Neutrino detection with ARGO

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24th International Workshop on Next Generation Nucleon Decay & Neutrino Detectors (NNN25), Sudbury

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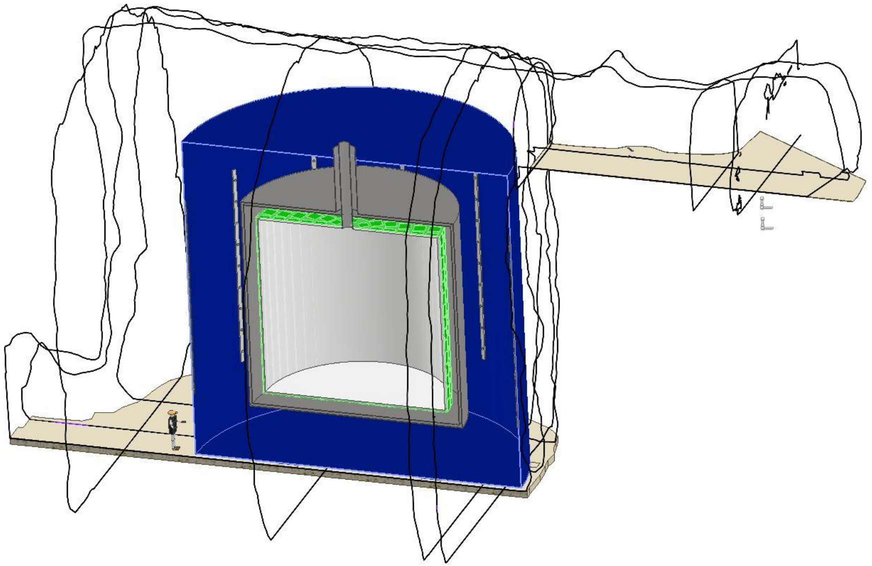
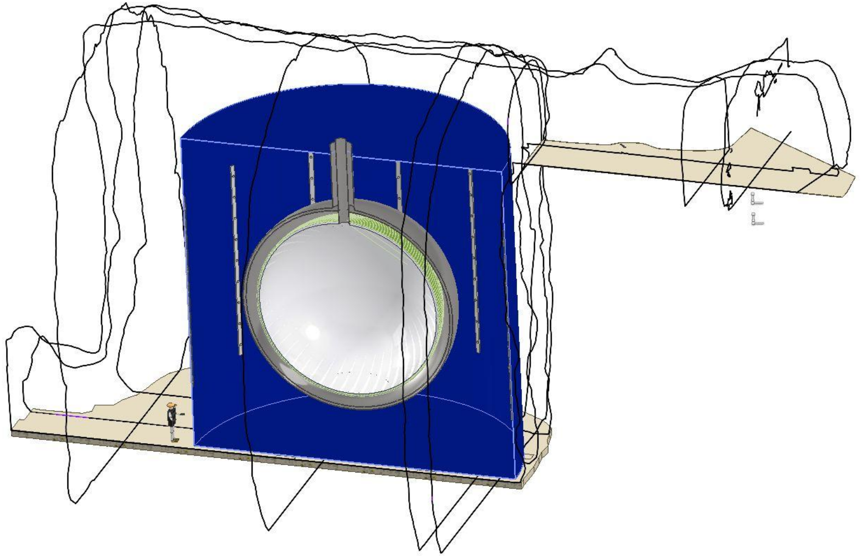
The Global Argon Dark Matter Collaboration

Timeline

ArDM DarkSide-50 DEAP MiniCLEAN	The Global Argon Dark Matter Collaboration (2017)	DS-20k {20 t fid., 100 ton total} Ops 2028 - 2038, LNGS	ARGO {300 t fid., 400 ton total} Project early 2030's, SNOLAB

400 researchers, 100 institutions, 14 countries

ARGO conceptual design in SNOLAB Cube Hall

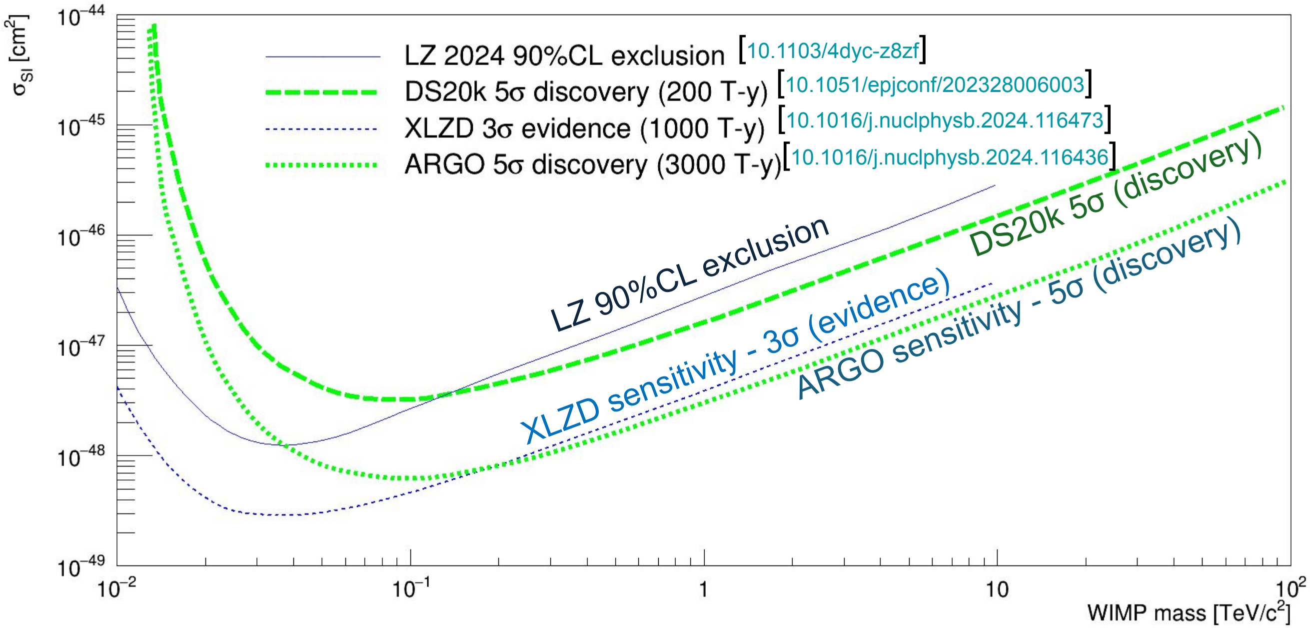
 

400 tonnes of underground argon, **300 tonnes fiducial mass**, 3000 tonne-year exposure.

200 m^2 of pixelated digital silicon photomultiplier (SiPM) readout.

NSERC-funded since 2021. SNOLAB Gateway-1a approval in 2025 for prototyping and concept development.

Sensitivity to WIMP search with ARGO



Complete suppression of ER backgrounds in argon leads to a stronger discovery potential with ARGO.

Broad Neutrino Sensitivity in ARGO

With a large fiducial mass, low-background, high-resolution LAr detector:

- Access to both low- and high-energy solar neutrinos.
- Excellent sensitivity to core-collapse supernova neutrinos.

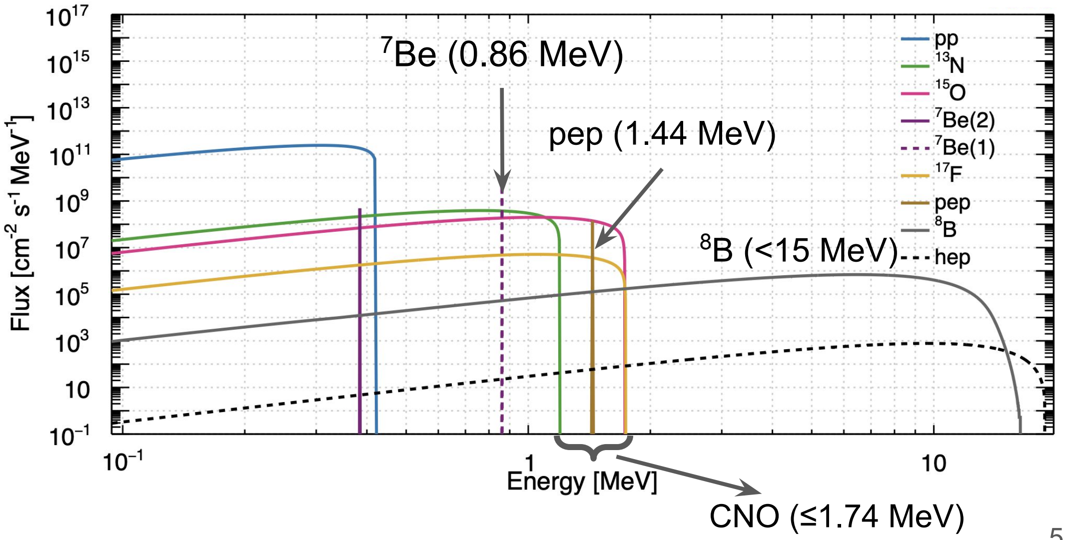
Detection Channels:

CC absorption: ^{8}B & hep neutrinos on ^{40}Ar

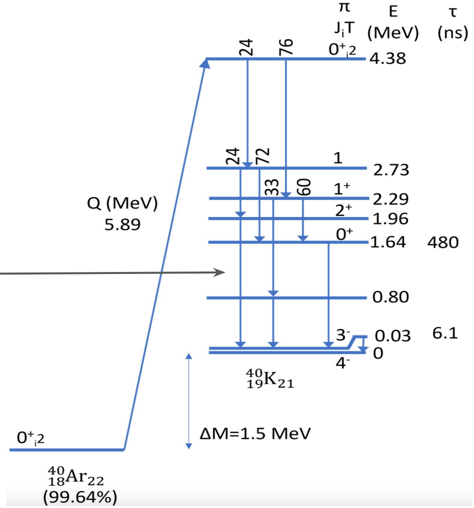
Elastic scattering: pep, ^{7}Be, CNO neutrinos

CEνNS: atmospheric & solar neutrinos

Solar neutrino flux at Earth [10.1201/9781315195612]



Charge-current absorption on ^{40}Ar

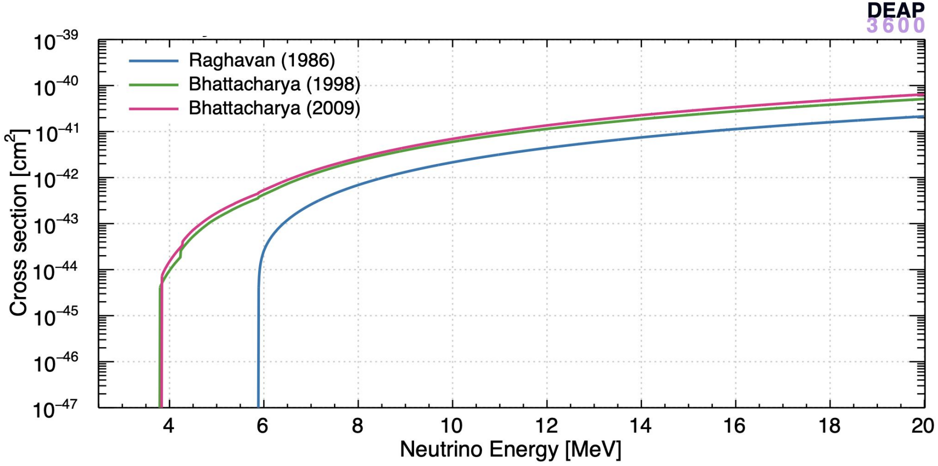


$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ (followed by γ de-excitation)

Super allowed 0+ → 0+ Fermi transition from ground state of ^{40}Ar to an excited state of ^{40}K with a reaction threshold of 5.9 MeV.
R. S. Raghavan [10.1103/PhysRevD.34.2088]

Gamow-Teller transitions lower the reaction threshold to 3.9 MeV. M. Bhattacharya et al. [10.1103/PhysRevC.58.3677, 10.1103/PhysRevC.80.055501]

Cross-section being measured by DEAP-3600. Results coming out soon!



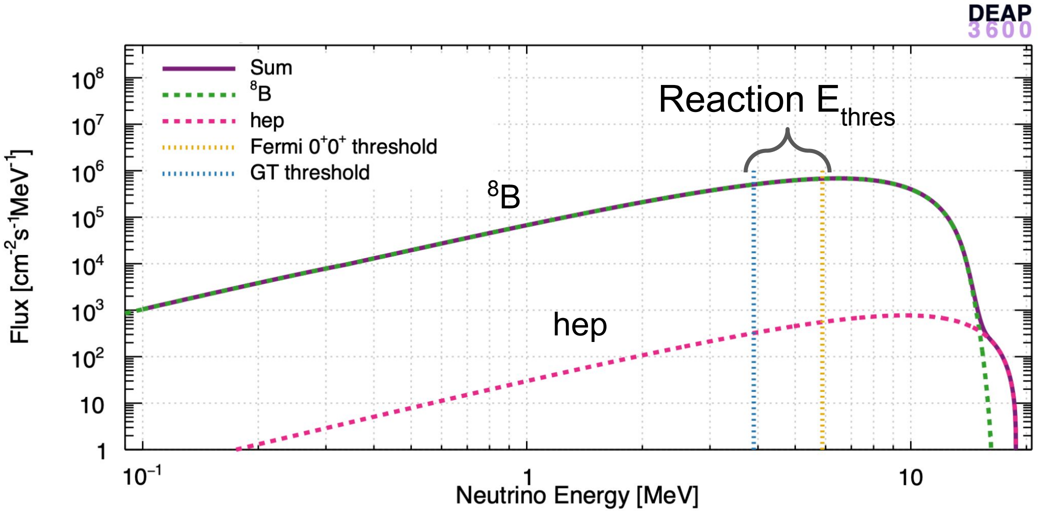
ARGO sensitivity to solar neutrino charge-current absorption

Considering the ^8B solar neutrino integrated flux from SNO measurements, [10.1103/PhysRevC.75.045502]

$$\Phi_{SNO} \approx 1.76 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$$

gives an expected rate,

$$\Gamma = 2.2 \text{ events/tonne-year in Ar}$$



~6600 events expected in 3000 tonne-year exposure.

High-statistics CC measurement with excellent energy resolution.

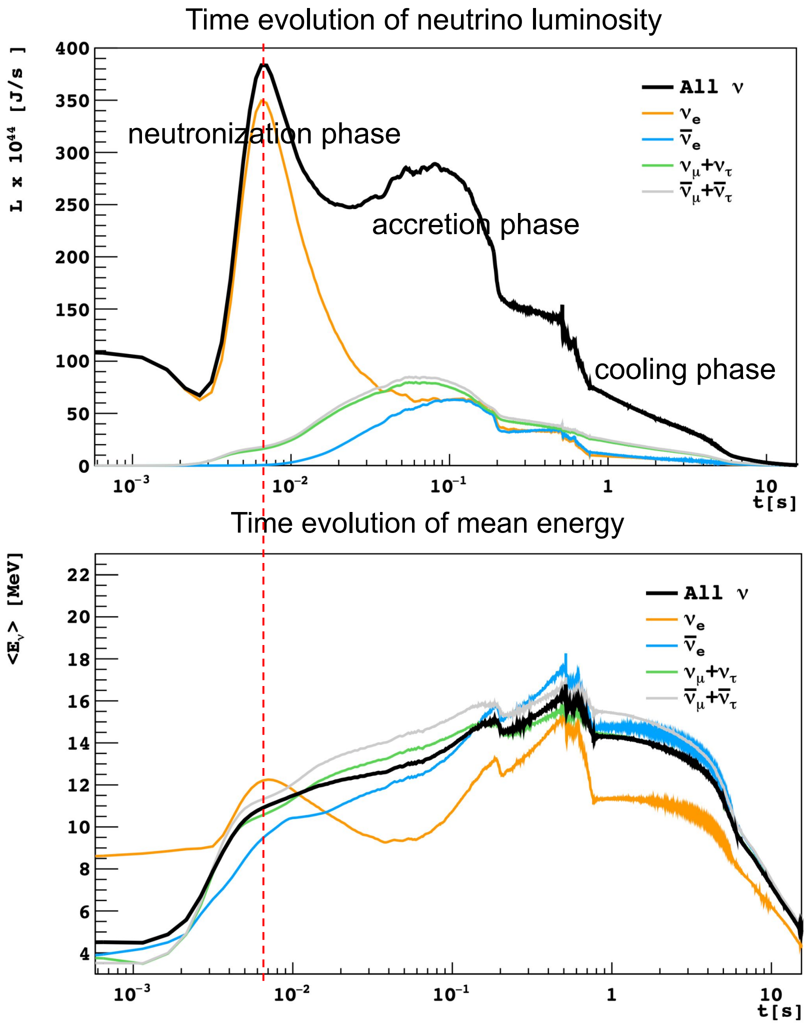
ARGO sensitivity to core-collapse supernova neutrinos

Unique sensitivity to supernova neutronization burst through ν_e CC absorption (water Cherenkov & scintillator detectors more sensitive to anti-ν_e via inverse β–decay.

Detecting this breakout ν_e burst enables:

- ➢ Probing neutrino oscillations in dense matter.
- ➢ Accurate timestamp of core bounce → Early warning & timing anchor for multi-Messenger Astronomy.

*Expected event rate & significance under investigation.



Garching group 1-d simulations [10.1088/2041-8205/767/1/L6]

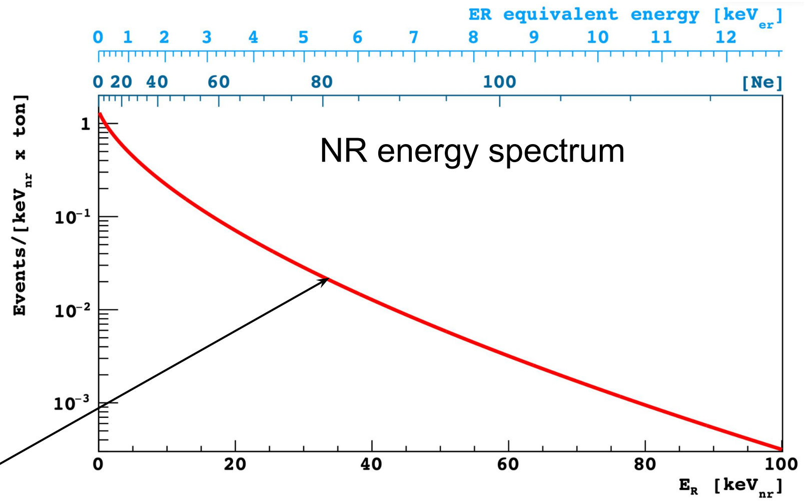
Sensitivity to core-collapse supernova neutrinos via CEνNS

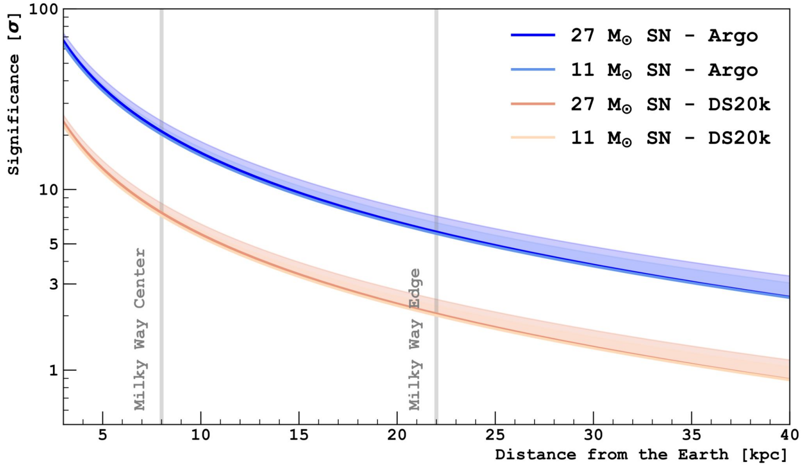
Colleagues from DS-20k estimated ARGO's sensitivity to SNe neutrinos via the CEνNS channel **in the context of a TPC**.

Exploit the secondary ionization e$^-$ signal in dual-phase TPC for efficient detection of low energy NRs from SNν – Ar scattering.

~0.5keV$_{nr}$ threshold demonstrated by DarkSide-50 [10.1103/PhysRevLett.121.081307]

Discovery potential up to Milky Way edge for neutrinos from the neutronization burst.





The DarkSide-20k collaboration [JCAP03(2021)043]

Probing the Solar Metallicity Problem with ARGO

CNO neutrino **flux differ by ~30%** between high-Z and low-Z solar models.

Borexino final result [10.1103/PhysRevD.108.102005]: $\Phi_{CNO} = 6.7_{-0.8}^{+1.2} \times 10^8\ cm^{-2}\ s^{-1}$ (compatible with High-Metallicity SSM).

With ARGO, 4-5 times higher scintillation yield & ultra-low background levels → CNO neutrino measurement with high precision.

Independent measurement with different target and systematics → robust way to address the metallicity problem.

Adapted from D. Franco *et al* JCAP08(2016)017

Neutrino Source	High-metallicity	Low-metallicity	Discrepancy
pp	5.97×10^{10}	6.03×10^{10}	−1.0%
pep	1.41×10^8	1.44×10^8	−2.1%
hep	7.91×10^3	8.18×10^3	−3.3%
^{7}Be	5.08×10^9	4.64×10^9	9.1%
^{8}B	5.88×10^6	4.85×10^6	19.2%
^{13}N	2.82×10^8	2.07×10^8	30.2%
^{15}O	2.09×10^8	1.47×10^8	34.8%
^{17}F	5.65×10^6	3.48×10^6	47.5%

Solar neutrino fluxes predicted by the GS98 (high-Z) and AGSS09 (low-Z) solutions with the SSM.

Observing CNO neutrinos in ARGO through neutrino-electron elastic scattering interactions

Considering,

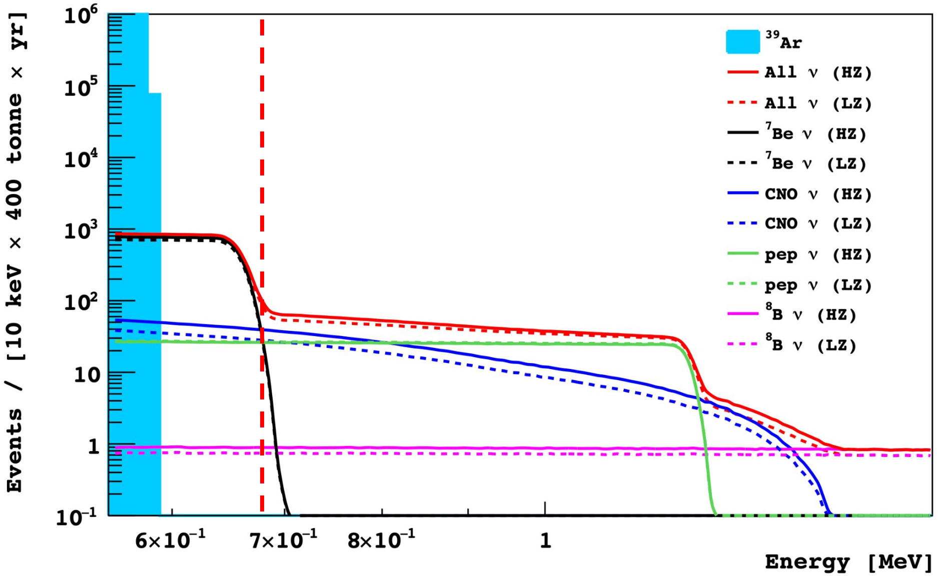
- the total CNO neutrino flux,
- recoil-energy cut > 0.665 MeV that excludes the ^{39}Ar β-continuum and the monoenergetic ^{7}Be 0.862 MeV line,

Gives a preliminary expected rate,

Γ(high vs. low-Z) ≈ 2.6 vs. 1.8 events/tonne-year

*uncertainties & expected significance under investigation

D. Franco *et al* JCAP08(2016)017



Simulated solar neutrino spectra in ARGO.

7860 vs. 5490 events expected for high-Z vs. low-Z in 3000 tonne-years.

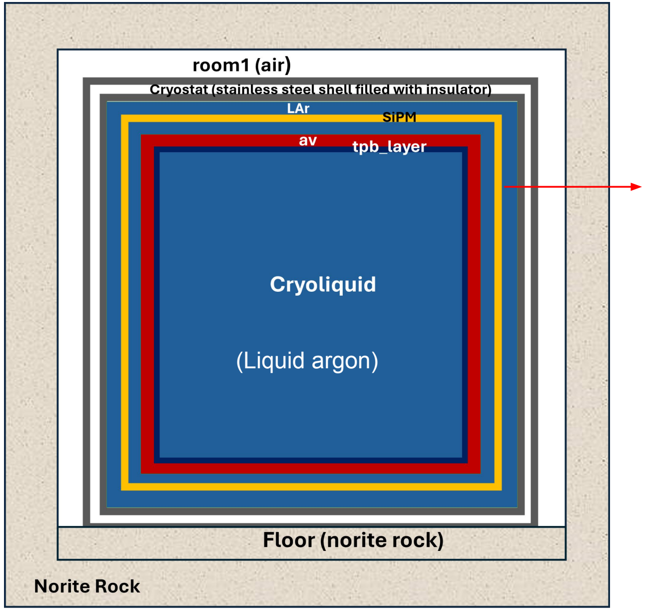
Investigating primary backgrounds for dark matter & neutrino detection

ARGO geometry in the RAT simulation framework

1) **Radiogenic neutron backgrounds** from detector components and surroundings.

2) **Electron recoil backgrounds**: primarily from beta-decays of ^{39}Ar isotope with an activity ≤ 0.7 mBq/kg in underground Ar.

3) **Background from surface radioactivity** (degraded alphas), at the level of 1 mBq/m^2.



SiPM optical plane entirely covering the acrylic vessel, providing 4π solid-angular photodetector coverage.

https://rat.readthedocs.io/en/latest/

Mitigating the radiogenic neutron backgrounds

Target: <1 neutron event leaking into the WIMP search ROI in 10 live-years.

Geometry A

3 m water shield on sides & top, unshielded bottom.

1.5 m thick LAr veto within protoDune cryostat.

AV cylinder (15 cm thick, 7 m x 7 m (ID x height))

Source of radiogenic neutron	Neutron leakage into WIMP ROI in 10 years
Norite Rock	31 ± **16**
protoDUNE cryostat	42 ± 17.6
SiPM (Si only)	0.06 ± 0.03
Acrylic Vessel	1.8 ± 0.8
Total	**75 ± 24**

Geometry B

2.5 m water shield on all sides

50 cm thick LAr veto within vacuum cryostat

AV sphere (10 cm thick, ID 8 m).

Source of radiogenic neutron	Neutron leakage into WIMP ROI in 10 years
Norite Rock	< 0.22 (95% C.L.)
Vacuum cryostat	6 ± 1
SiPM (Si only)	0.113 ± 0.006
Acrylic Vessel	1.66 ± 0.05
Total	**8 ± 1**

Rejecting ER backgrounds through pulse-shape discrimination

Exploit the different lifetimes of LAr excimer states.

Singlet (6 ns) vs. triplet (1600 ns) → strong ER background rejection.

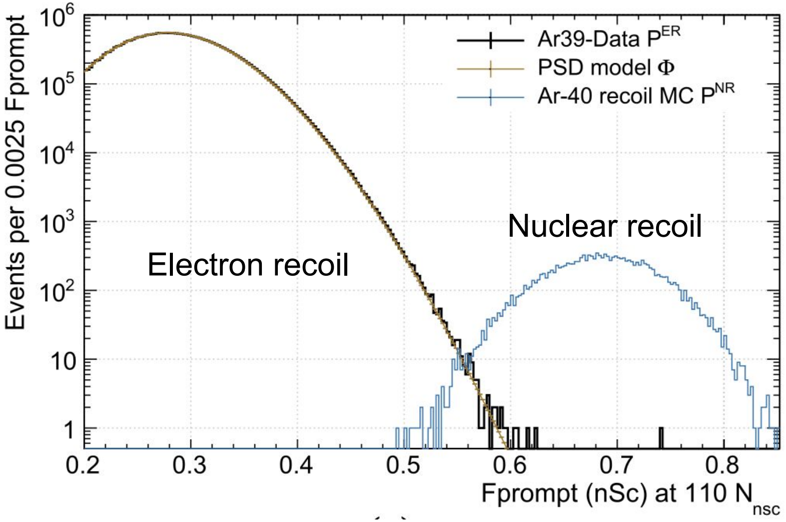
PSD parameter, $$f_p = \frac{\int_0^{t_p} S(t)\,dt}{\int_0^{t_{tot}} S(t)\,dt} \in (0, 1)$$

Using PSD, **ER background rejection at ~10^{-9} demonstrated by DEAP-3600**.

In ARGO,

- ➢ SiPM photodetectors (optical crosstalk noise)
- ➢ Increased Rayleigh scattering (much larger size)

10.1140/epjc/s10052-021-09514-w



F_p distribution in the lowest PE bin of the ROI

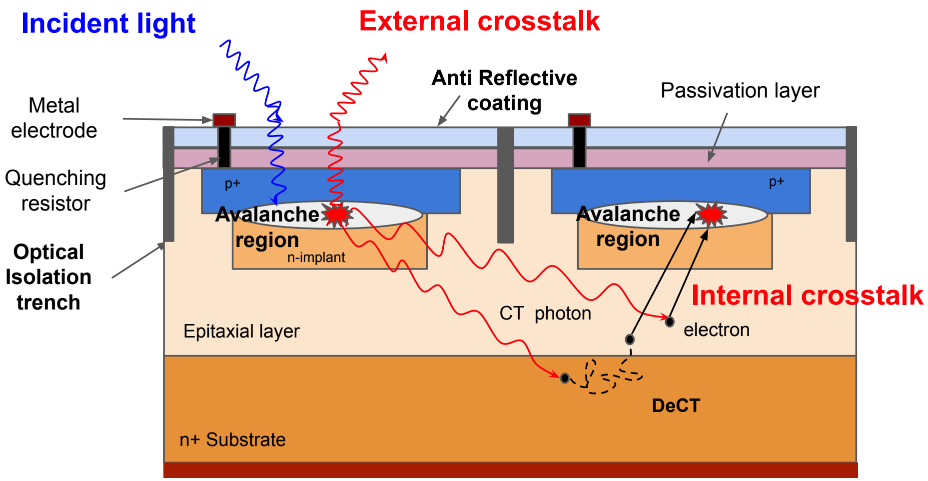
Modeling photon detection in SiPMs with optical crosstalk

Developed detailed geometrical model of photon detection with pixelated SiPMs, including the correlated optical crosstalk noise.

Model benchmarked against recent measurements.

Studying the impact of optical crosstalk on,

- detector energy threshold
- photon hit clustering patterns
- event position reconstruction



Vertical cross-section of a SiPM

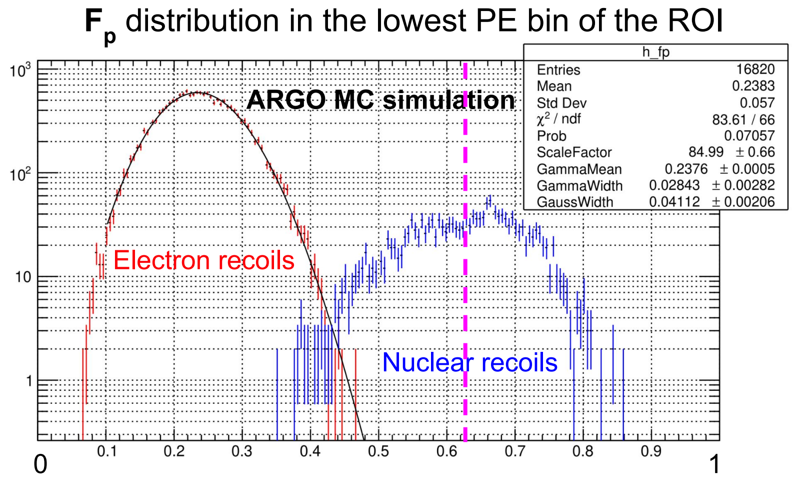
Pulse-shape discrimination with SiPMs

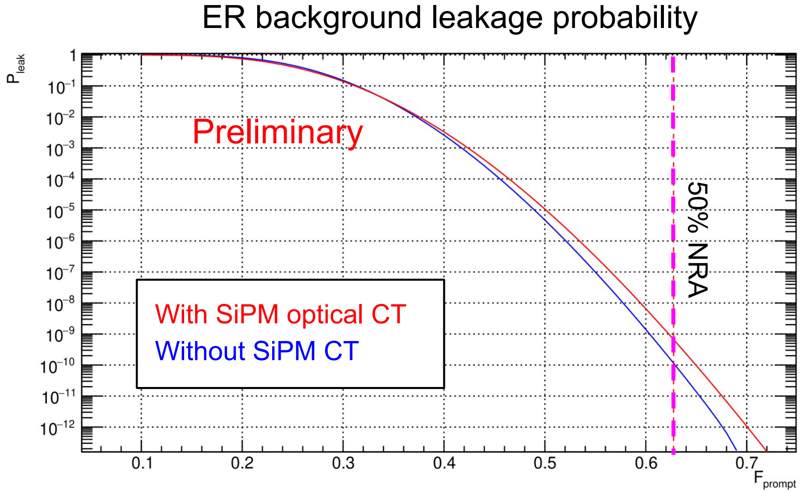
Target: < 0.05 ER events in the ROI in 10 live-years.

Leakage probability *PL(f)* at f_p value corresponding to 50% NRA → probability for an ER event to occur in the [**f**, 1] range.

$$PL(f) = \frac{\int_f^1 PSD(f)df}{\int_0^1 PSD(f)df}$$

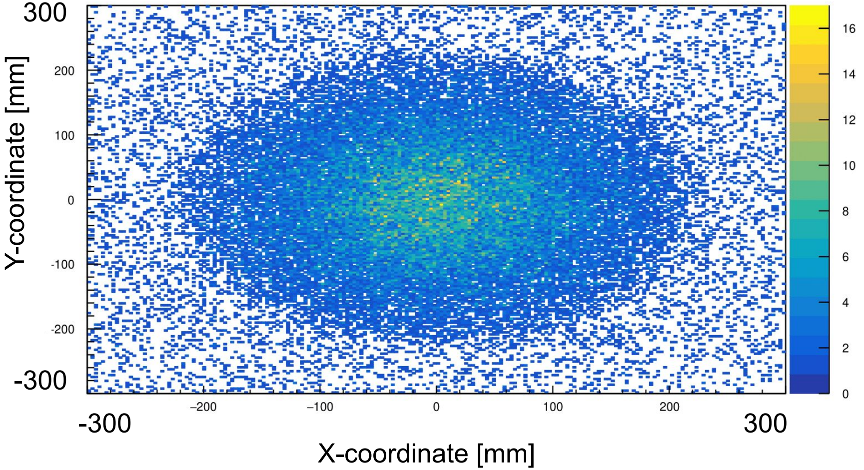
- evaluating detector performance with current SiPM specifications.
- determining constraints on SiPM devices to reach targeted performance.



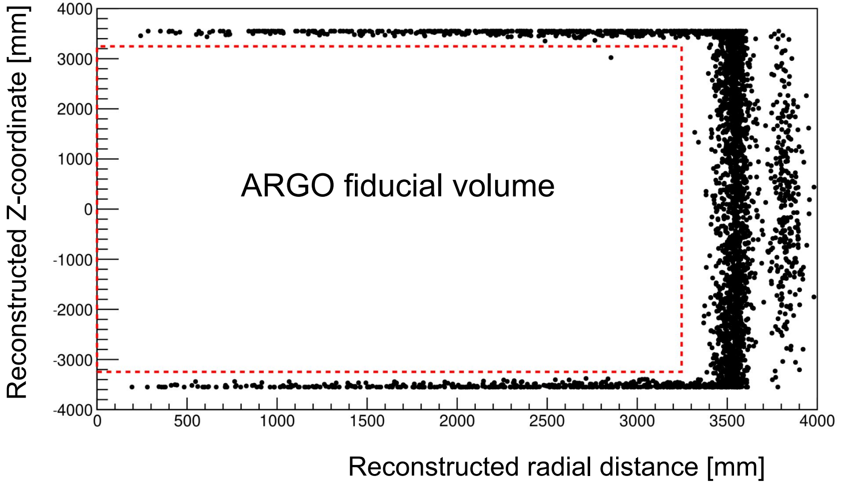


Position reconstruction and event ID with pixelated photodetectors

Photon hit clustering for surface events, with a 3mm x 3mm pixelated readout



Surface alpha event reconstruction based on photon time-of-flight

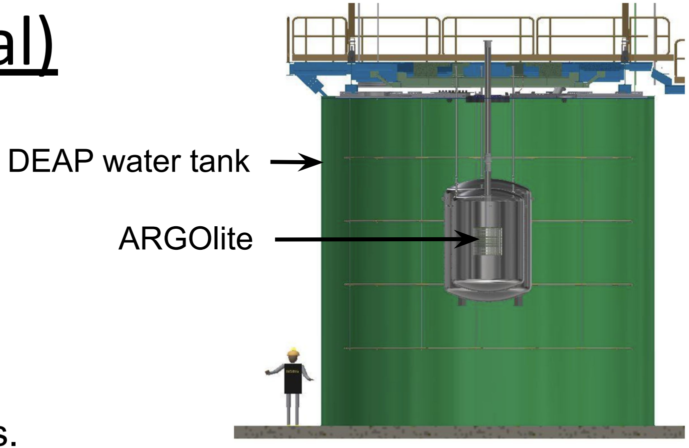


Event ID based on characteristic hit patterns – a powerful tool for background rejection.

Time/charge–based position reconstruction algorithms for external & surface backgrounds.

Target of demonstrating a combined surface alpha rejection at 10^{-7} or better.

ARGOlite: A single-phase UAr prototype in the DEAP shield tank at SNOLAB (CFI IF 2025 Proposal)



Re-use DEAP systems: cryogenics, purification, shield tank.

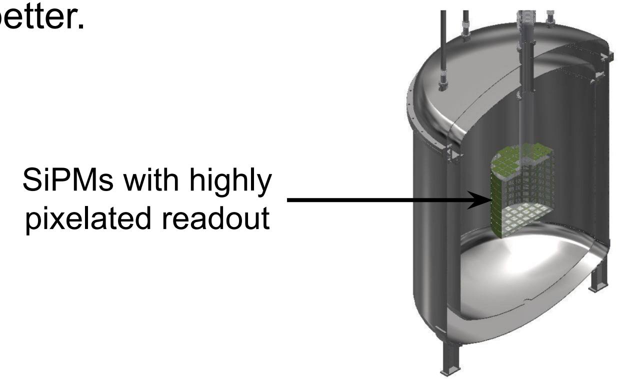
Pixelated digital photodetectors (2 m^2 array) and AI-based DAQ.

Target:

- demonstrate ER/NR PSD at 10^{-9} with pixelated digital SiPMs.
- demonstrate surface alpha rejection (combined) at 10^{-7} or better.
- qualify the full optical chain for ARGO design.

New capabilities for materials assays:

- surface alpha assay at 10 μBq/m^2 and ^{42}Ar (^{39}Ar) in UAr.
- direct material neutron rates, high sensitivity.



Photon-to-digital converters (Sherbrooke & TRIUMF, Canada; LNGS, U. L'Aquila, FBK, Italy

Two paths for pixelated digital photodetectors within our 2025 CFI IF:

1) **Sherbrooke PDCs:** fully digital system in which each SPAD is vertically stacked onto a CMOS readout.

2) **ATARI system LNGS:** analog sum of 3 mm x 3 mm SPAD arrays (pixels) on the SiPM chip, then readout for each pixel in 3D.

Currently fabricating some sample wafers to evaluate performance and yield, to decide on the $2m^2$ array for ARGOlite.

3D packaging

2.5D packaging

Conclusions

- ARGO is a **300-ton UAr fid. mass DM detecto**r planned at SNOLAB. Flagship project of GADMC.
- Core team in Canada leading ARGO development (Alberta, Carleton, CNL, Laurentian, Sherbrooke, SNOLAB, Queen's, TRIUMF).
- DM **sensitivity extending into the neutrino fog**; complete suppression of ER and instrumentals.
- Important neutrino measurements adding information to **neutrino mixing, multi-messenger astronomy**.
- Exploring potential for NDBD sensitivity with ARGO, e.g., loading Ar with a candidate NDBD material.
- Developing a **prototyping facility** for ARGO, **including digital SiPMs**, that will replace DEAP-3600 in 2027, for operation from **2028 – 2030**.
- Approximate timeline is **prototyping + design in place by 2031** to move ahead with ARGO project implementation.

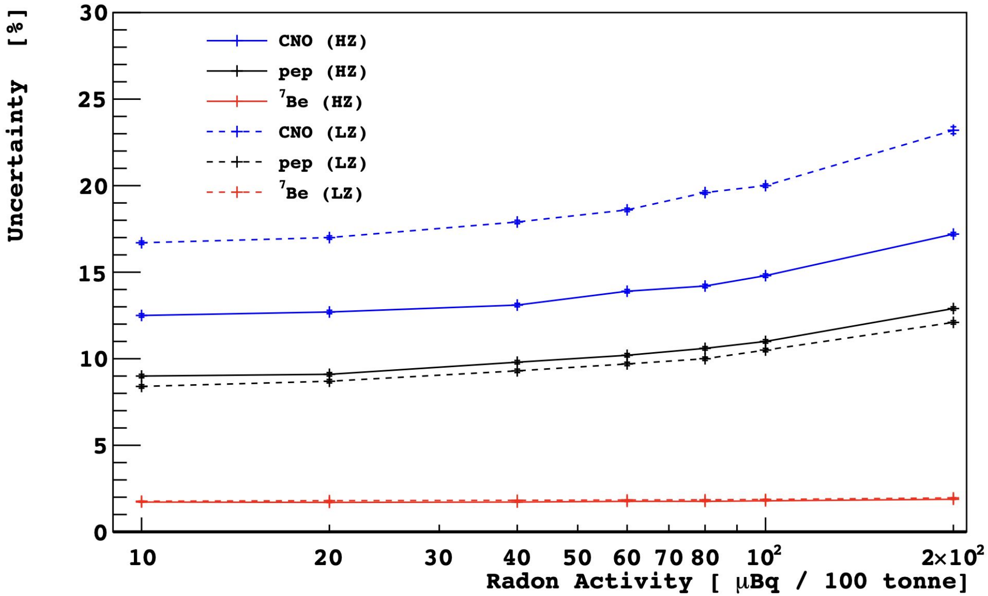
The Global Argon Dark Matter Collaboration

With many thanks for support to:

- CFI and NSERC (Canada)
- IN2P3 (France)
- INFN (Italy)
- STFC (UK)
- NSF and DOE (U.S.)
- Poland and Spain Ministries for Science and Education

Backup slides

Statistical uncertainties on the solar neutrino components, as a function of the ^{222}Rn activity.



Other background sources: ^{85}Kr, ^{42}Ar, external γs

^{85}Kr [Q(β−) = 0.687 MeV, $\tau_{1/2}$ = 10.75 yr]: 1.5 mBq/kg 90% C.L. upper limit, DEAP-3600.

^{42}Ar [Q(β−) = 0.599 MeV, $\tau_{1/2}$ = 33 yr]: ≈ 40 μBq/kg (AAr, DEAP-3600), expect much level in UAr.

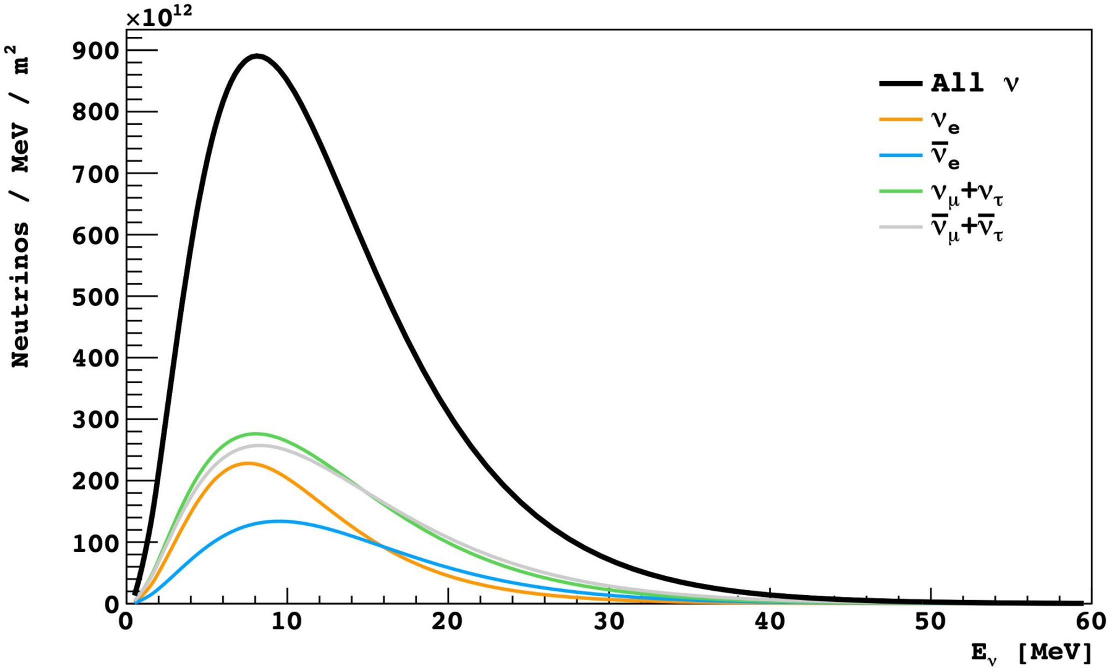
Proposed a 4-inch diameter, 20-m tall distillation column in 2025 CFI IF to help design a high throughput ~200m column that could be used for ARGO @ 300 kg/day.

Reduce the ^{85}Kr activity ~1 μBq/tonne through cryogenic distillation in columns with thousands of equilibrium stages.

Source	Origin	Attenuation length [cm]	Survived Fraction without FV	Survived Fraction with FV
^{40}K	Photosensors	3.9	0.3×10^{-2}	1×10^{-6}
^{214}Bi	Photosensors	4.2	1.1×10^{-2}	9×10^{-6}
^{208}Tl	Photosensors	3.6	0.7×10^{-2}	2×10^{-6}
^{60}Co	Cryostat	5.1	0.1×10^{-2}	3×10^{-6}

Fraction of events producing single energy deposition in the [0.6, 1.3] MeV. 30 cm fid. vol. cut from the TPC walls.

core-collapse supernova neutrino flux

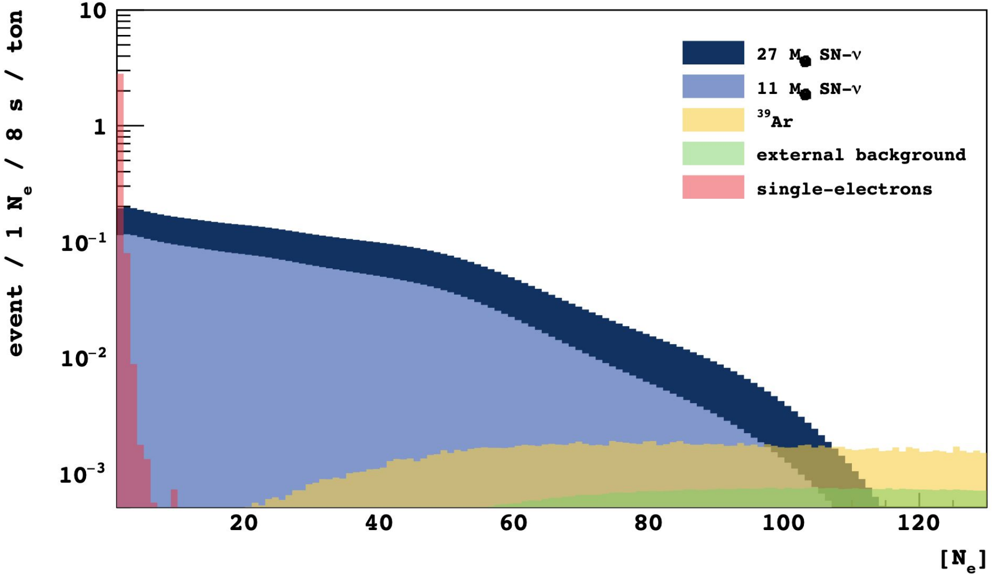


The DarkSide-20k collaboration [JCAP03(2021)043]

Energy spectrum from a core-collapse 27 M☉ SN at 10 kpc

Sensitivity to core-collapse supernova neutrinos via CEνNS

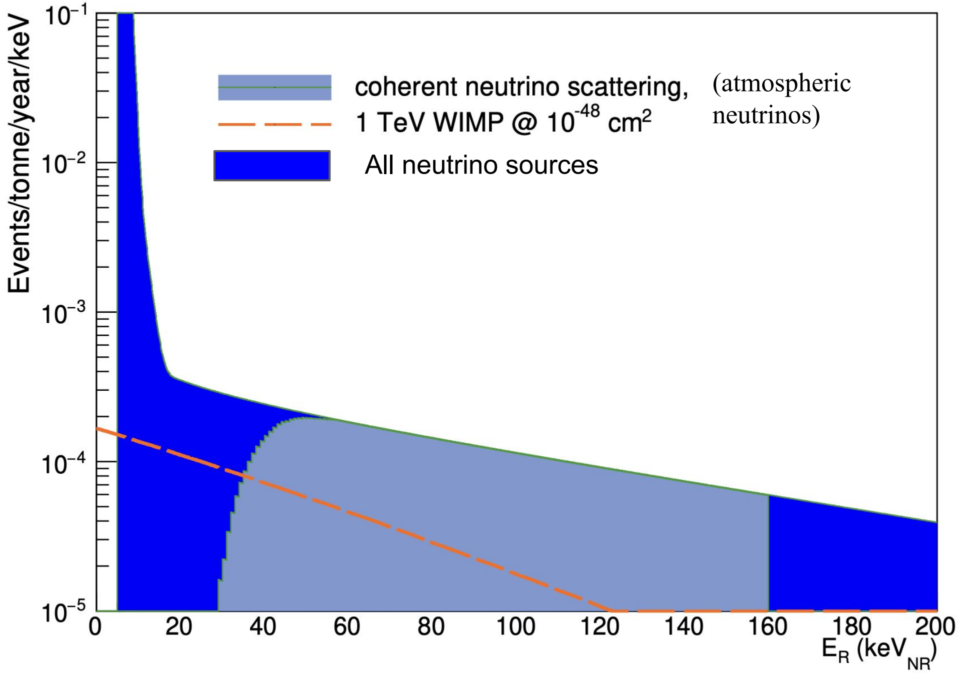
The DarkSide-20k collaboration [JCAP03(2021)043]



	DarkSide-20k	Argo
11-$M_\odot$ SN-νs	181.4	1396.6
27-$M_\odot$ SN-νs	336.5	2591.6
^{39}Ar	4.3	33.8
external background	1.8	8.8
single-electrons	0.7	5.1

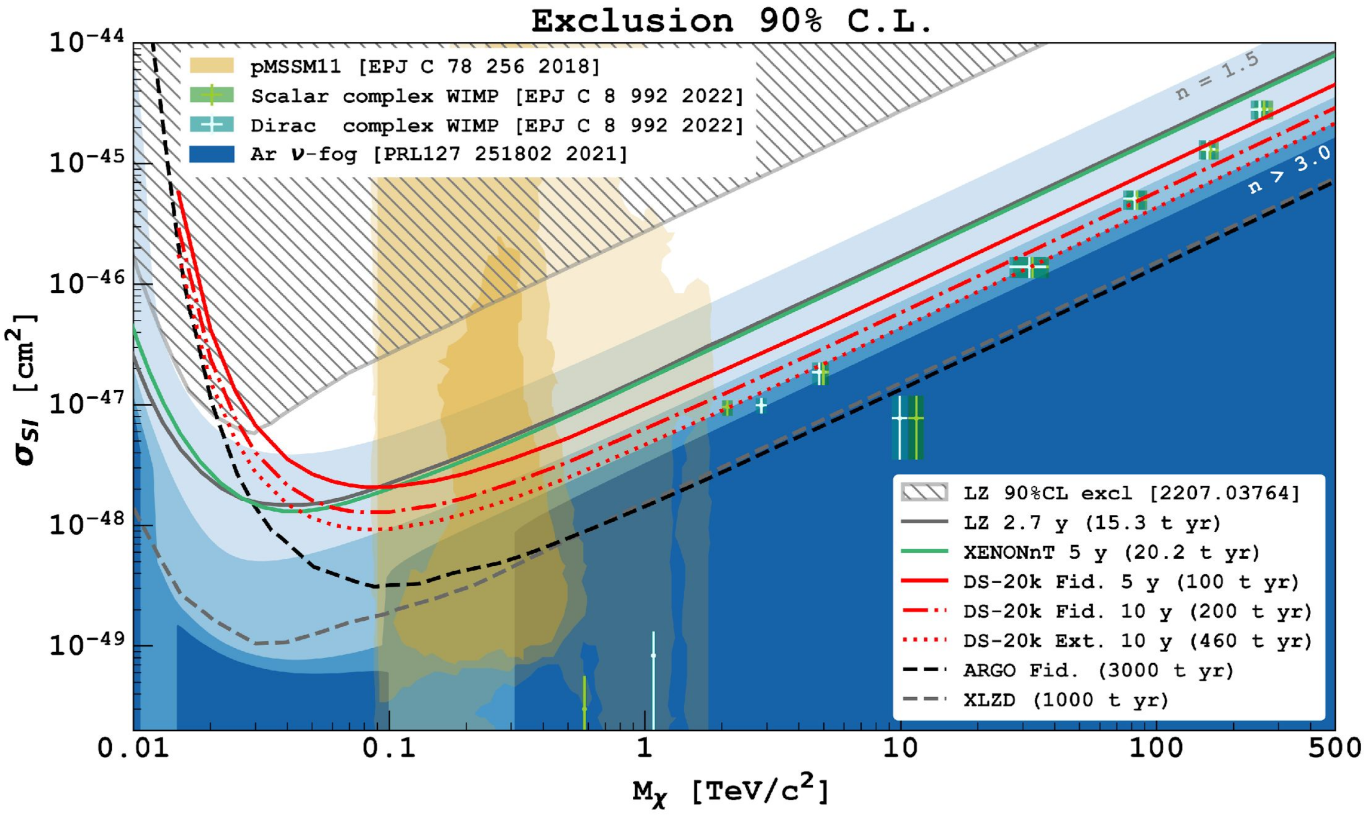
Event statistics expected in DarkSide-20k and Argo within the [3, 100] N_{e-} energy window and in 8 s from the beginning of the burst.

Coherent neutrino scattering background events in argon



Source	ARGO
CevNS (NR)	46 (atmospheric neutrinos)
ν ES (ER)	0
Others (scaled)	0.05
Total	46

ARGO projected sensitivity for 10 live years



Measurements of optical crosstalk photon yield in SiPM avalanches

Number of crosstalk photons generated in an avalanche

External CT photon yield per avalanche

4 V_{oV}

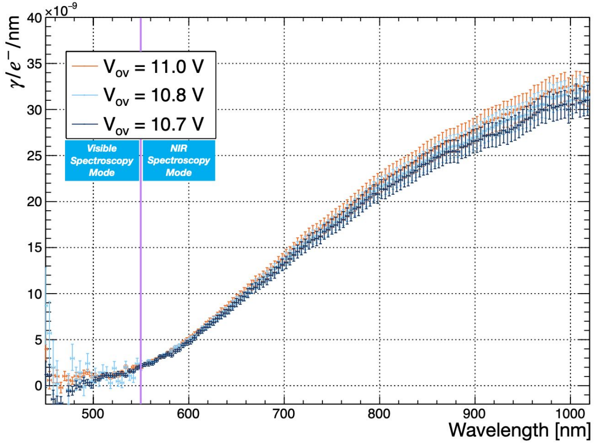
Device	Source Photon per		Photon Yield/Avalanche		
	Avalanche	e^-	Air	LAr	LXe
HPK VUV4	47 ± 9	$(1.0 \pm 0.2)\times10^{-5}$	0.50 ± 0.08	0.8 ± 0.1	1.1 ± 0.2
FBK VUV-HD3	56 ± 7	$(1.2 \pm 0.2)\times10^{-5}$	0.76 ± 0.11	1.8 ± 0.2	1.7 ± 0.2

Laser Induced SiPM Luminescence

Kurtis Raymond (TRIUMF, SFU), Fabrice Retière (TRIUMF)

NPSS 2023 Conference

Differential emission spectrum of crosstalk photons in HPK VUV4 SiPMs



J. McLaughlin et. al., DOI: 10.3390/s21175947

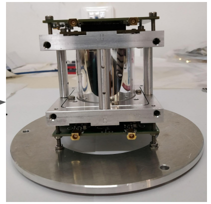
Around 50 - 60 optical crosstalk photons are generated during each avalanche process in SPADs.

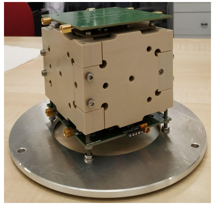
Roughly, 1 - 2 photons escape the SiPM bulk per avalanche and are emitted into the detector volume.

The CT photons have infrared wavelengths, and therefore have a low detection efficiency.

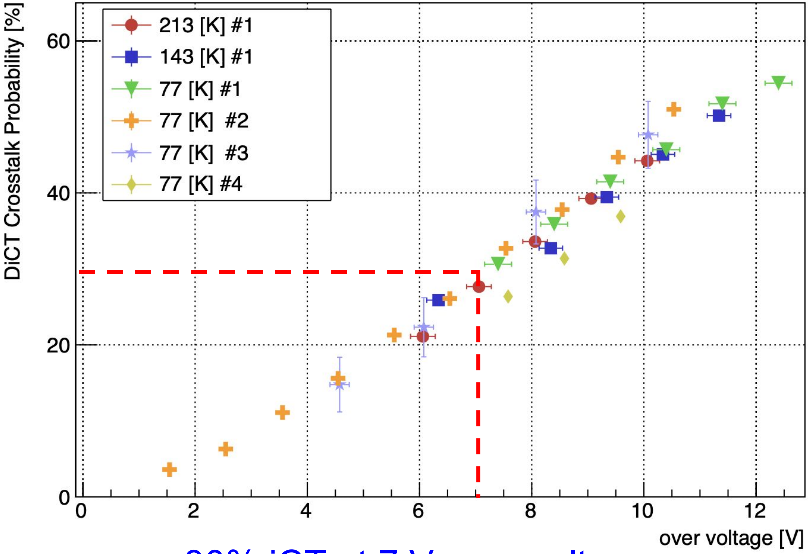
Measurements of internal and external crosstalk PE yield provide an idea about the size of this effect

Small-scale liquid argon prototype detectors equipped with SiPM tiles used for making precise measurements of external crosstalk



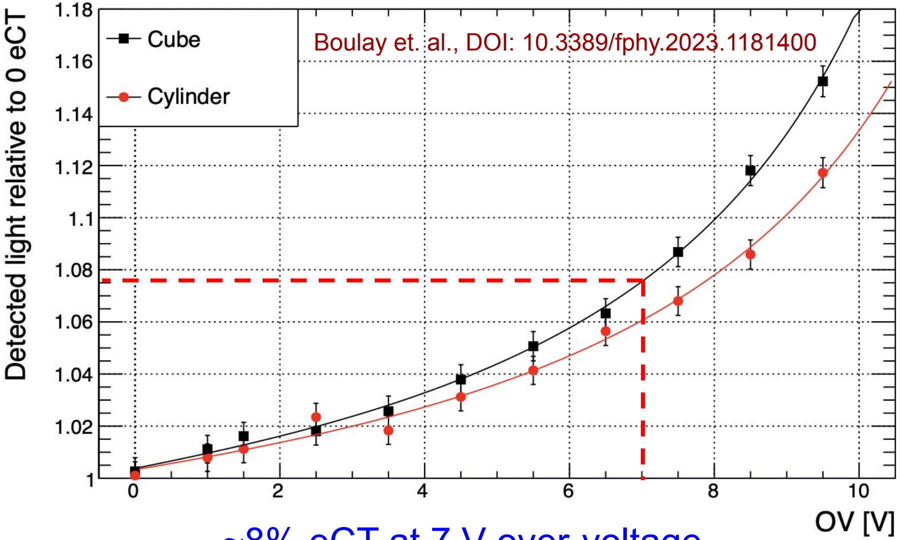


Internal crosstalk probability vs over-voltage



~30% iCT at 7 V over-voltage

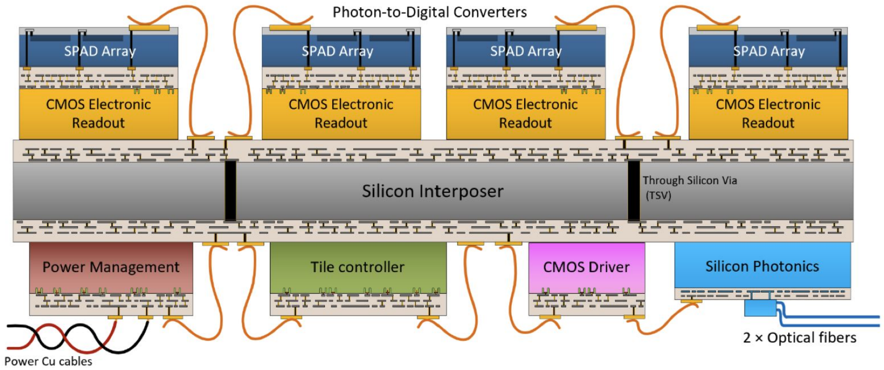
Photoelectron gain due to eCT vs OV



~8% eCT at 7 V over-voltage

3D Photon-to-Digital Converters (U. Sherbrooke)

U. Sherbrooke

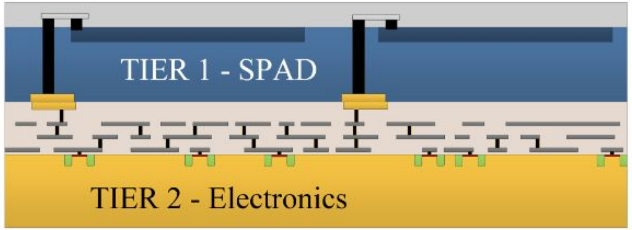


Schematic of a full 3D integrated photon detection module

- ❖ Embedded signal processing: sum, dark count filters, time-to-digital conversion, etc.
- ❖ Single photon resolution on the whole dynamic range.
- ❖ Significantly lower power consumption.
- ❖ Disabling noisy SPADs: reducing noise.
- ❖ Programmable hold-off delay: afterpulsing mitigation

Pratte JF et al. Sensors (2021); 21(2):598. doi: 10.3390/s21020598

- SPAD array and CMOS readout vertically stacked (3D) to form a single detector chip



Smart DAQ system with edge computing for ARGO (U. Sherbrooke)

Data acquisition for ARGO will be a challenge:

- Huge area of photodetectors
- Immense number of channels
- Complex cryogenic environment

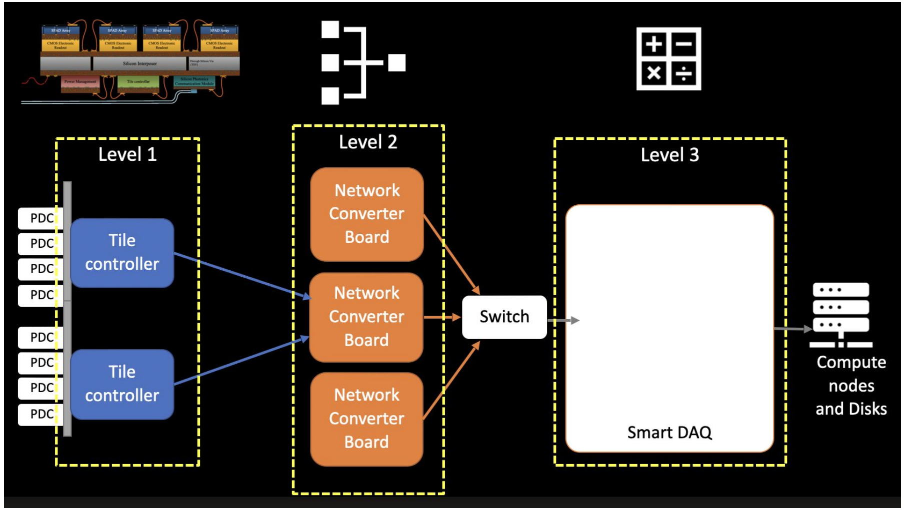
Noise estimate :

- Dark count rate : 0.1 cps/mm^2
- PDC surface : 250 m^2
- Total noise rate : 25 Mcps (dominant event rate)

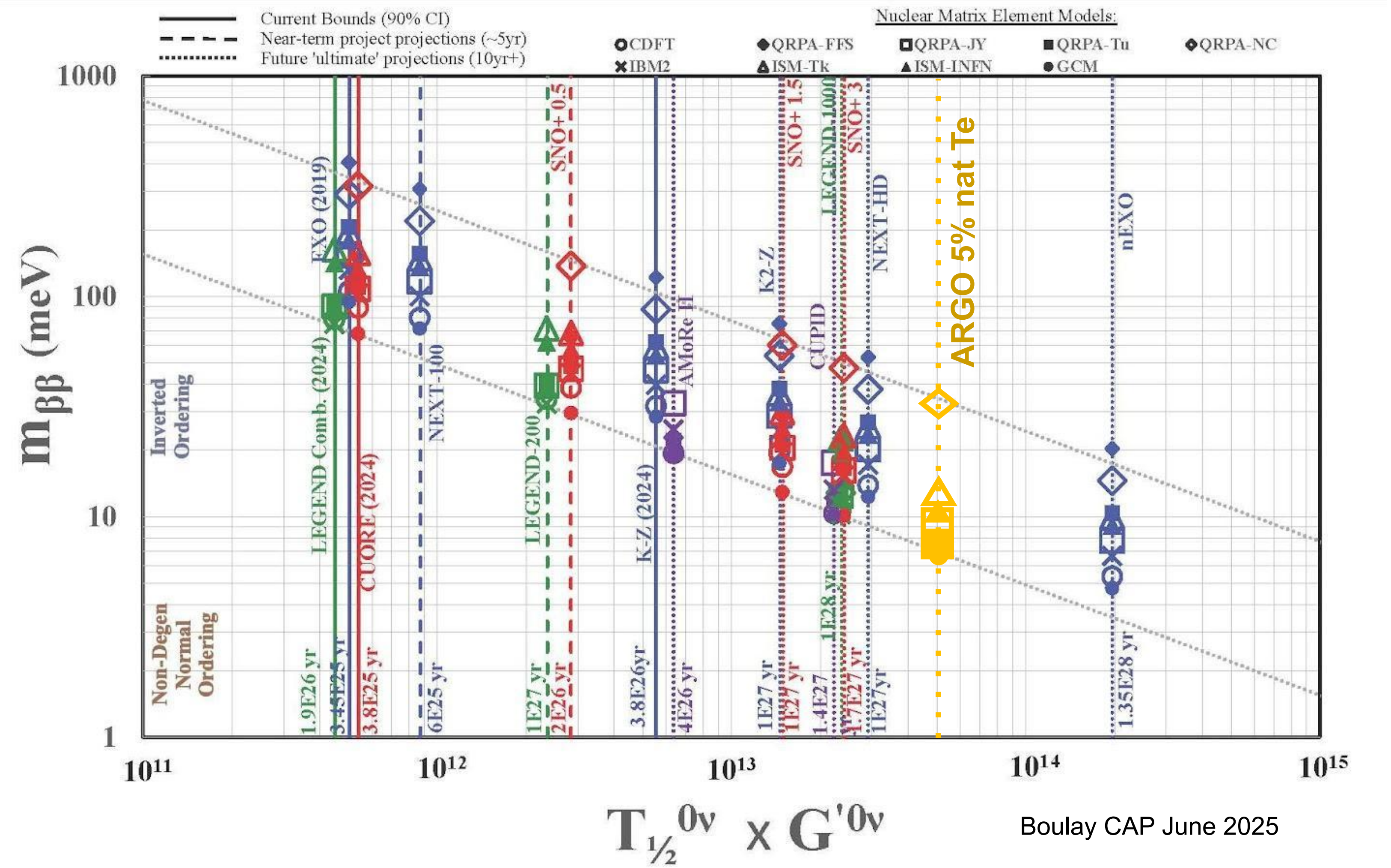
Multi-level real time analysis:

- low-level preprocessing and neural networking to filter (real-time smart veto) & reduce data before sending it to subsequent stages of DAQ architecture.

- Machine Learning on distributed FPGA for high level analysis on more complex signals & for monitoring DAQ performance.



Data acquisition architecture using smart triggering

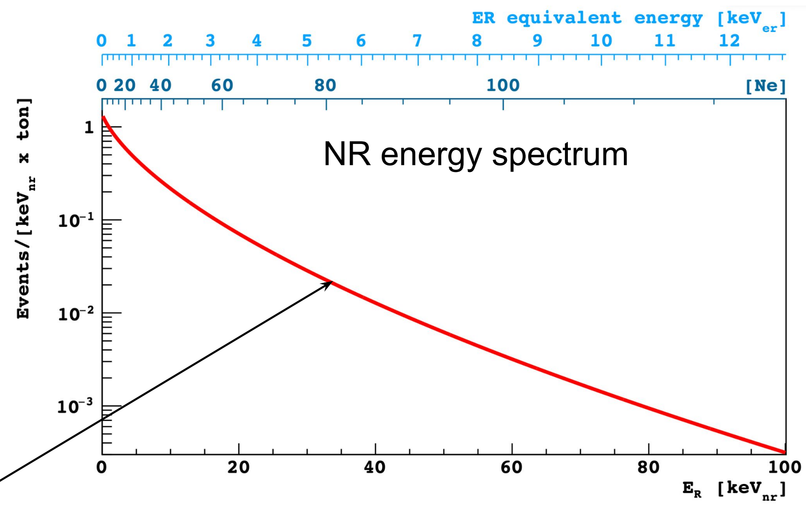

Current Bounds (90% CI)
Near-term project projections (~5yr)
Future 'ultimate' projections (10yr+)
Nuclear Matrix Element Models:
CDFT
IBM2
QRPA-FFS
ISM-Tk
QRPA-JY
ISM-INFN
QRPA-Tu
GCM
QRPA-NC
$m_{\beta\beta}$ (meV)
1000
100
10
1
Inverted Ordering
Non-Degen Normal Ordering
EXO (2019)
LEGEND Comb. (2024)
CUORE (2024)
NEXT-100
LEGEND-200
SNO+ 0.5
K-Z (2024)
AMoRe II
K2-Z
SNO+ 1.5
CUPID
LEGEND 1000
SNO+ 3
NEXT-HD
ARGO 5% nat Te
nEXO
1.9E26 yr
3.45E25 yr
3.8E25 yr
6E25 yr
1E27 yr
2E26 yr
3.8E26yr
4E26 yr
1E27 yr
1E27 yr
1.4E27
1E28 yr
1.7E27 yr
1E27yr
1.35E28 yr
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
$T_{1/2}^{0\nu}$ x $G'^{0\nu}$

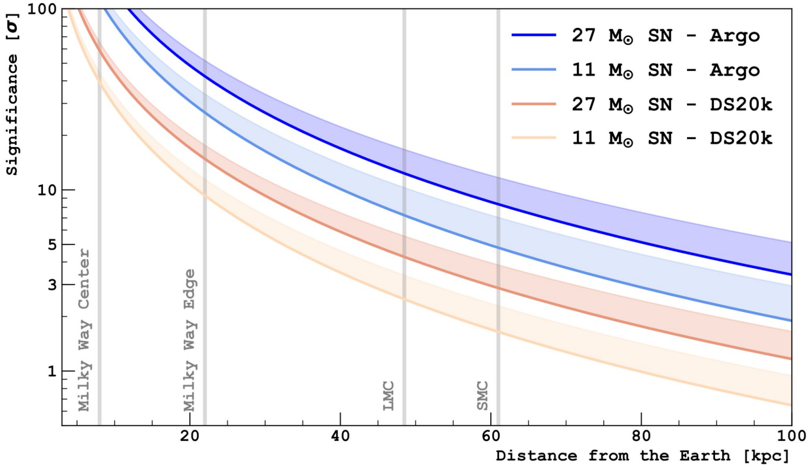
Sensitivity to core-collapse supernova neutrinos via CEνNS

Colleagues from DS-20k estimated ARGO's sensitivity to SNe neutrinos via the CEνNS channel **in the context of a TPC**.

Exploiting the secondary ionization e^- signal in dual-phase TPCs for efficient detection of low energy nuclear recoils from SNν – Ar scattering. [10.1103/PhysRevLett.121.081307]

Discovery potential up to the Small Magellanic Cloud (Milky Way edge) for the total (neutronization burst) flux of SN neutrinos.





The DarkSide-20k collaboration [JCAP03(2021)043]

Neutrino-electron elastic scattering interactions

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

To calculate the CNO neutrino rate, consider a recoil-energy cut ≥ 0.665 MeV that excludes the ^{39}Ar β-continuum and the monoenergetic ^{7}Be 0.862 MeV line.

For each CNO component (N-13, O-15, F-17) integrate over neutrino energy E_ν the product:
(component spectral shape) × (ν–e^- cross section above T_{thr}=0.665 MeV for that E_ν) to get a **mean cross section per emitted neutrino** for each component.

Multiply this by the **component flux** and by the **number of electrons/tonne** to get events/tonne-year.