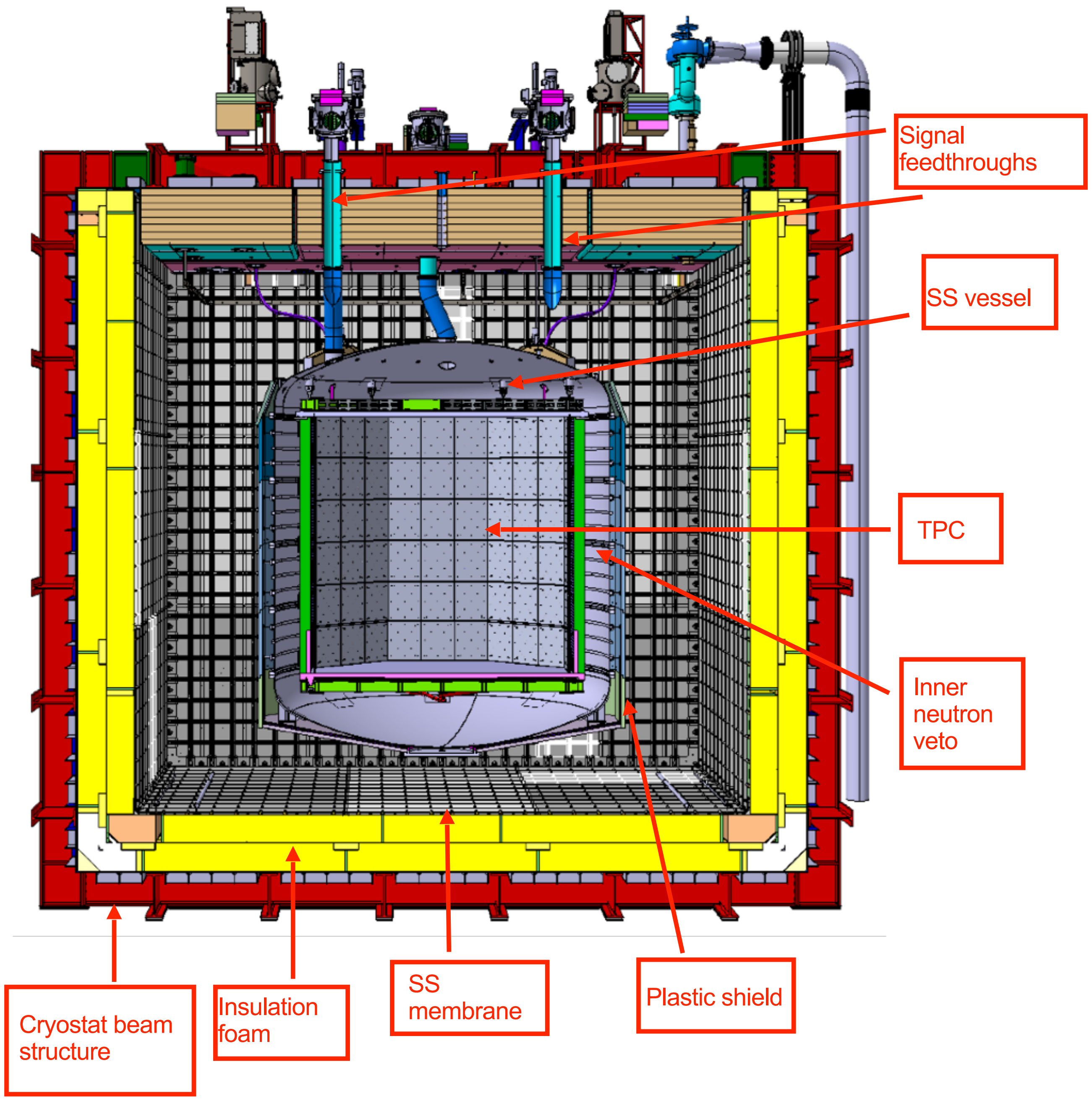
Optical planes: ~2x10 m^2
Total PDUs used (TPC): 528
Readout Channels: 2112

- A Motherboard which houses 16 Tiles →
  → Active adders sum tiles in groups of 4
  → Differential transmitter → 4 Readout CHs
- A power Management Unit allows for remote switching of HV and LV for **each tile independently**
- ~1.8 W consumption in LN



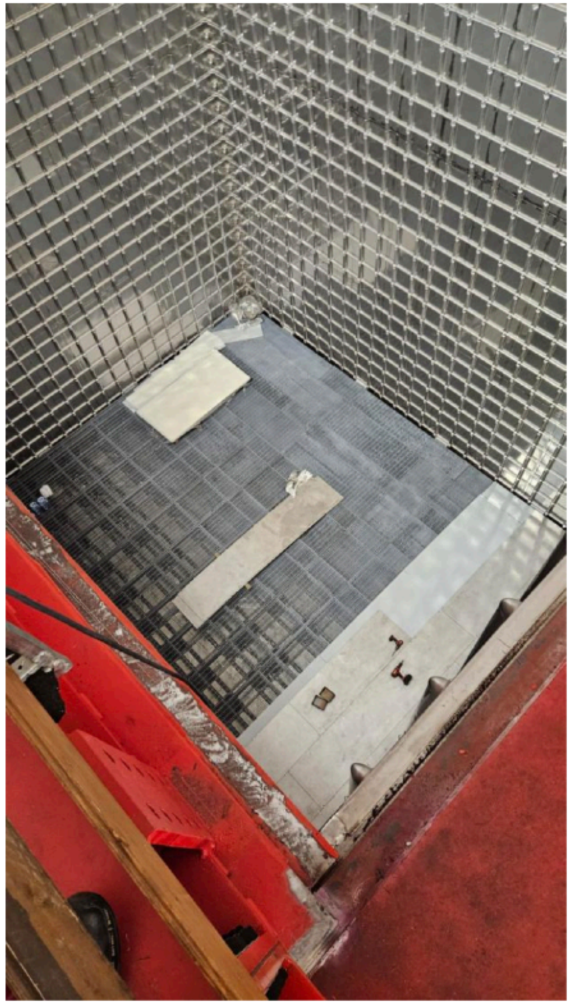
DarkSide-20k

- DUNE-like membrane cryostat filled with AAr
- Outer muon veto: 32 PDUs on the outside of the plastic shield
- ~ 7 cm plastic shield around SS vessel
- Integrated TPC& Inner veto within SS vessel & UAr



Construction underway at LNGS since 2023

Hall C at LNGS

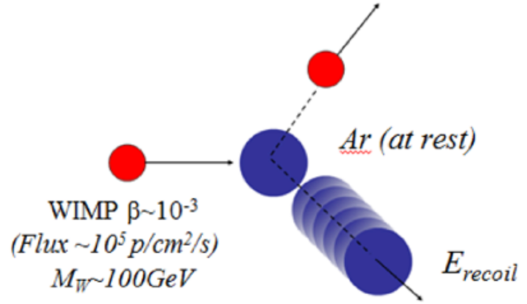


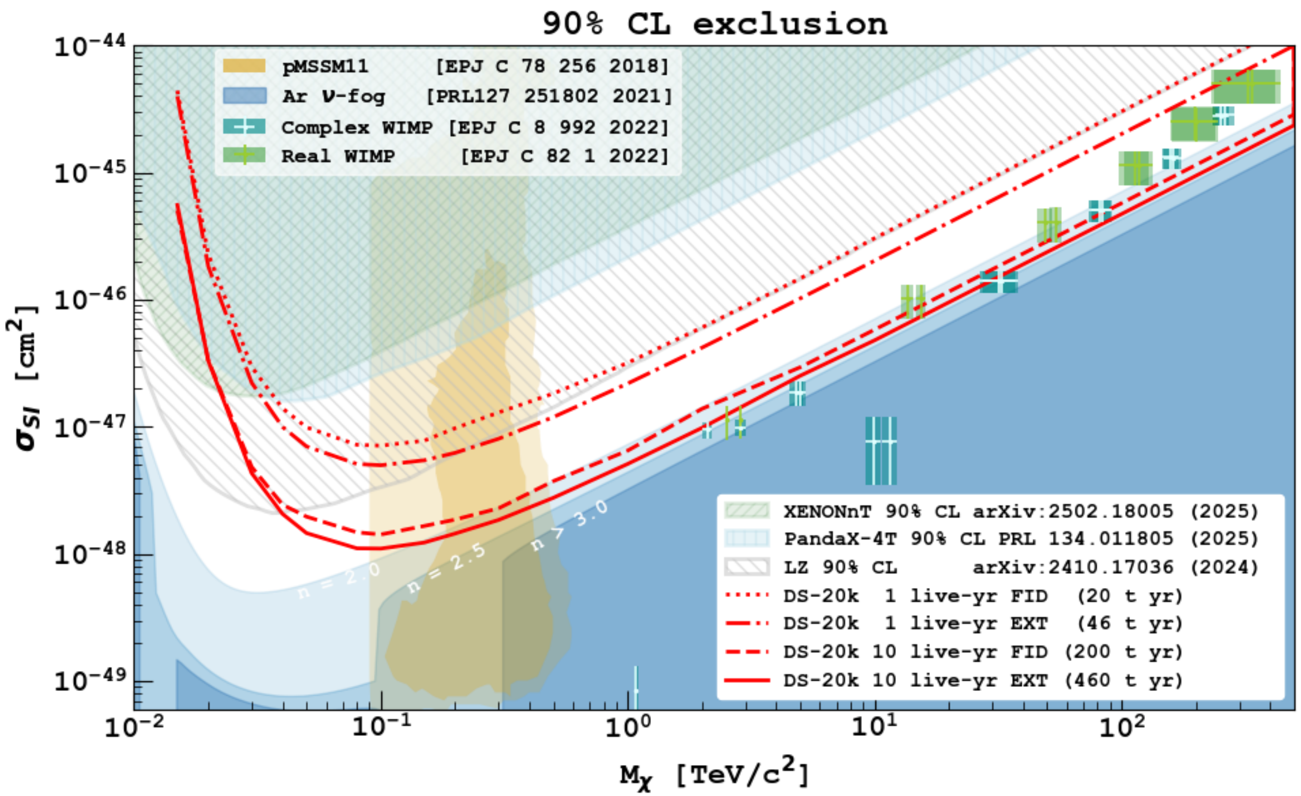
Backgrounds and mitigation

Source	Strategy & Tools
β/ γ	UAr, PSD, material selection, …
Radon progeny	Surface cleaning, Rn suppressed air, …
Radiogenic neutron, mostly (α, n)	Neutron veto, fiducialization, material selection, …
Cosmogenic neutron	Muon veto
Neutrino induced NRs	Irreducible (~3.2 ev in 200 t-y)

High mass WIMP analysis

- Target: Argon nuclei
- Large exposure
- Topology-based background discrimination: multi-scatter vs single-scatter
- Pulse-shape based bkg discrimination (PSD) > 10^8 setting NR acceptance ~ 40 keV_{nr}
- Two volumes in analysis:
  - FID: low instrumental background rate < 0.3 events in ROI (30-200 keVnr) with 200 t-yr exposure
  - EXT: background dominated by radiogenic neutrons from photosensors and experimental Hall



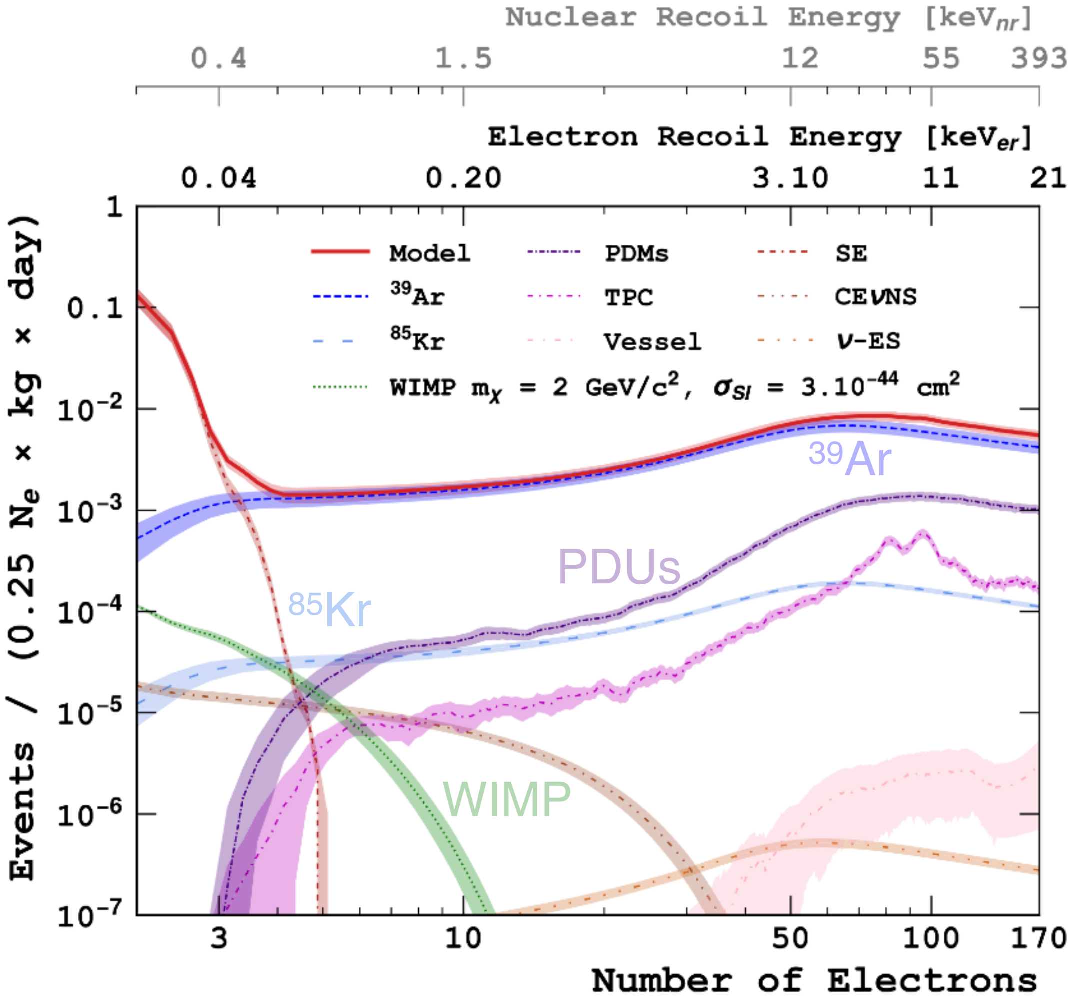


Sensitivity to light dark matter

- S2 only analysis → no PSD
- ERs are the main background (mainly from ^{39}Ar)
- ER rate: 80 Hz (before cuts) → 51% live-time
- Spurious Electron (SE): origin might be trapped electrons by impurities and released later → extrapolated from DS-50
- Techniques already applied to DS-50 data (best limits in the [1.2, 3.6] GeV c^{-2} mass range)
- Analysis cuts:
  - Single S2 pulse in 3.7 ms
  - Removal of anomalous low S2 signals (α from the TPC walls)
  - FV cut: 30 cm from TPC walls → 34 tons
- ROI: $N_{e^-} \in [4,170]$ ($N_{e^-} \in [2,170]$)

^{39}Ar dominant for $N_e \geq 4$
Reduced ^{85}Kr activity wrt DS-50
Spurious Electrons dominant for $N_e \leq 3$

[Nature Communication Physicsl (2024) 7:422]



39Ar assumed to be 0.73 mBq/kg (DS-50 level)
85Kr assumed to be 19 µBq/kg (reduced by a factor 100 wrt DS-50)

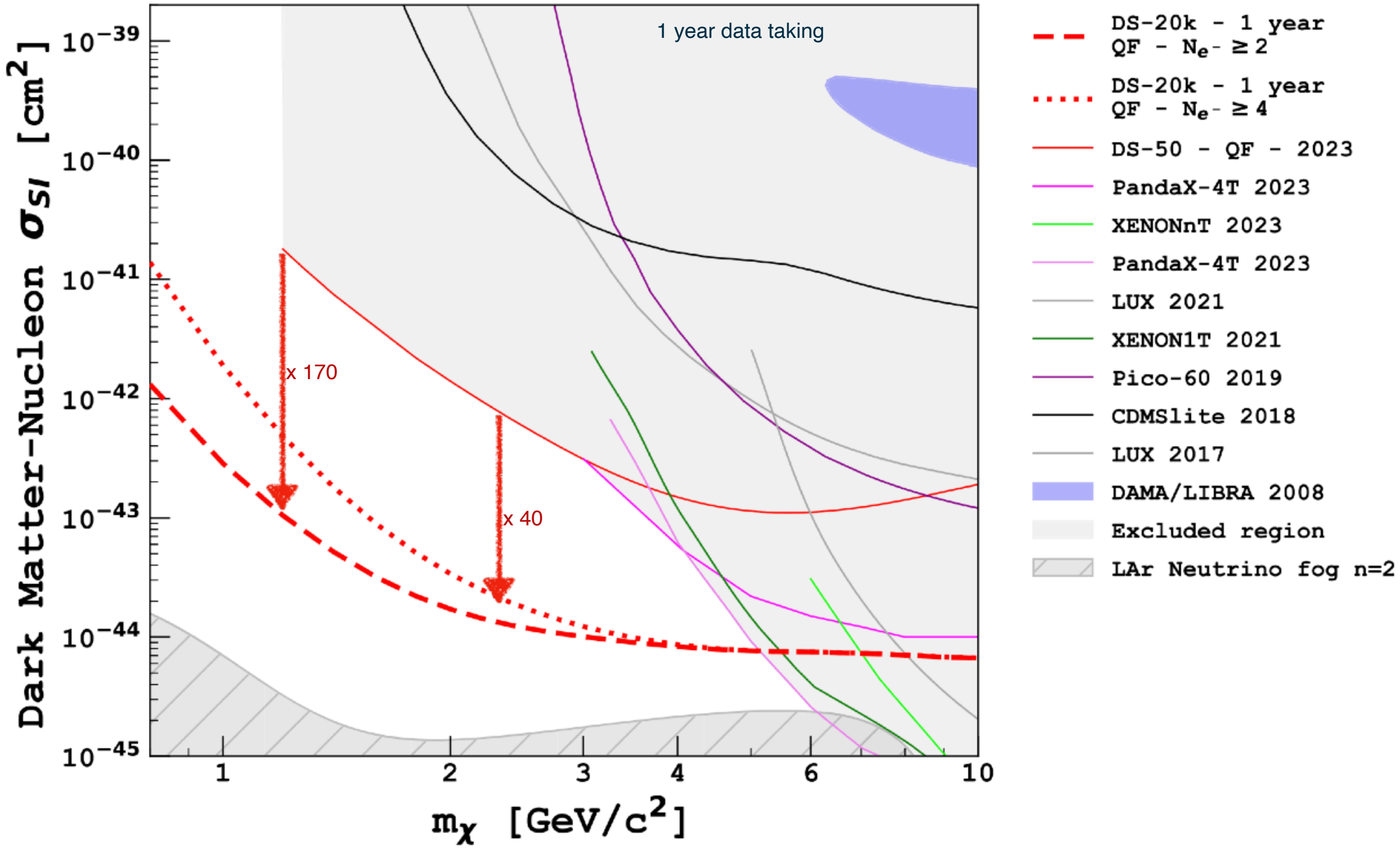
Sensitivity to light dark matter

More than one order of magnitude of improvement with respect to DarkSide-50 after one live-year of data taking

2 fit scenarios:

Conservative (almost indep. of SE modelling): Fit from $N_e = 4$ (DS-50 strategy)

Ultimate: Fit from $N_e = 2$ assuming good control spectral shape of SE in DS-20k

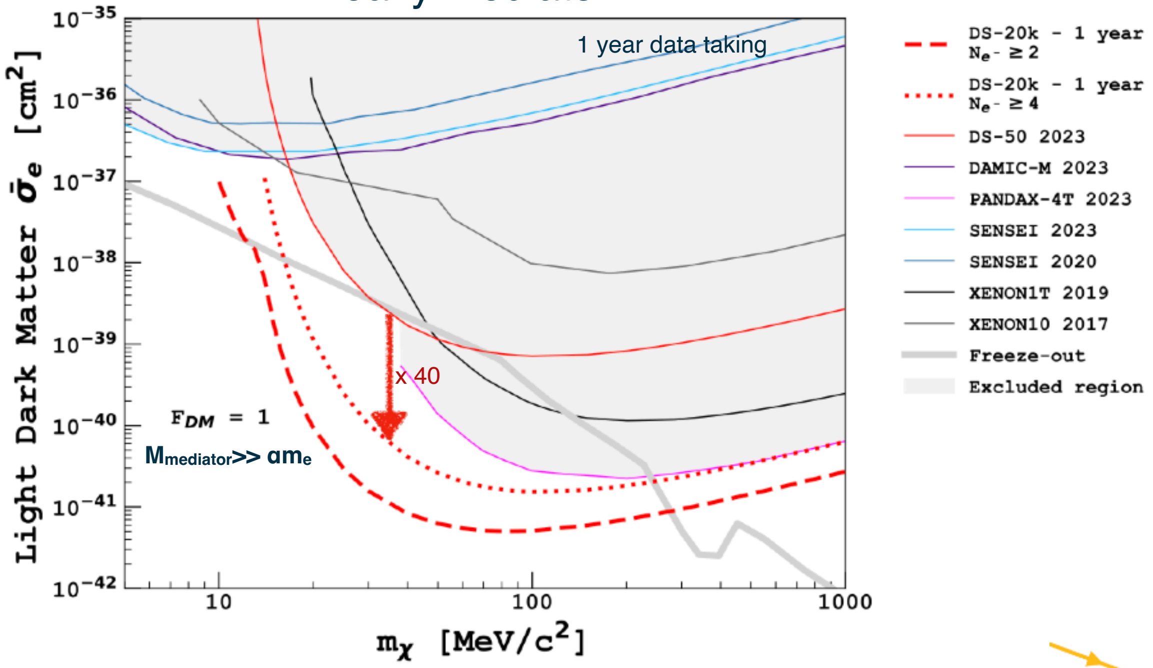


[Nature Communication Physicsl (2024) 7:422]

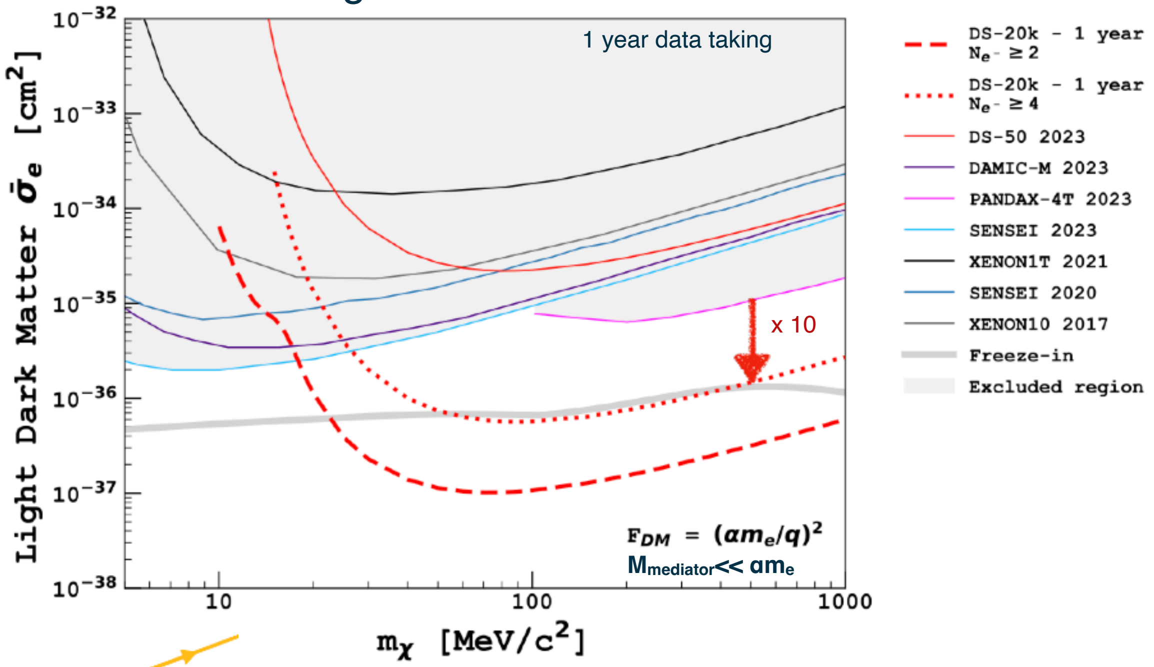
Sensitivity to light dark matter

WIMP-electron cross section
Heavy and light mediators

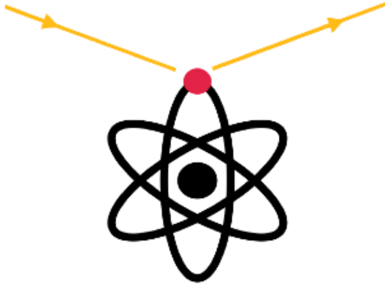
heavy mediator



light mediator



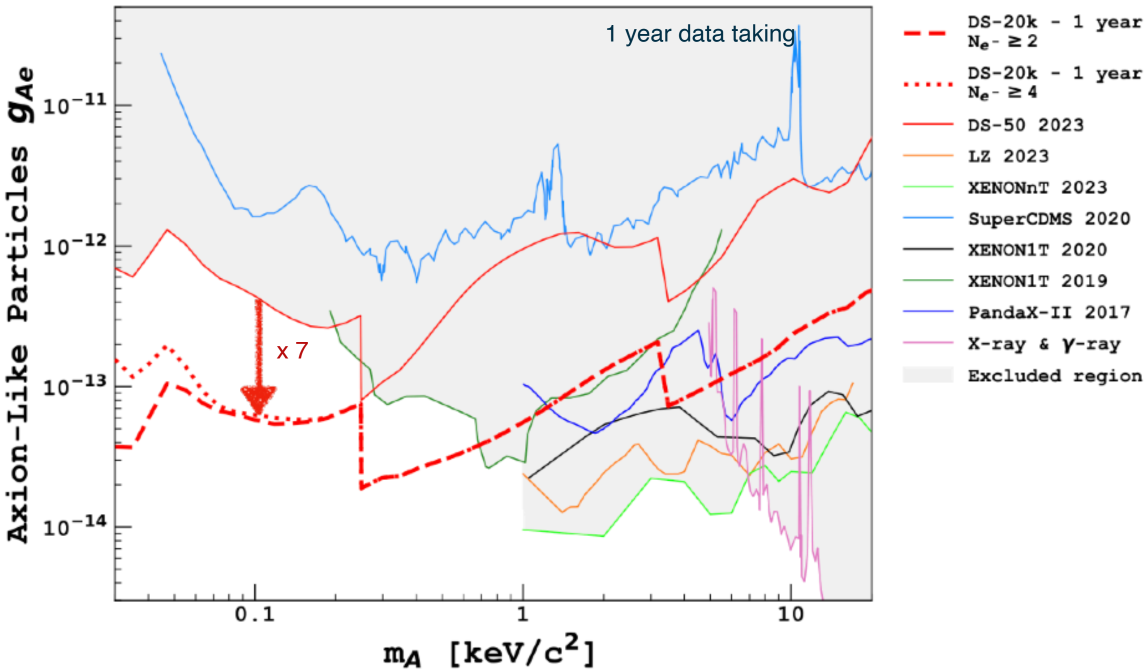
- Elastic scatter of Light Dark Mater (LDM) off bound electrons
- LDM = Sub GeV fermion or scalar boson
- The mediator can be heavy F~1 or light F~1/q^2

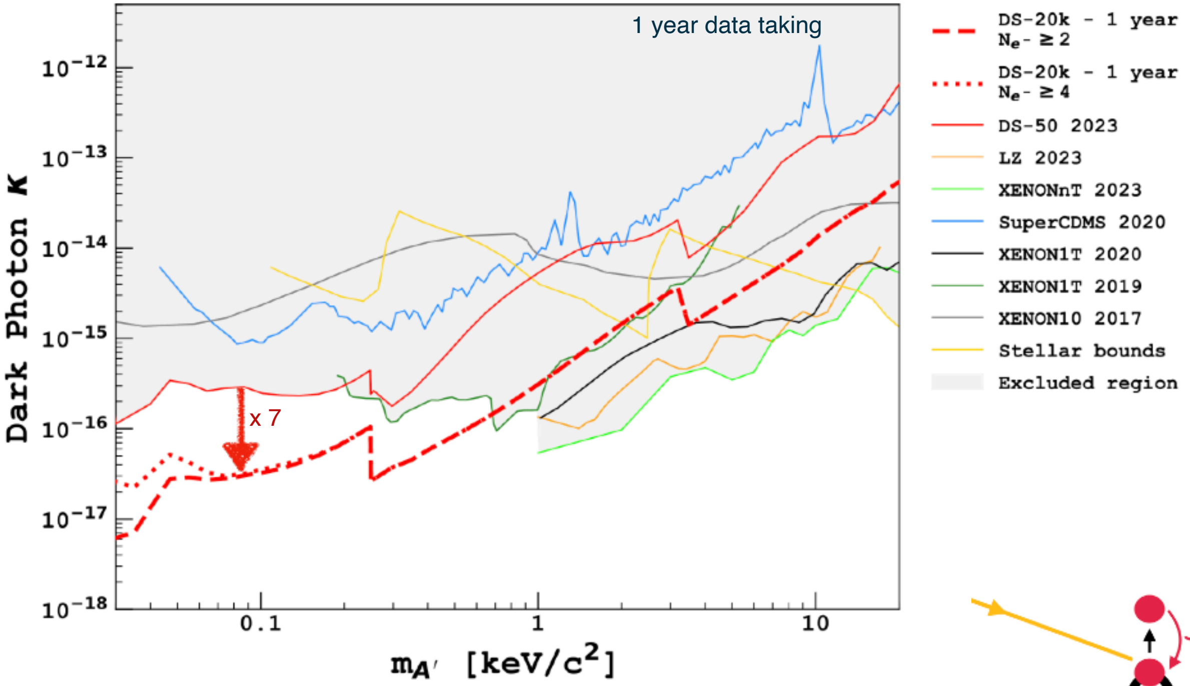


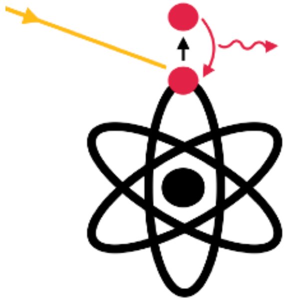
$$\frac{dR}{d\ln E_{er}} = N_T \frac{\rho_{DM}}{m_\chi} \times \frac{\bar{\sigma}_e}{8\mu_{\chi e}^2} \times \sum_{n\ell} \int |f_{\rm ion}^{n\ell}(k',q)|^2 |F_{\rm DM}(q)|^2 \eta(v_{\rm min}) q\, dq$$

[Nature Communication Physicsl (2024) 7:422]

Sensitivity to light dark matter







- Absorption by shell electrons of axion-like particles or vector-boson DM results in a monoenergetic signal at the particle's rest mass
- g_{Ae} is the ALP-electron coupling, κ is the kinetic mixing strength between DP and SM photons

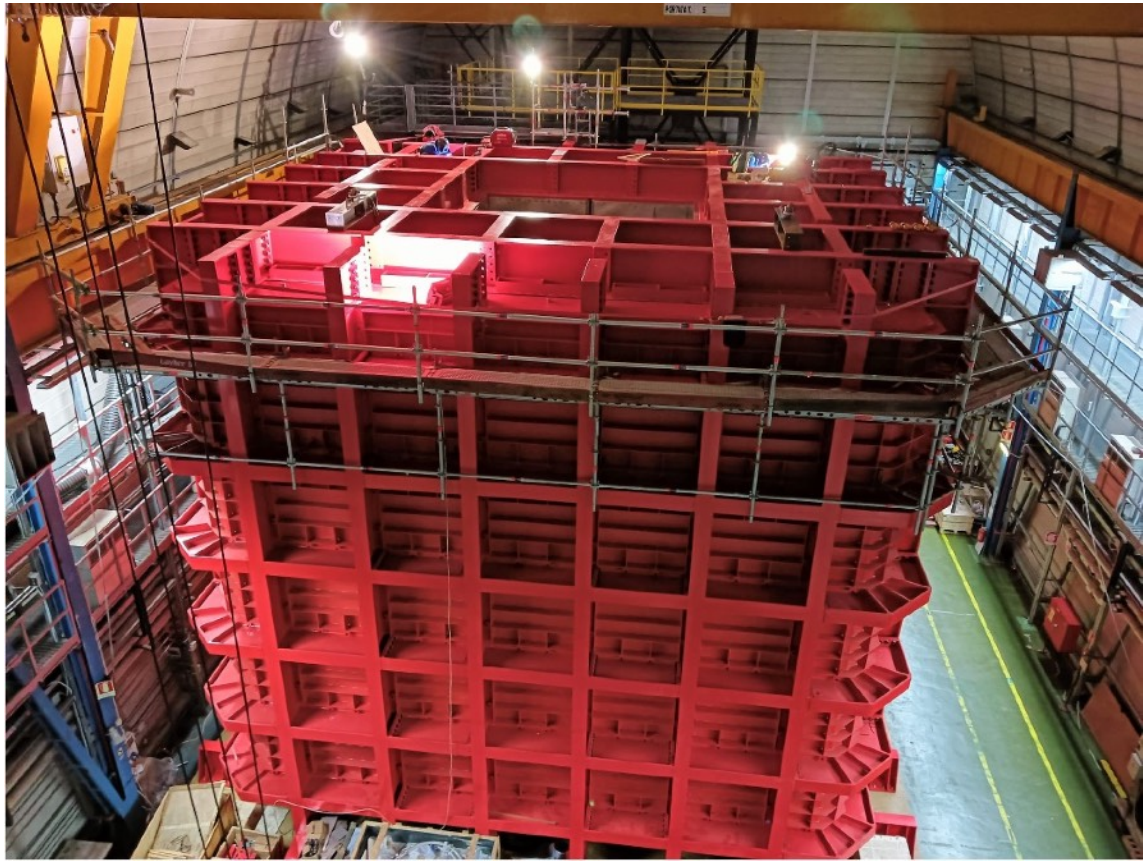
$$R = N_T \frac{\rho_{\rm DM}}{m_{\rm A}} \times \frac{3 m_{\rm A}^2 g_{\rm Ae}^2}{16\pi\alpha m_e^2} \sigma_{\rm pe}(m_{\rm A} c^2) c$$

$$R = N_T \frac{\rho_{\rm DM}}{m_{\rm A'}} \times \kappa^2 \sigma_{\rm pe}(m_{\rm A'} c^2) c.$$

[Nature Communication Physicsl (2024) 7:422]

Conclusions

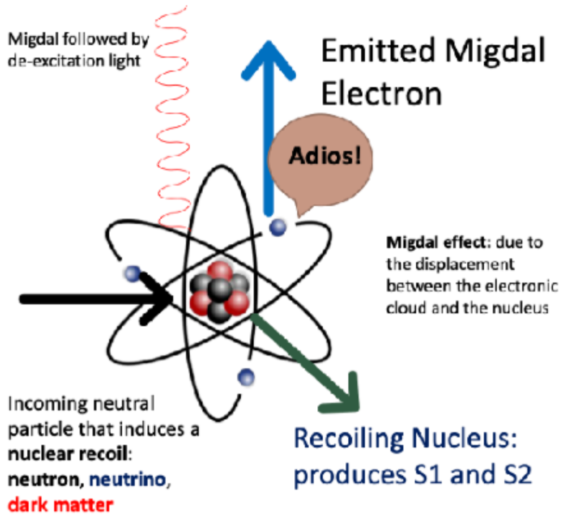
- The construction of DarkSide-20k is ongoing at LNGS
- TPC with UAr is well suited for high- and low-mass WIMP searches
- The high-mass WIMP search will be fully complementary with existing ongoing Xe-based detectors
- The low energy analysis further strengthens the physics reach of DarkSide-20k with a leading role below 5 GeV/c^2
- Expect to probe > 1 order of magnitude of uncharted theory parameter space within 1 year for a variety of dark matter particles

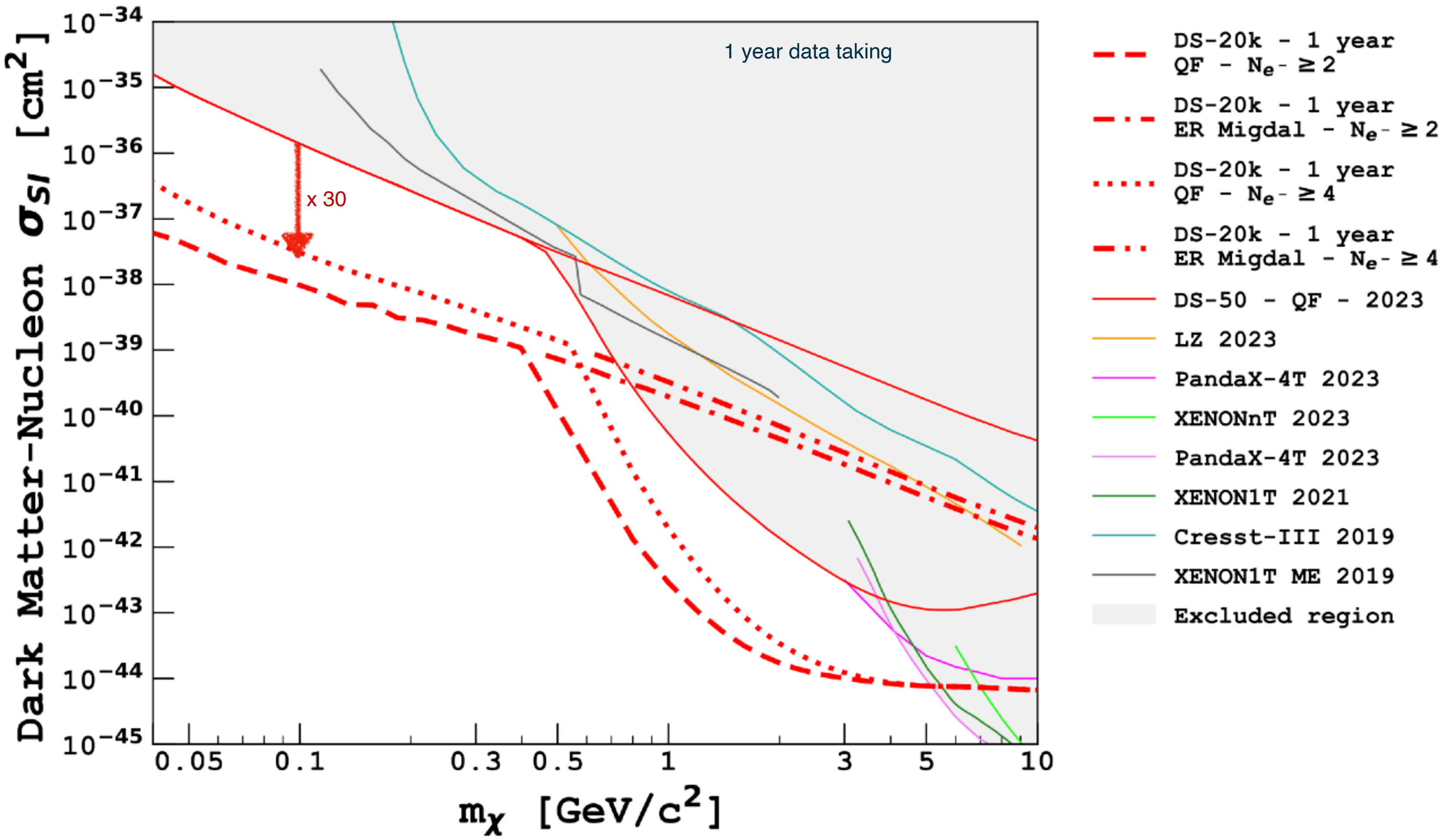


Backup

Sensitivity to light dark matter

Migdal effect: extra electron recoil component increases the probability of exceeding the detection threshold → wider range of WIMP masses can be explored

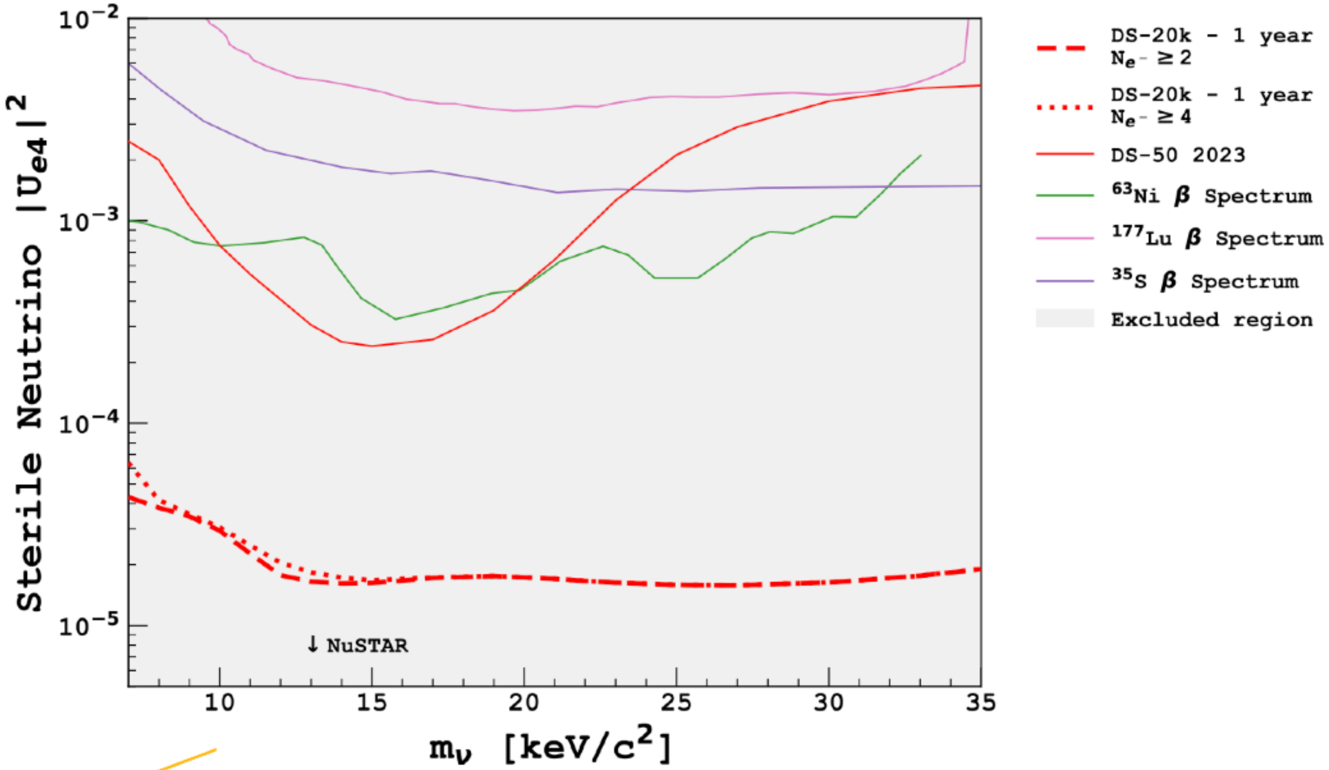


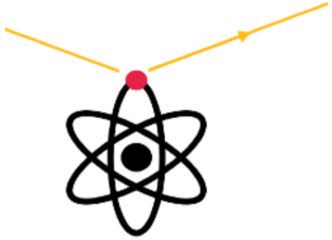


[Nature Communication Physicsl (2024) 7:422]

Sensitivity to light dark matter

- Inelastic scatter of sterile ν_s off bound electrons
- Possible mixing with active neutrinos → PMNS-like matrix element $|U_{e4}|^2$
- Best direct limits in 1 year but phase space already rejected by NuSTAR indirect measurements



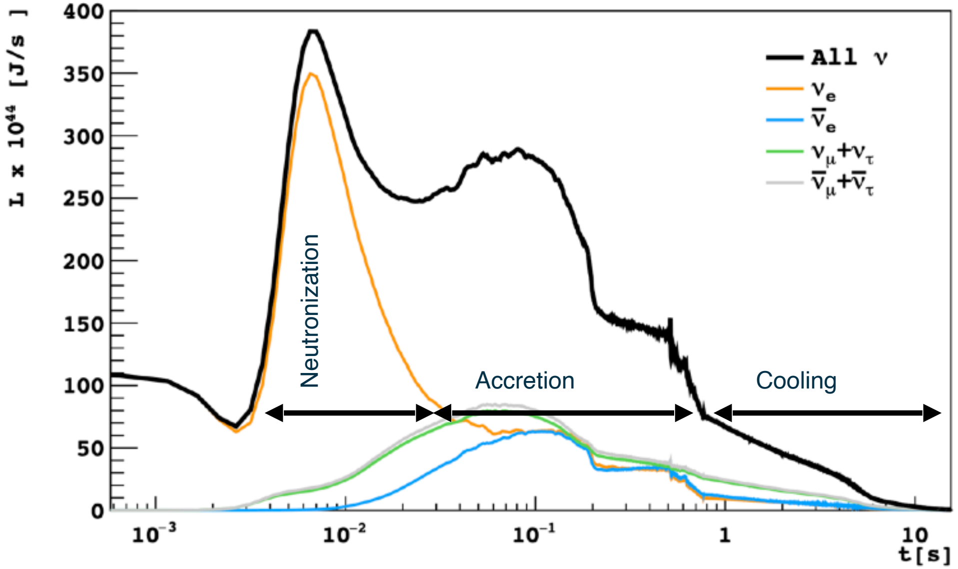


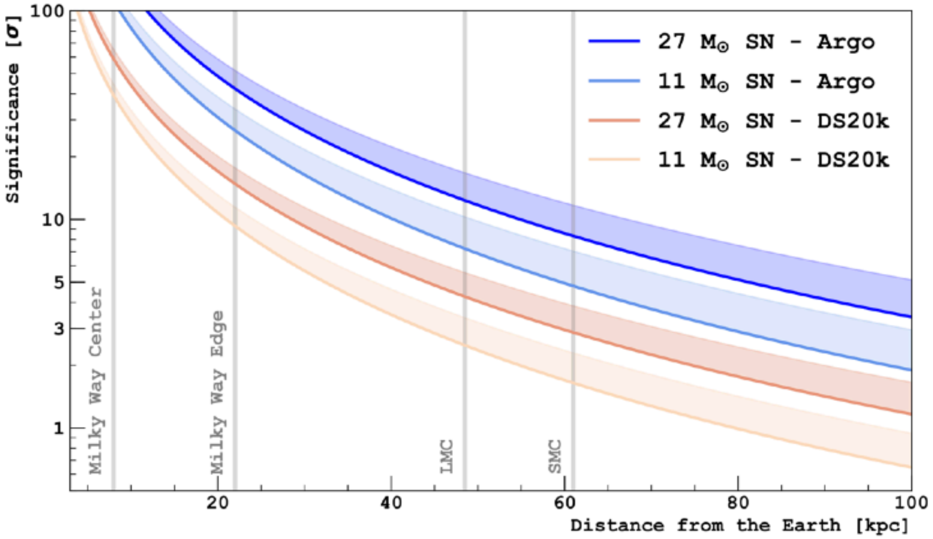
$$\frac{dR}{dE_{\rm er}} = N_T \frac{\rho_{\rm DM}}{m_\nu} \sum_{n\ell} 2(2\ell+1) \int \frac{d\sigma_{n\ell}}{dE_{\rm er}}(v, m_\nu, |U_{e4}|^2) f(v)\, v\, dv$$

[Nature Communication Physicsl (2024) 7:422]

Sensitivity to supernova ν

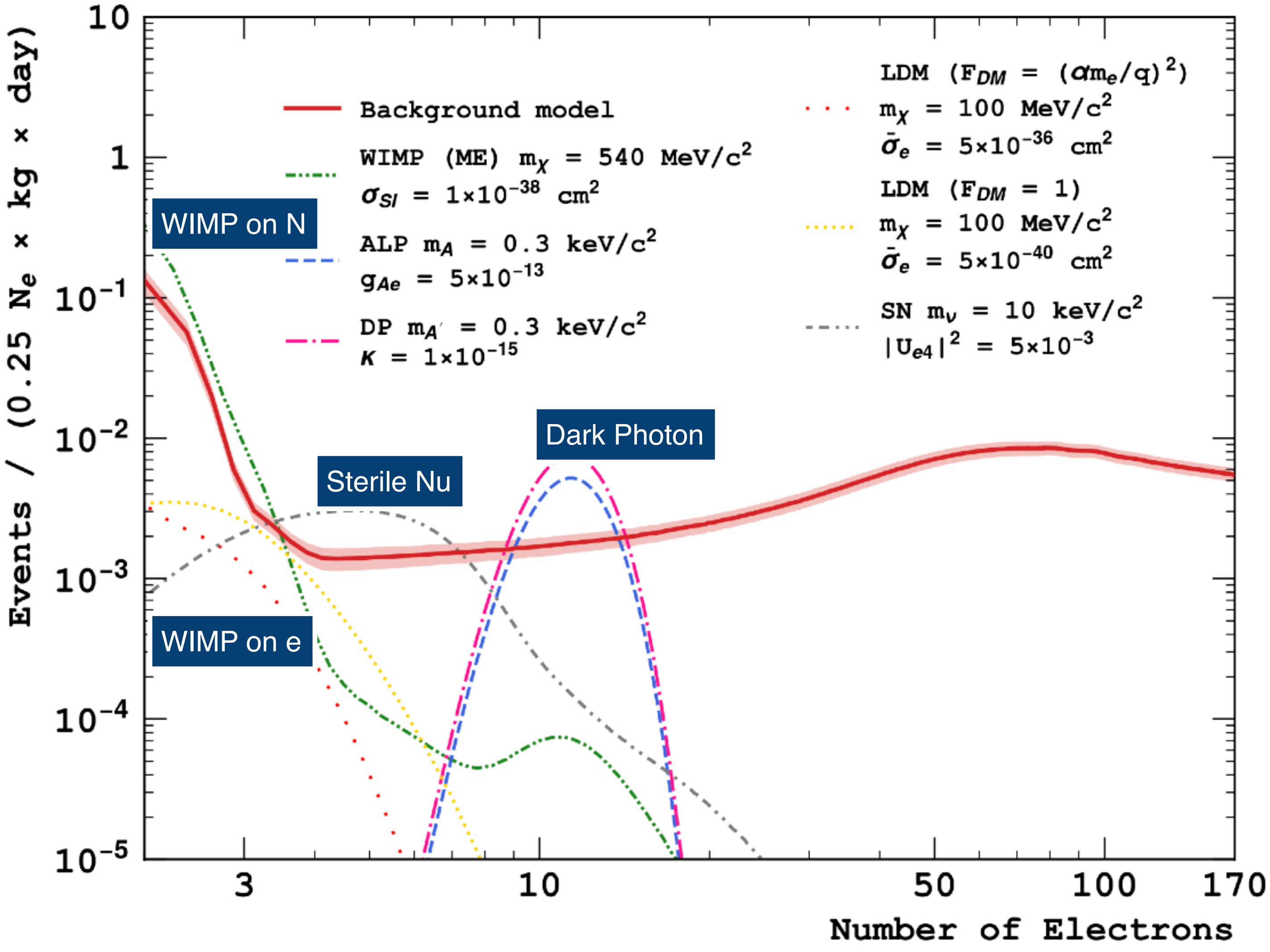
- Supernovae can provide constraints to the neutrino absolute mass and mass ordering
- Water Cherenkov and scintillator detectors are mostly sensitive to $\overline{\nu}_e$ inverse beta decay and ν_e elastic scattering
- DUNE is mostly sensitive to ν_e via charge current interaction
- DS-20k can detect all flavor (anti)neutrinos via coherent elastic neutrino-nucleus scattering ($CE\nu NS$)
  - S2 only analysis
  - Inferred background from DS-50
- DS-20k has the potential to discover supernova bursts throughout our galaxy

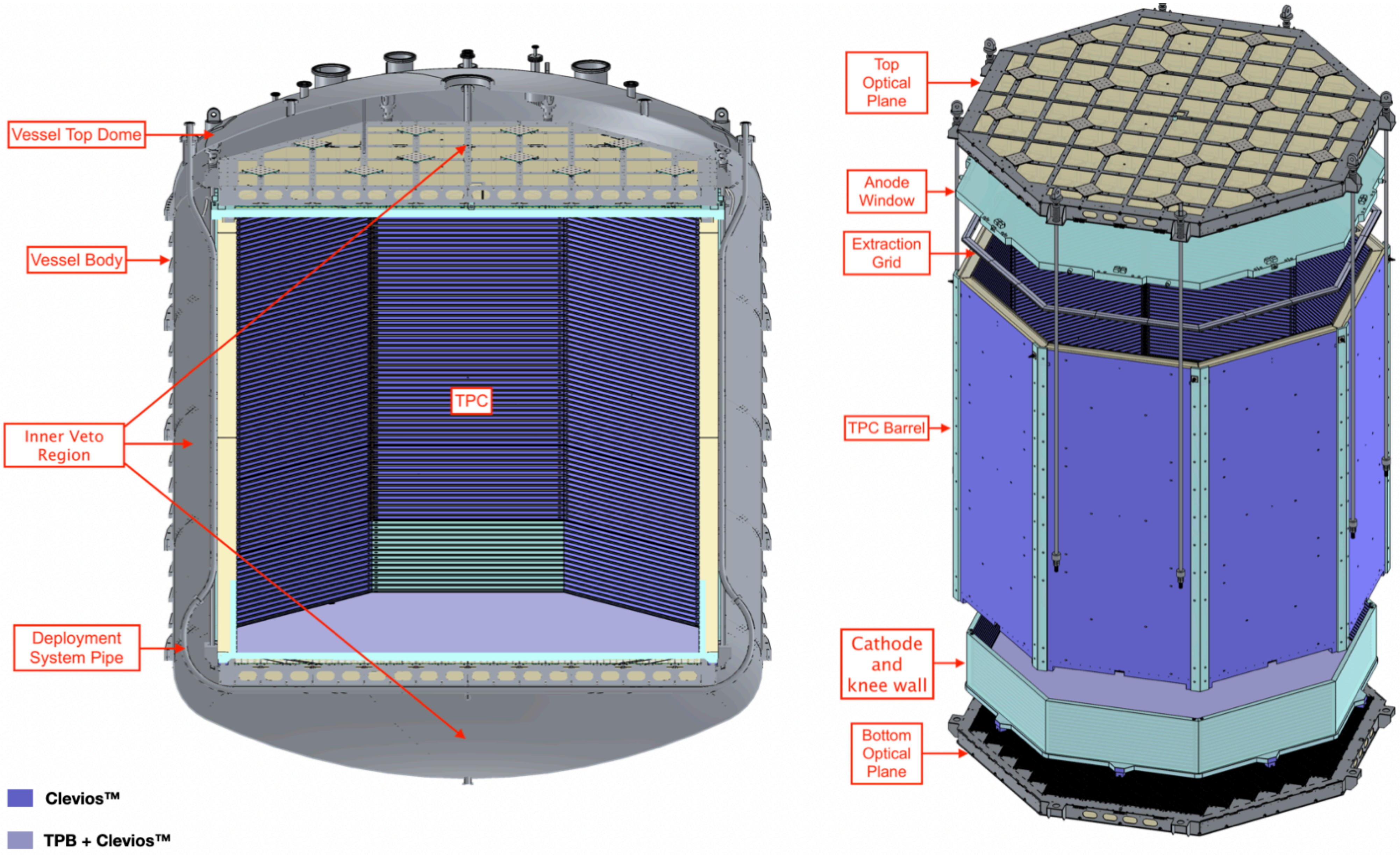




[JCAP 03, 043 (2021)]

DS20k lowmass DM signal models

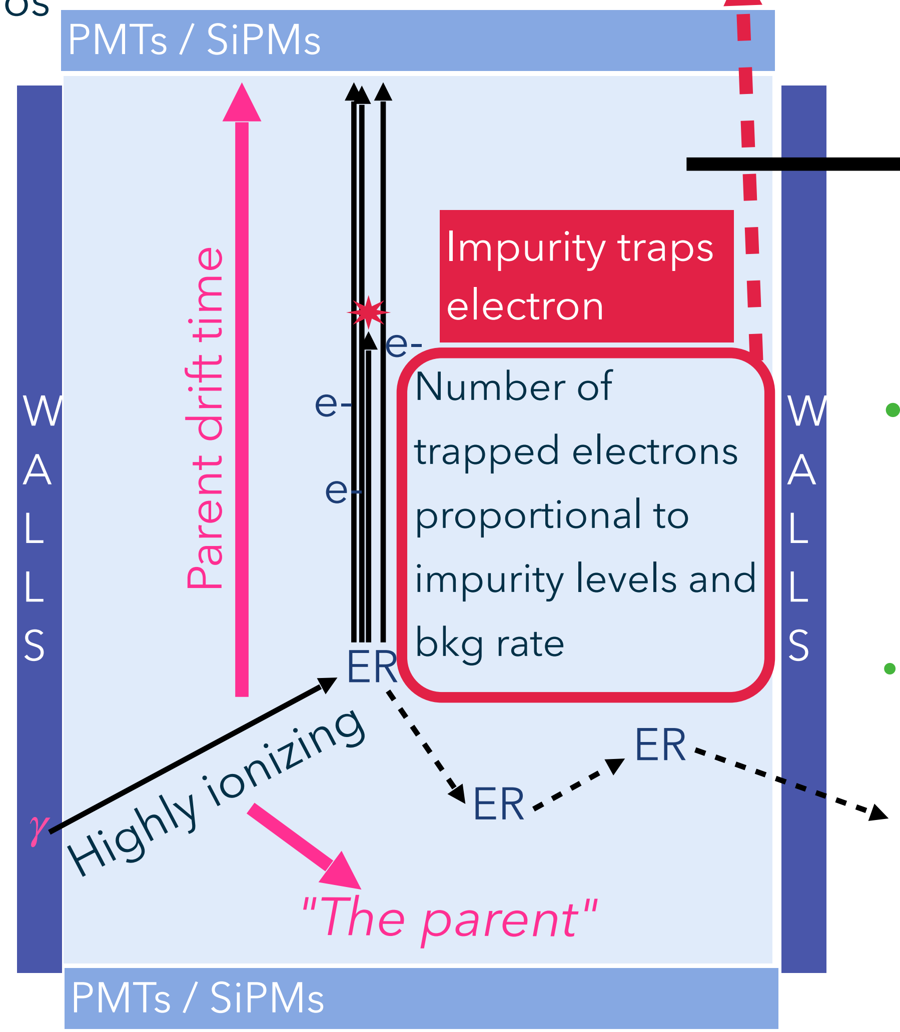




Vessel Top Dome
Vessel Body
TPC
Inner Veto Region
Deployment System Pipe
Clevios™
TPB + Clevios™
Top Optical Plane
Anode Window
Extraction Grid
TPC Barrel
Cathode and knee wall
Bottom Optical Plane

Single Electron Background

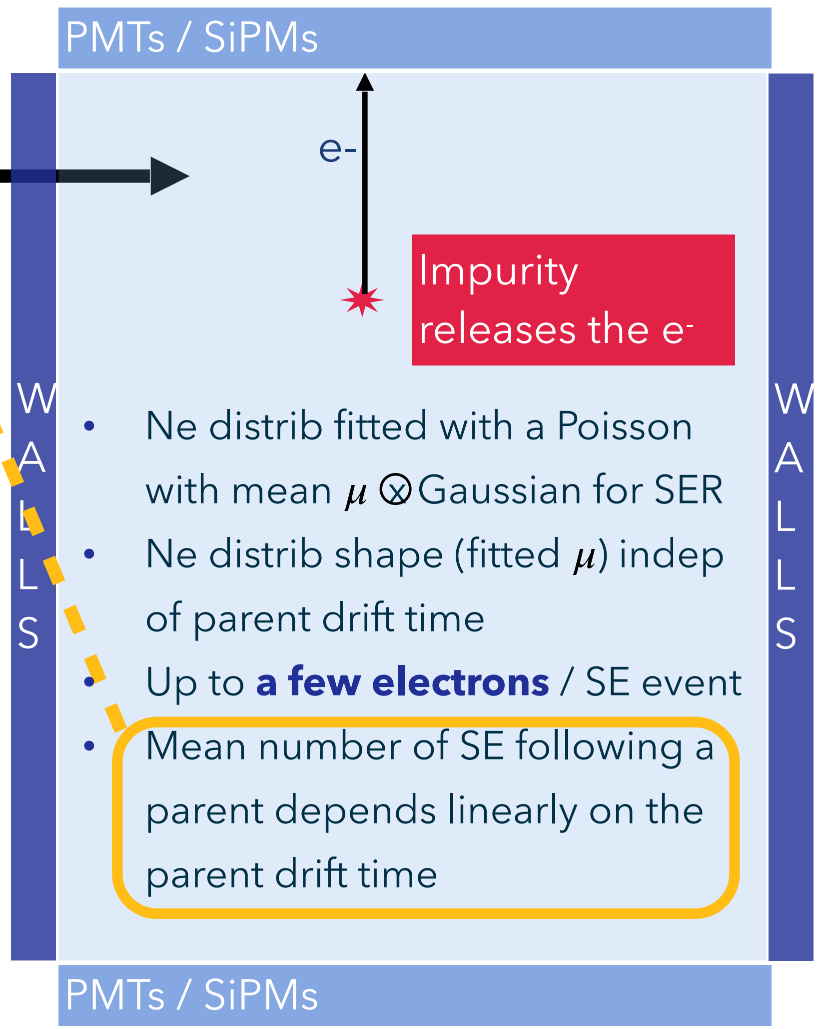
- **Extrapolated** from DarkSide-50 data
- **DS20k rate** = DS50 rate scaled with bkg rate and max. drift time ratios



Later

- **Time dependency** (ΔT) with the previous highly ionizing event (the parent)
- ΔT measured to be 3 exponentials (1 uncorrelated component, 1 fast, 1 slow)

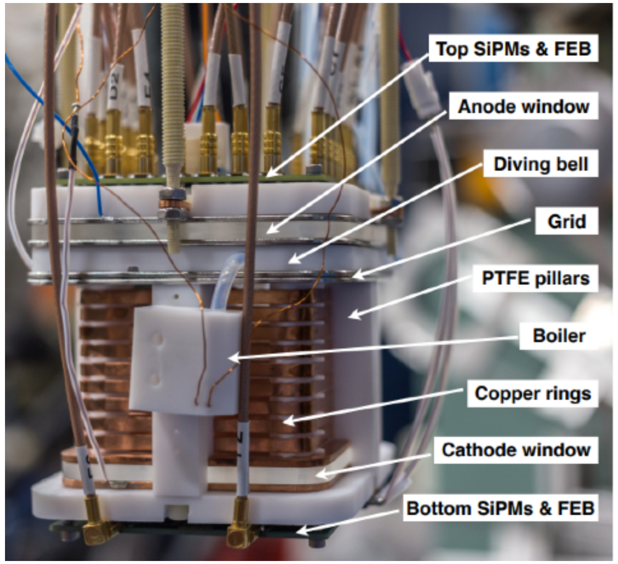
- **DS20k shape (in Ne):** takes into account expected single electron resolution (SER) and electron lifetime



- Ne distrib fitted with a Poisson with mean $\mu \otimes$ Gaussian for SER
- Ne distrib shape (fitted μ) indep of parent drift time
- Up to **a few electrons** / SE event
- Mean number of SE following a parent depends linearly on the parent drift time

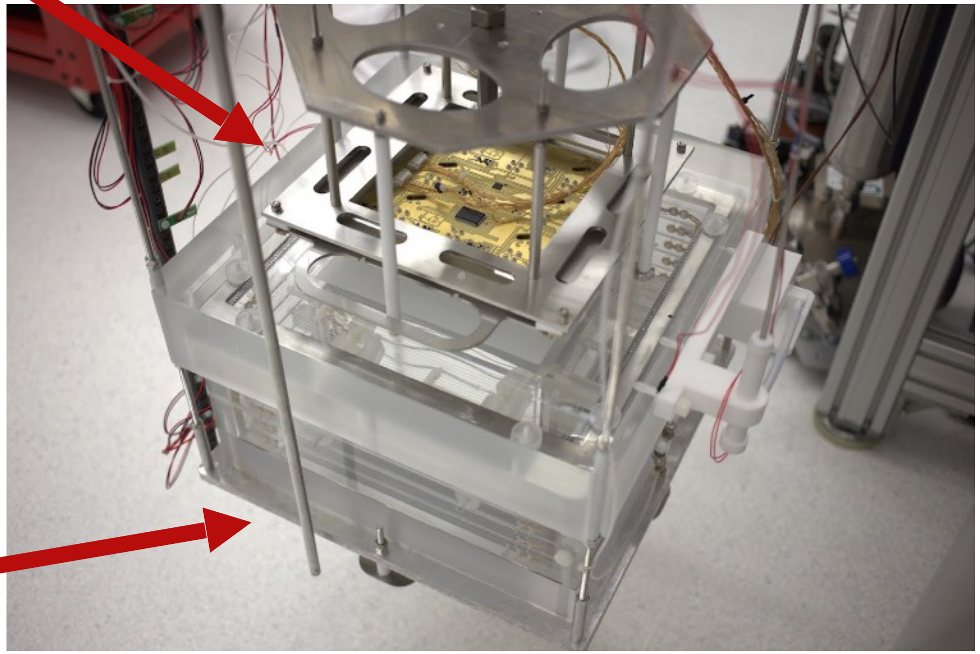
In Liquid Argon…

Agnes. P et al. Eur. Phys. J. C 81, 1014 (2021)
DarkSide-20k Collaboration Eur. Phys. J. C 84, 24 (2024)



TOP PDU

BOTTOM PDU



ReD – Recoil Directionality

Contraints on directional sensitivity for NR in LArTPCs

2 Phase LArTPC

~6 months LN calibration

> 1 y in cryogenic environment

DarkSide Proto-0 – DS-20k Prototype with