DarkSide-20k

A Direct Dark Matter Search in the DarkSide-20k detector

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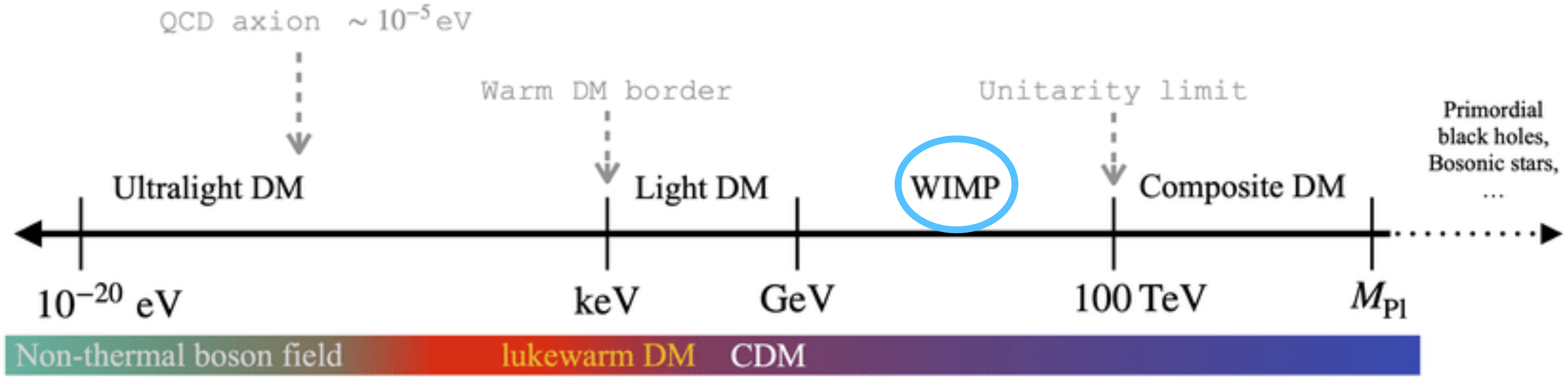
on behalf of the DarkSide Collaboration

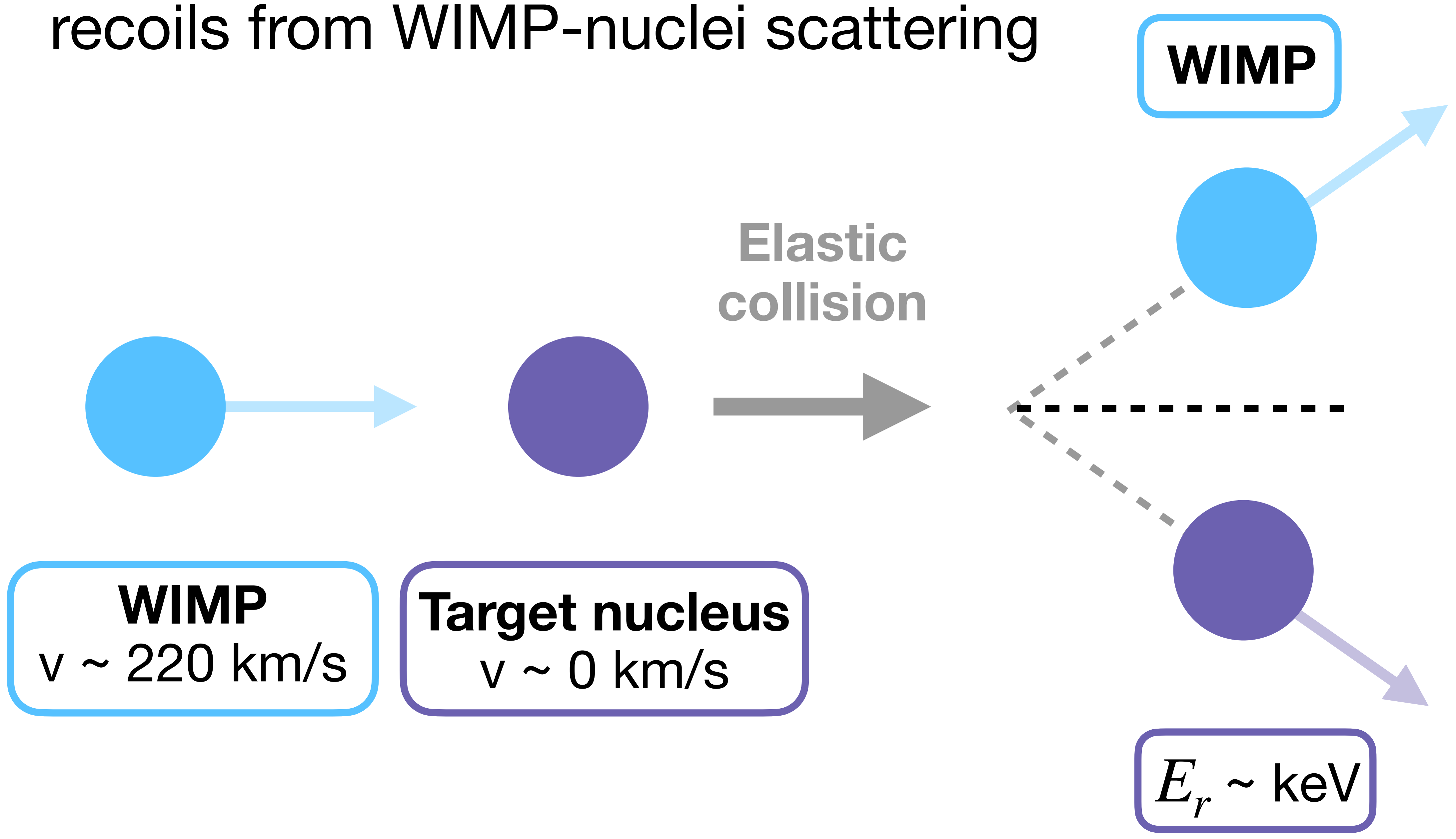
8th July 2025 ∘ EPS-HEP 2025

Dark matter: a direct search



DS20k signal

recoils from WIMP-nuclei scattering



Differential WIMP-nucleus interaction rate:

$$\frac{dR}{dE_r} = \frac{\sigma_{SI}}{2\mu^2 m_\chi} \quad A^2F^2(E_r) \quad \rho_0 \int_{v_{min}}^{\infty} \frac{1}{v} f(v) dv$$

WIMP model

σ_{SI}: WIMP-nucleon cross section

m_χ: WIMP mass

μ: reduced mass

Target material

A: Atomic number

$F(E_r)$: Form factor describing nuclear structure

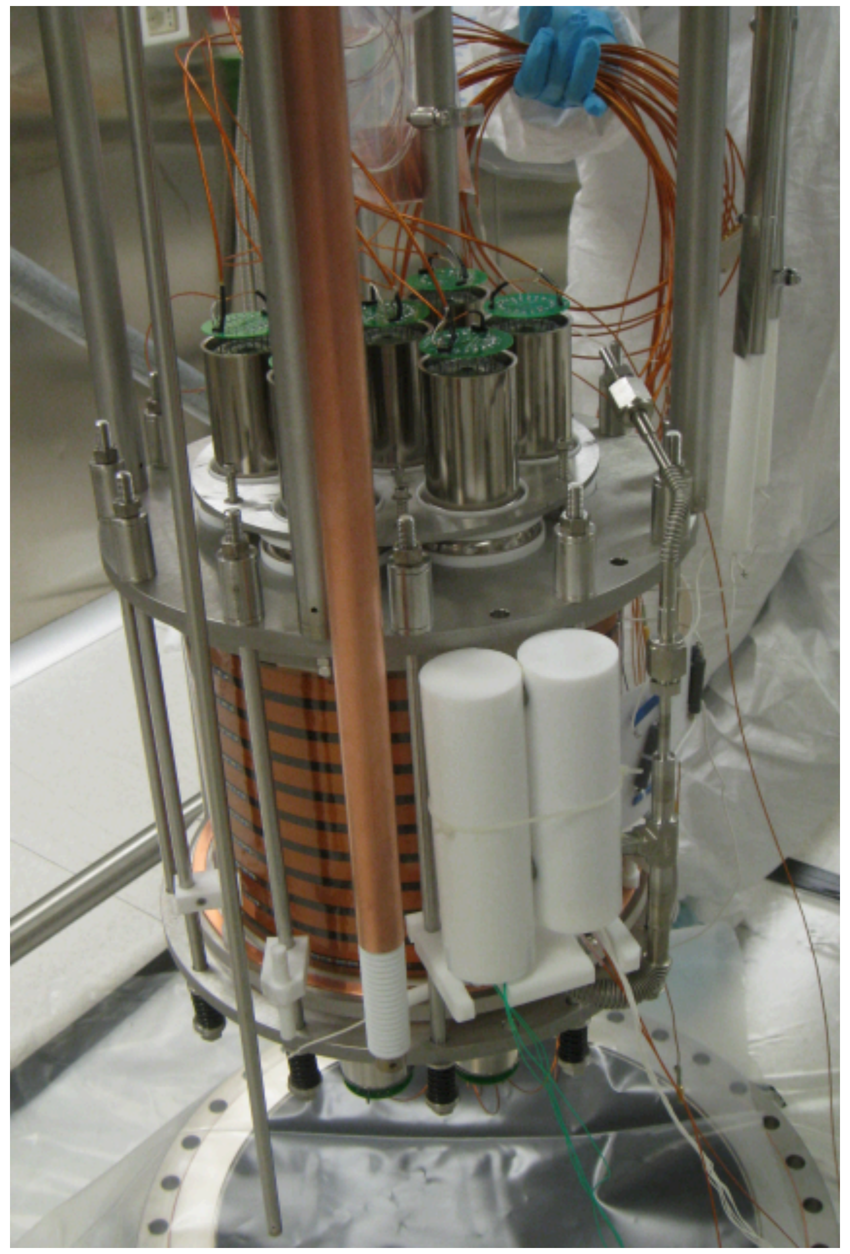
Standard Halo Model

$\rho_0 = 0.3\ GeV/cm^3$ (local density)

$$v_{min} = \sqrt{\frac{m_N E_r}{2\mu^2}}$$

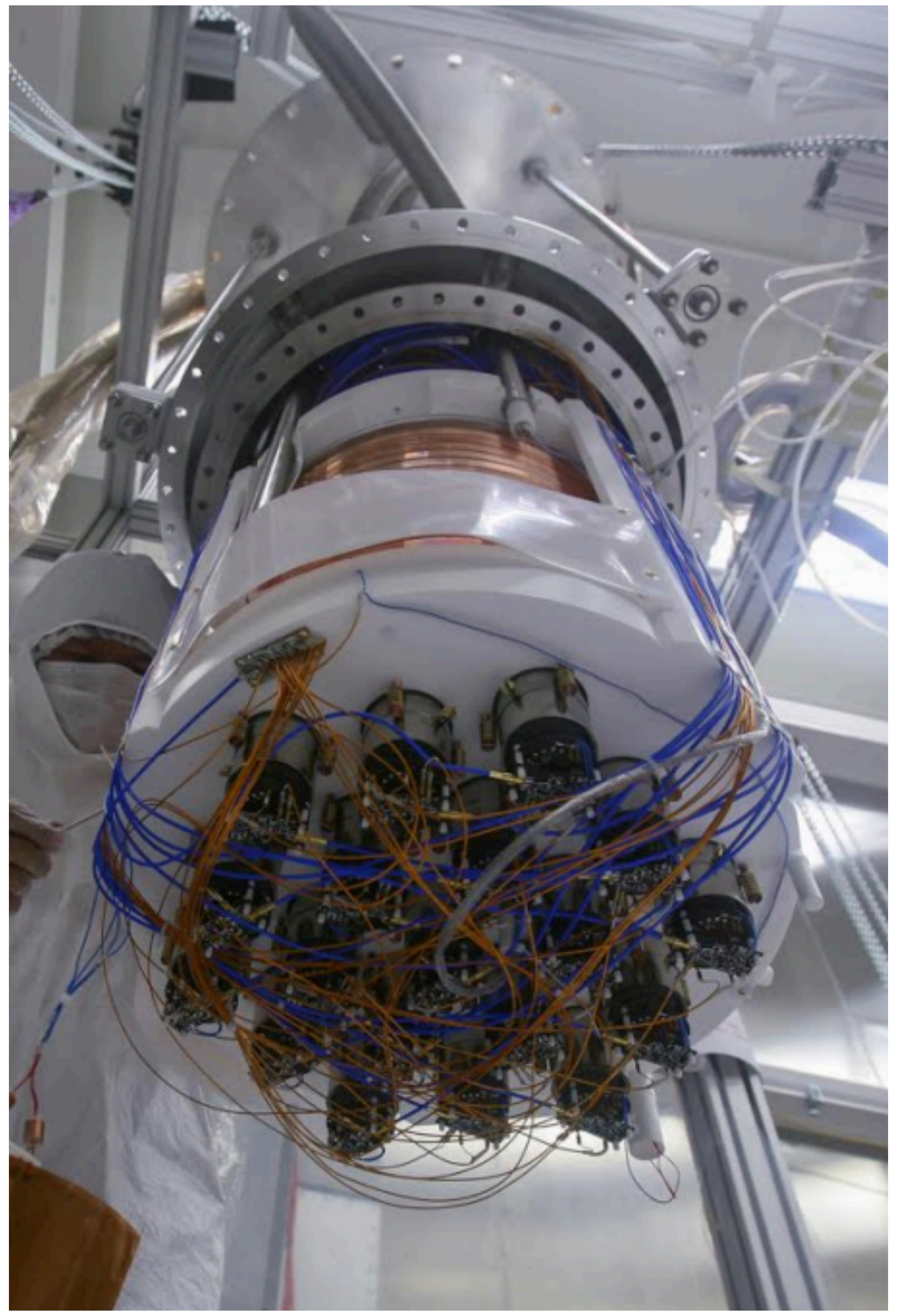
The DarkSide programme: WIMP dark matter direct detection using liquid argon

2011 - 2012 | 2013 - 2021 | 2027 - 2037 | 2030 +



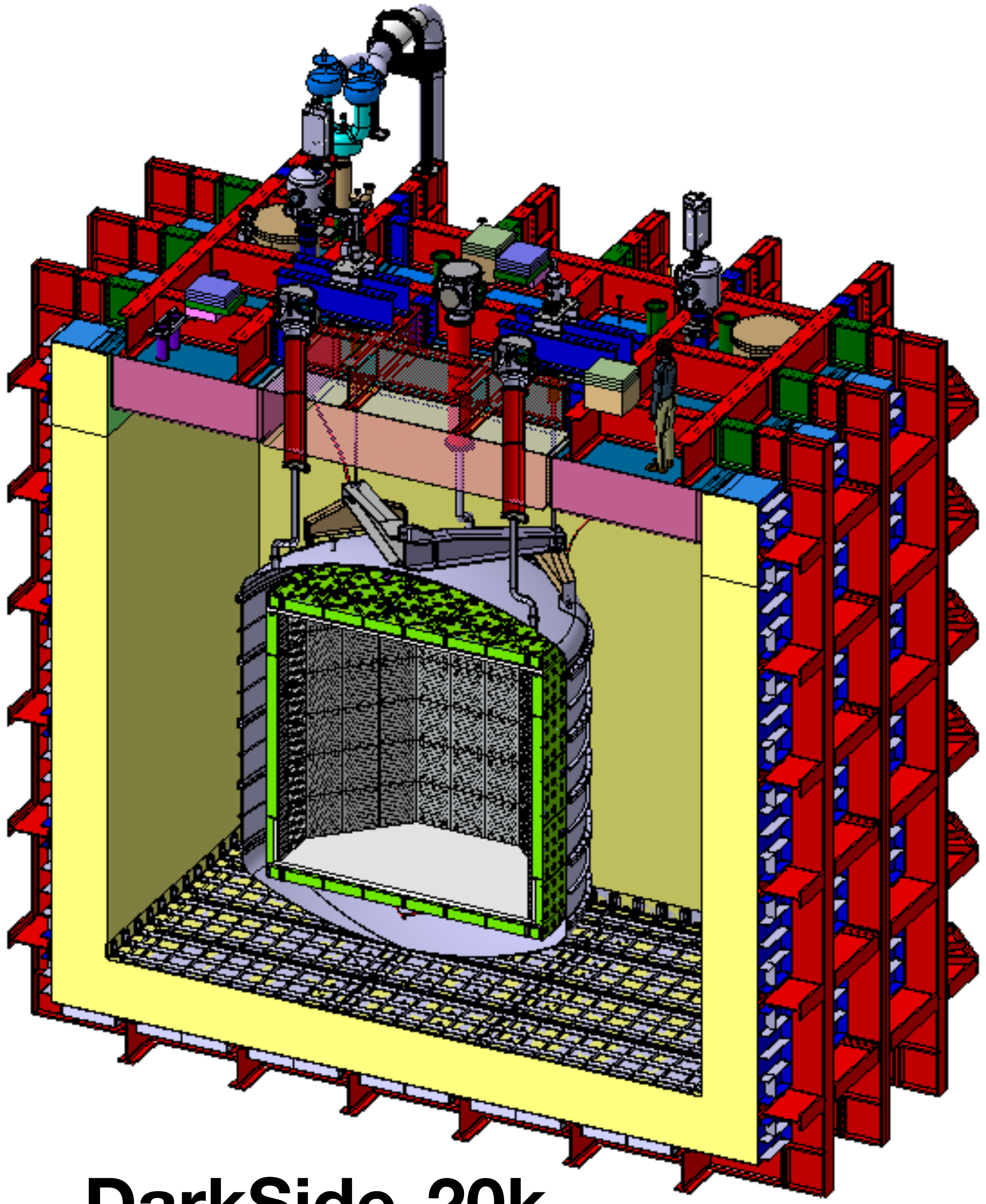
DarkSide-10

- ~10 kg atmospheric argon (AAr)
- No DM limit goal



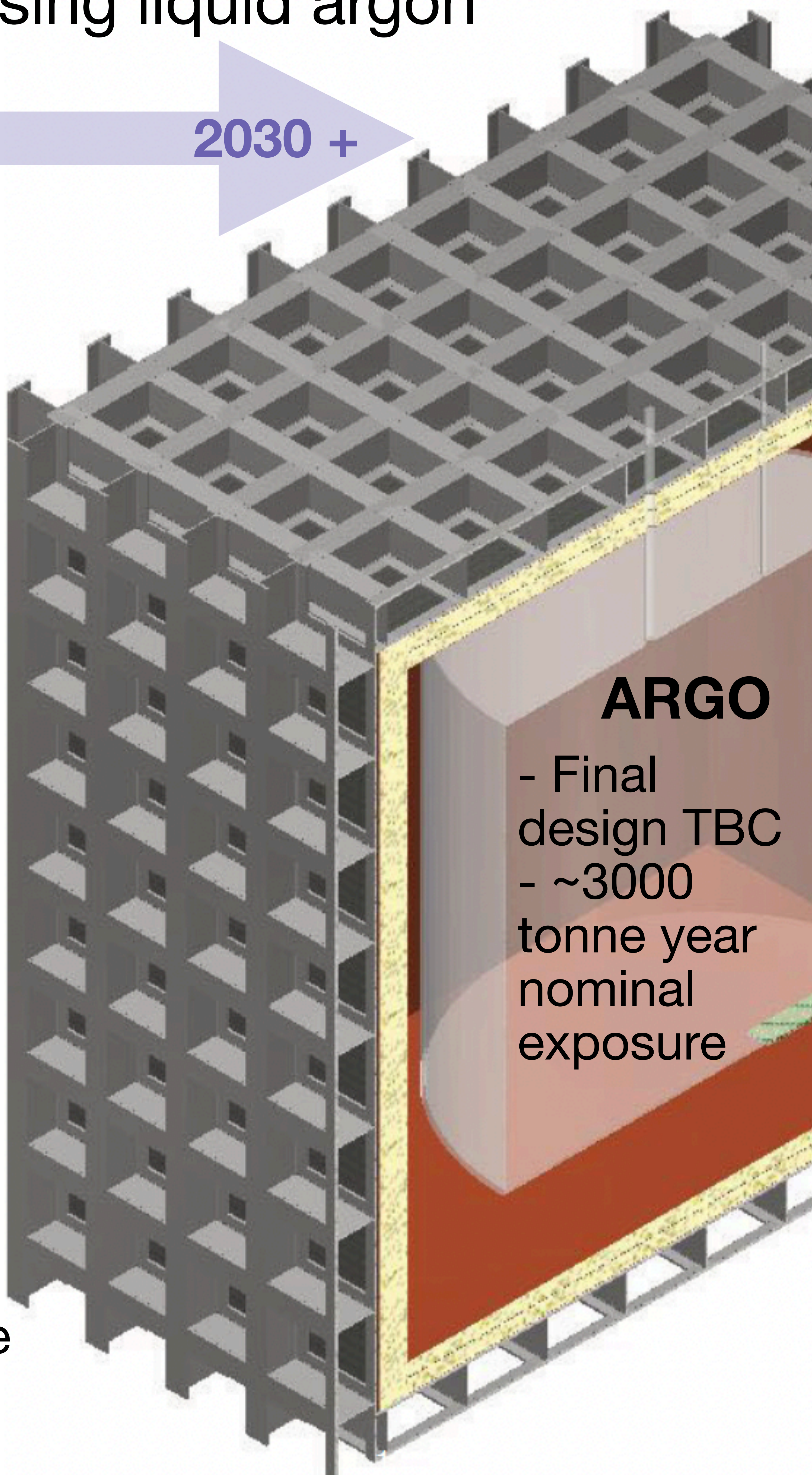
DarkSide-50

- ~50 kg underground argon (UAr)
- Leading low-mass WIMP limit (arXiv:2207.11966)
- (12,306 ± 184) kg day exposure



DarkSide-20k

- ~50 tonnes UAr
- Novel SiPM photosensors
- 200 tonne year nominal exposure



ARGO

- Final design TBC
- ~3000 tonne year nominal exposure

DarkSide-20k: detector design

Currently under construction in Hall C, LNGS, Italy

Data taking: 2027 - 2037

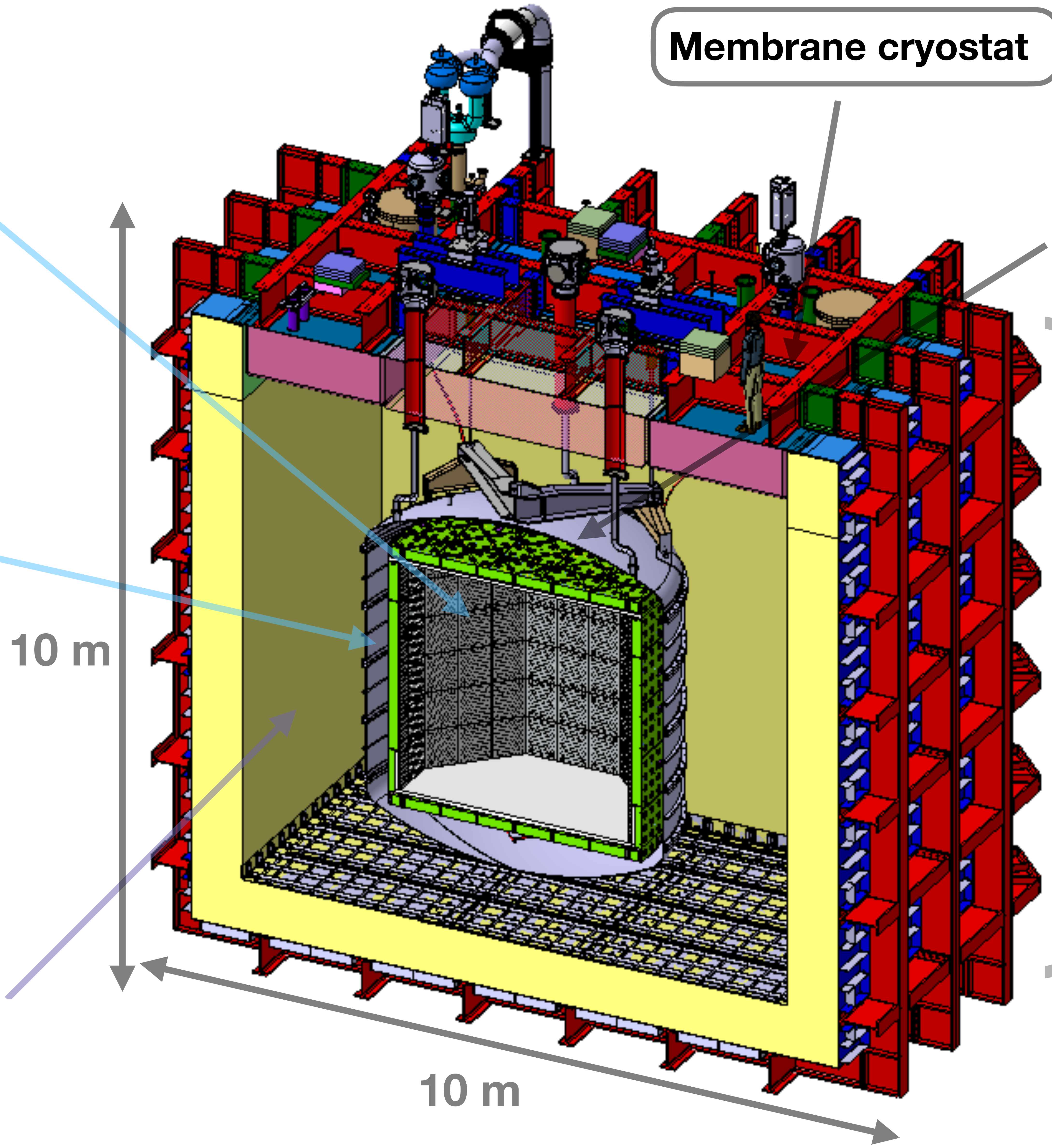
Inner detector

Dual-phase TPC
- 51.1 tonnes underground argon (UAr)
- 20 tonnes fiducial volume
- Light yield: 10 PE/keV

Inner (Neutron) Veto
- PMMA structure
- 35 tonnes UAr surrounding TPC
- Light yield: 2 PE/keV

Outer detector

Outer (Muon) Veto
- 600 tonnes atmospheric argon (AAr)
- Light yield: 132 PE/MeV



Membrane cryostat

Stainless steel vacuum vessel separating inner detector UAr from outer detector AAr

SiPM photosensor readout
~26 m^2 of highly sensitive photosensor coverage

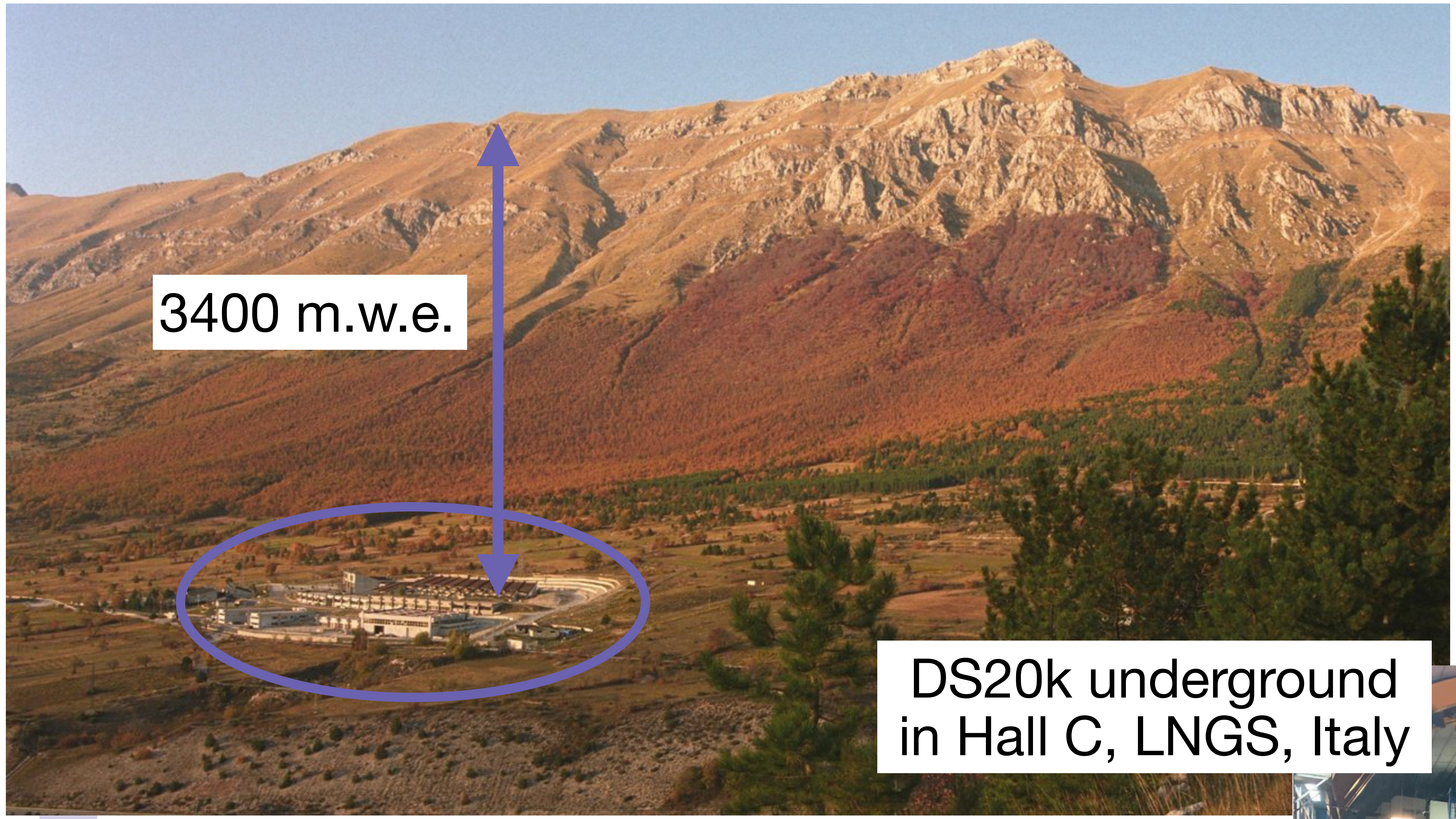
20.8 m^2 in TPC

4.8 m^2 in IV

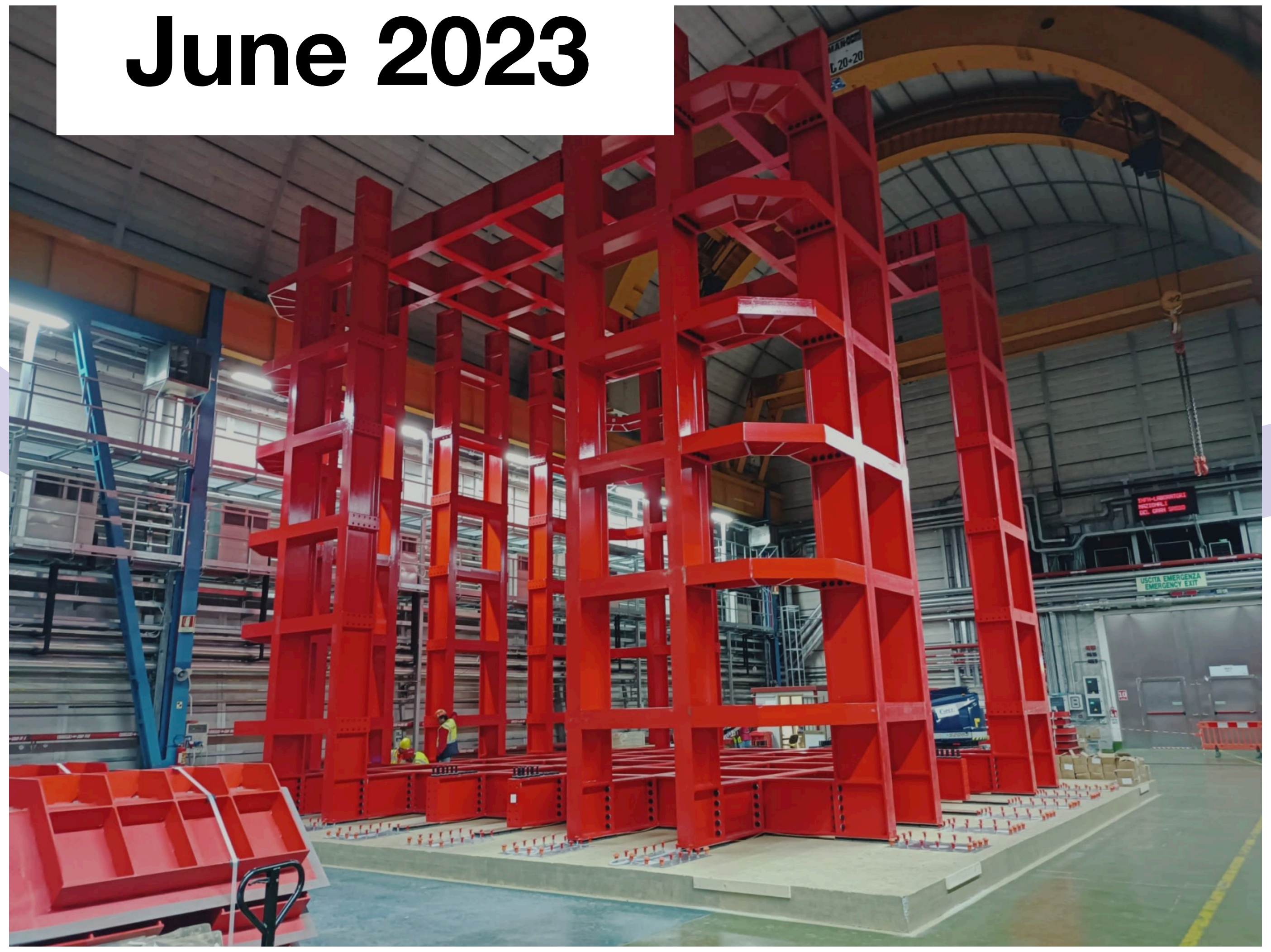
1.2 m^2 in OV

—> more on photosensors in Pablo Kunze's talk

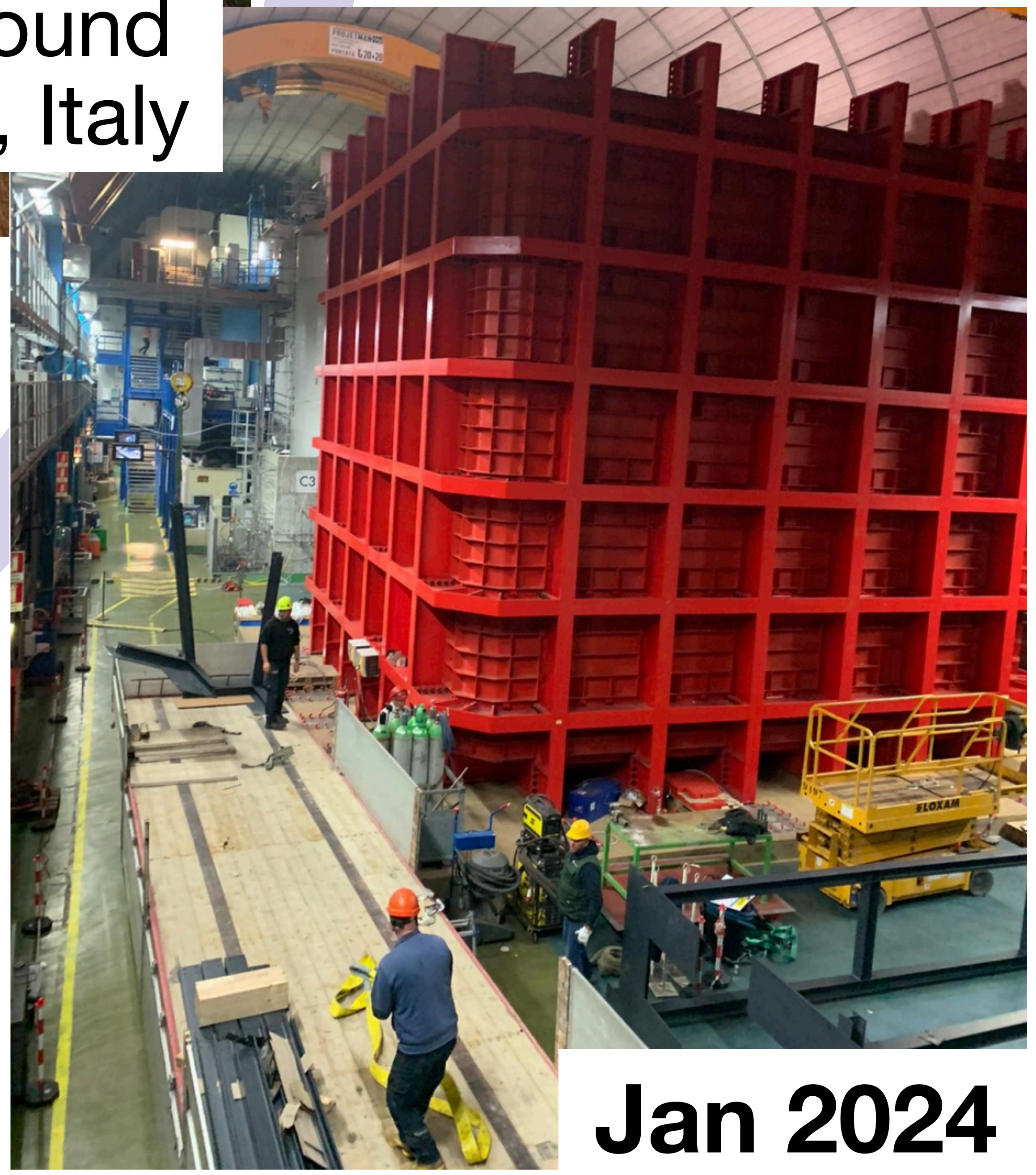
DarkSide-20k: construction progress



DS20k underground
in Hall C, LNGS, Italy

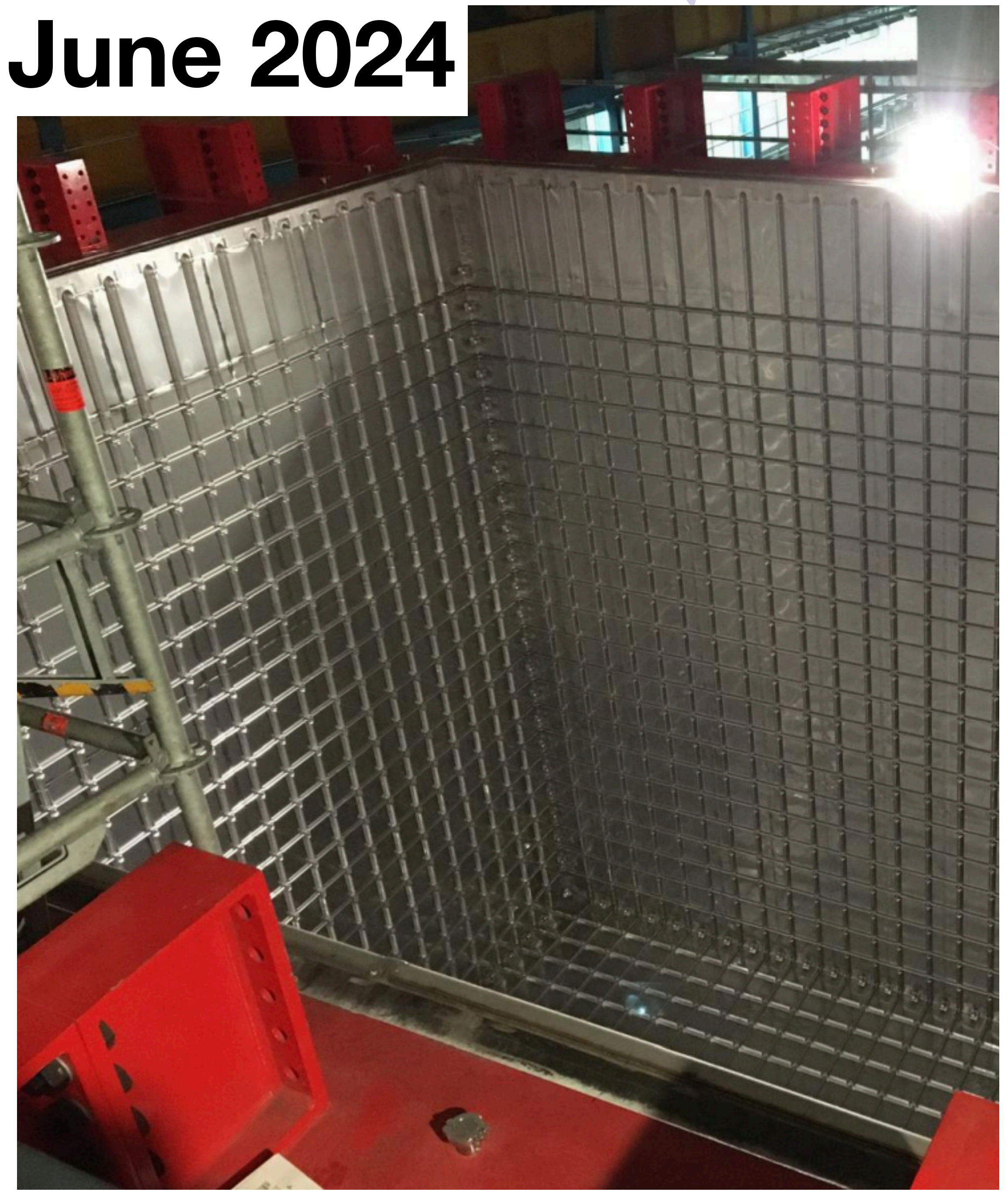


June 2023



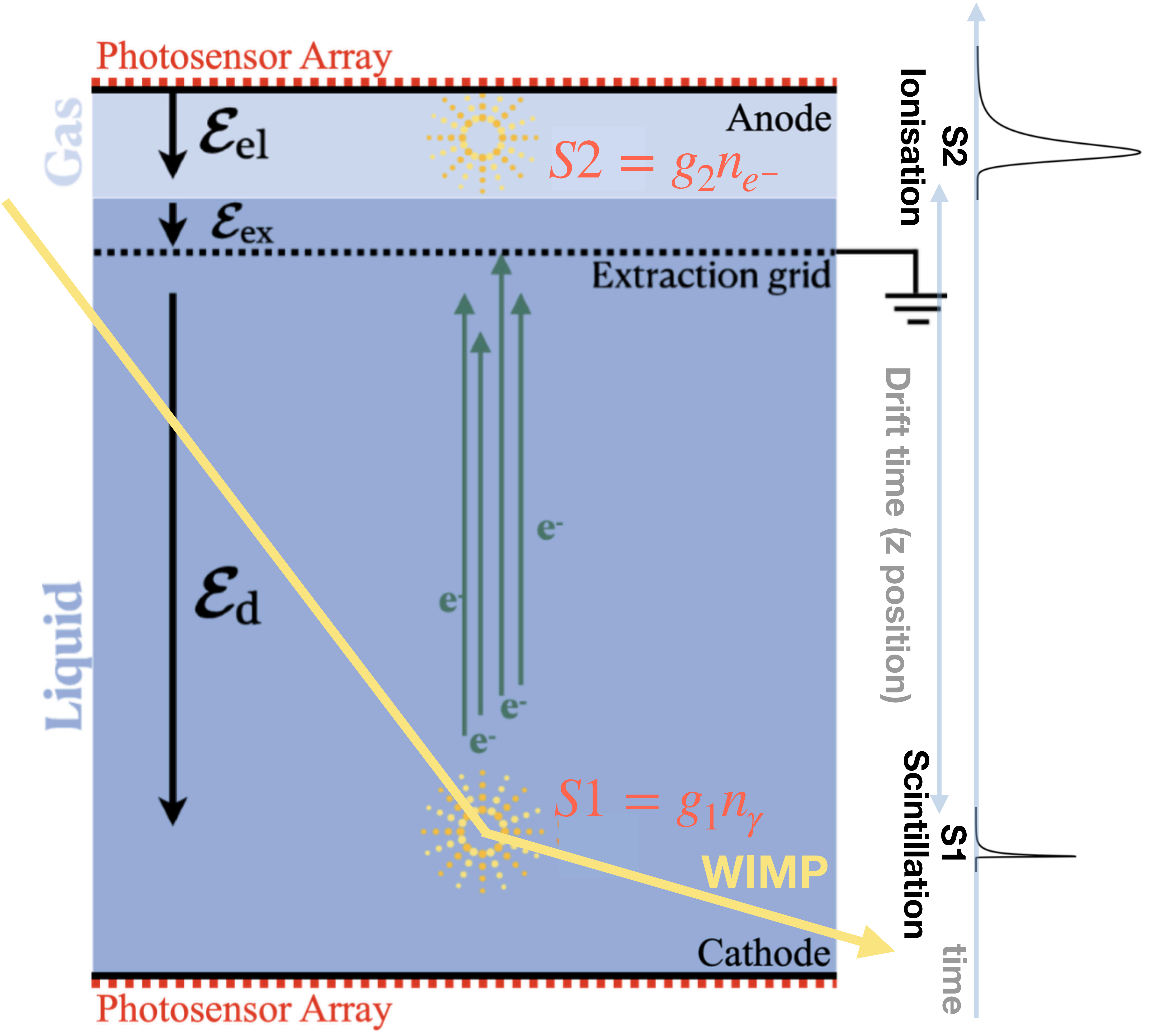
Jan 2024

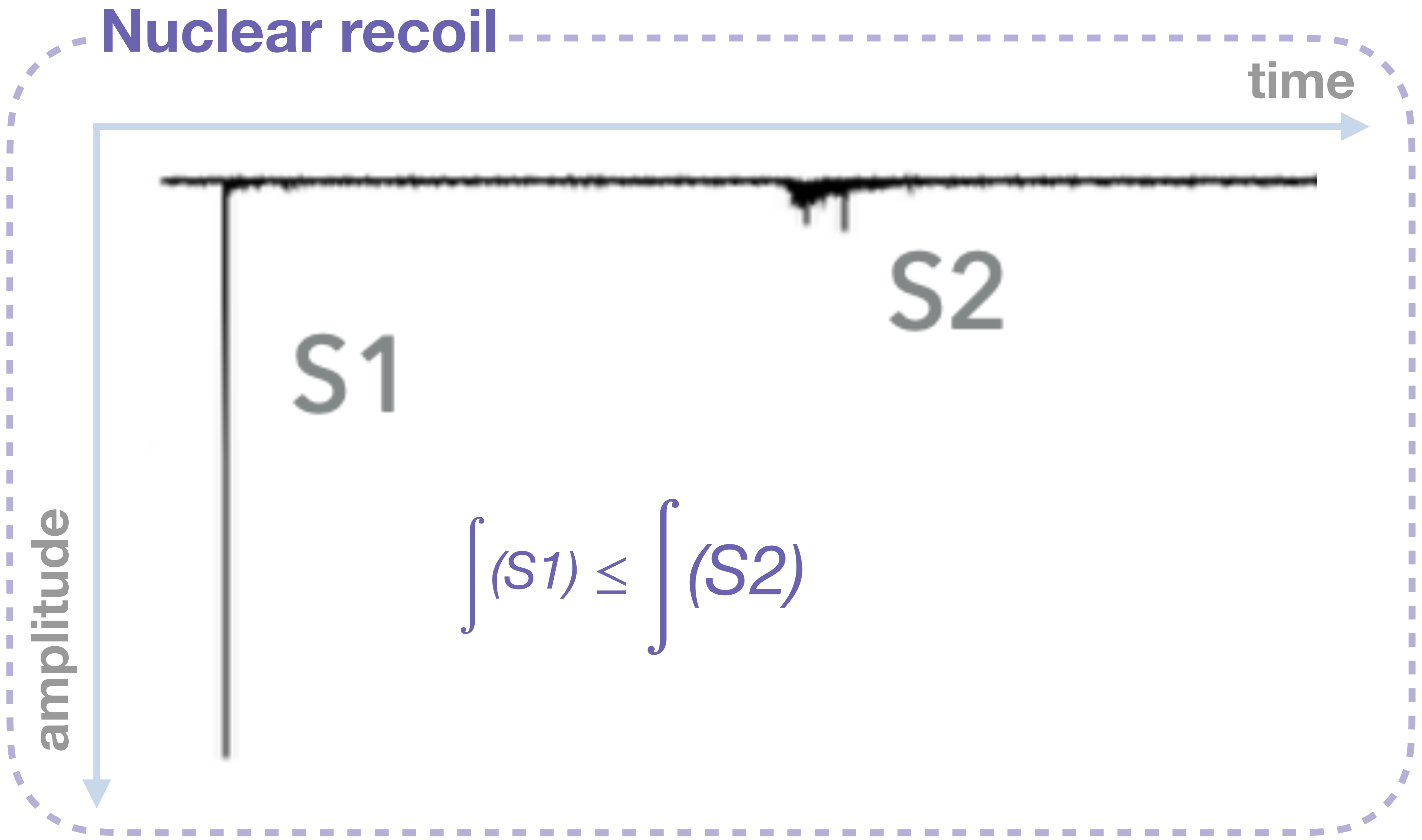
March 2024

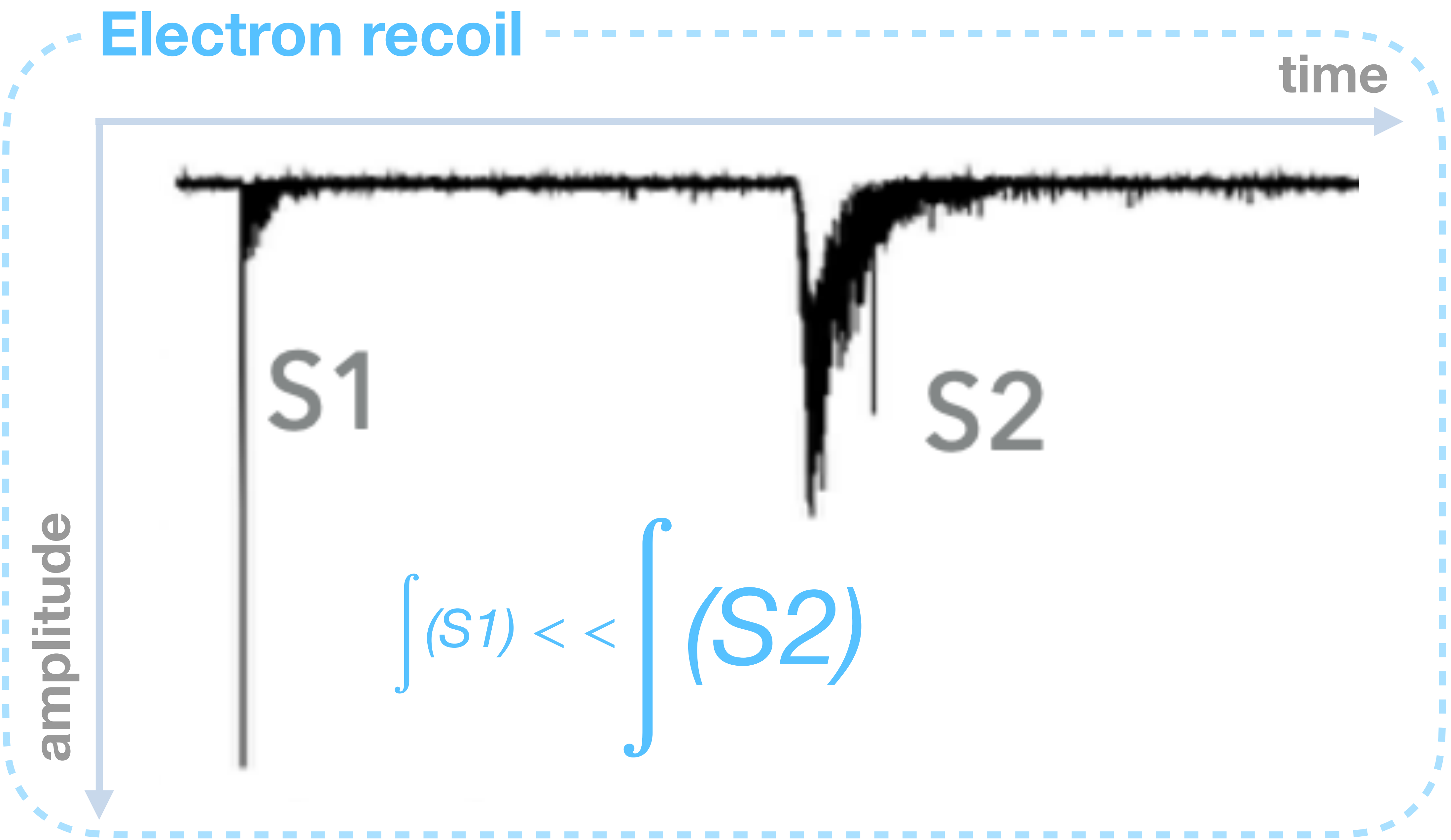


June 2024

Liquid argon: particle interactions in a dual phase Time Projection Chamber



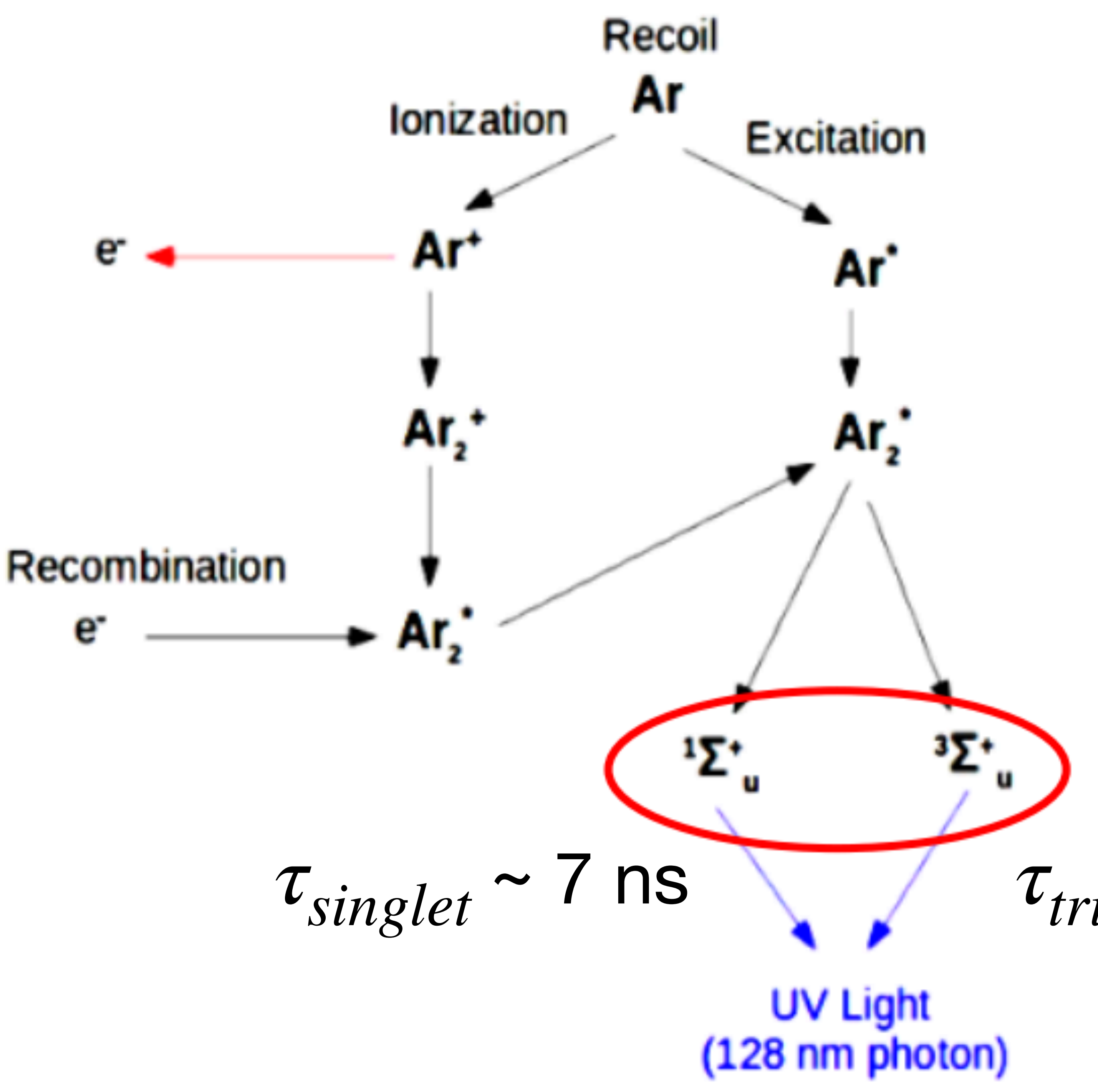




Liquid argon: pulse shape discrimination

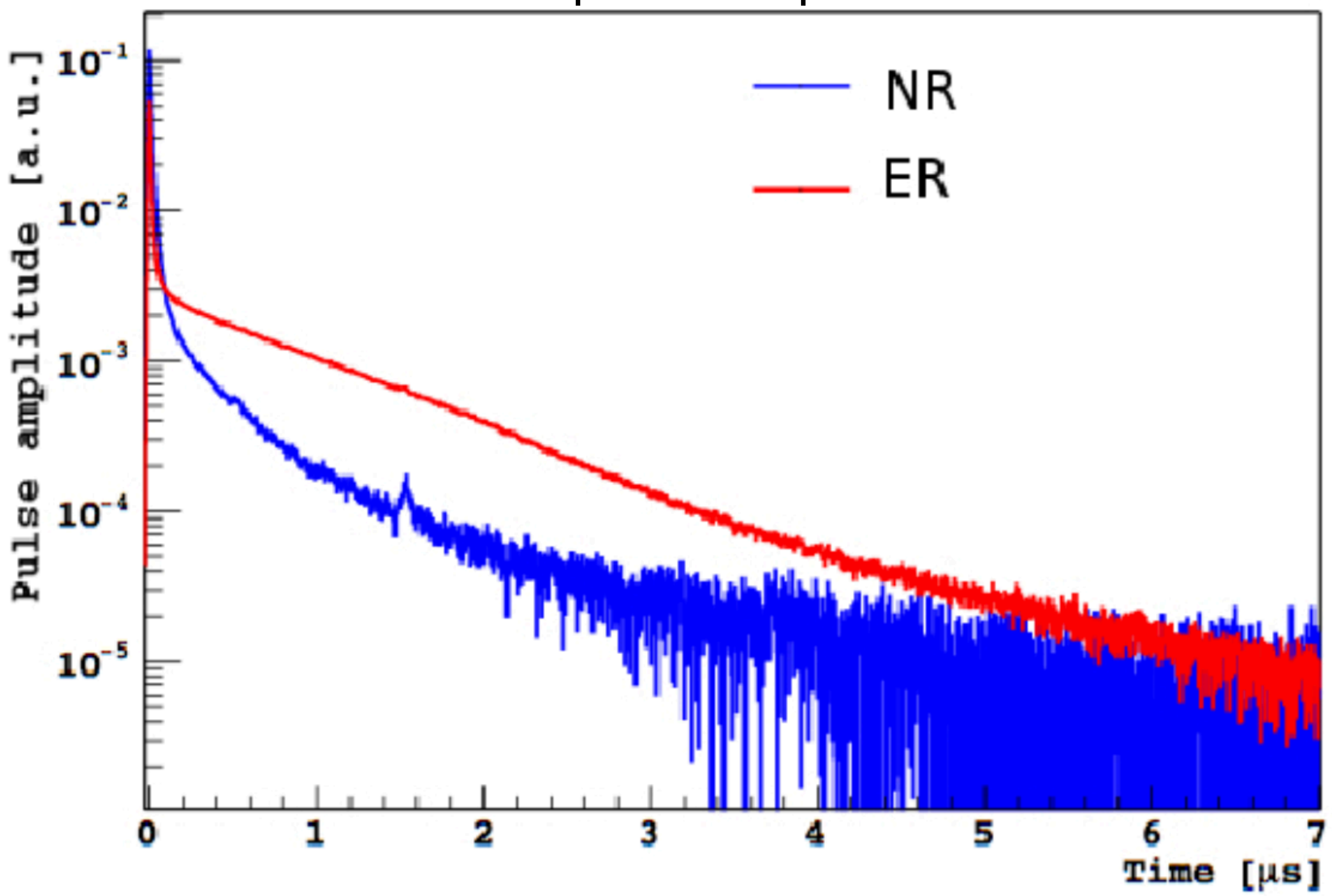
Time profile of scintillation (S1) informs interaction type

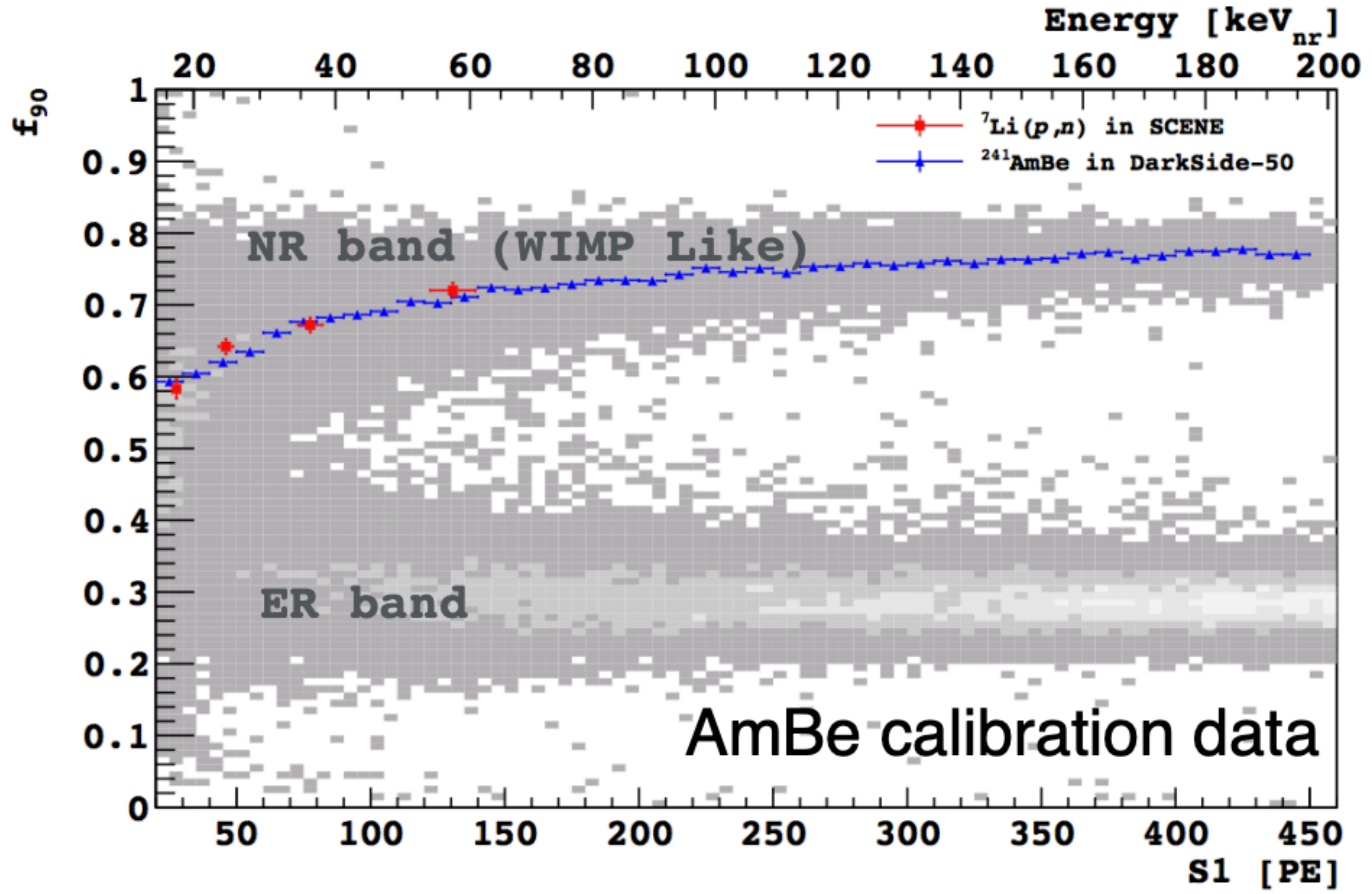
- ER and NR events - different ionisation densities in LAr —> different ratios of singlet and triplet excitation states



$\tau_{singlet}$ ~ 7 ns $\tau_{triplet}$ ~ 1600 ns

S1 pulse shape in LAr





DEAP: demonstrated ER rejection with 10^{-9} electron leakage at 50% NR @ 110 PE (EPJ C 81, 823 (2021))

Backgrounds: sources and mitigation strategies

GOAL instrumental background: < 0.1 neutron in WIMP ROI [30 - 200 keV] in full 200 t yr exposure

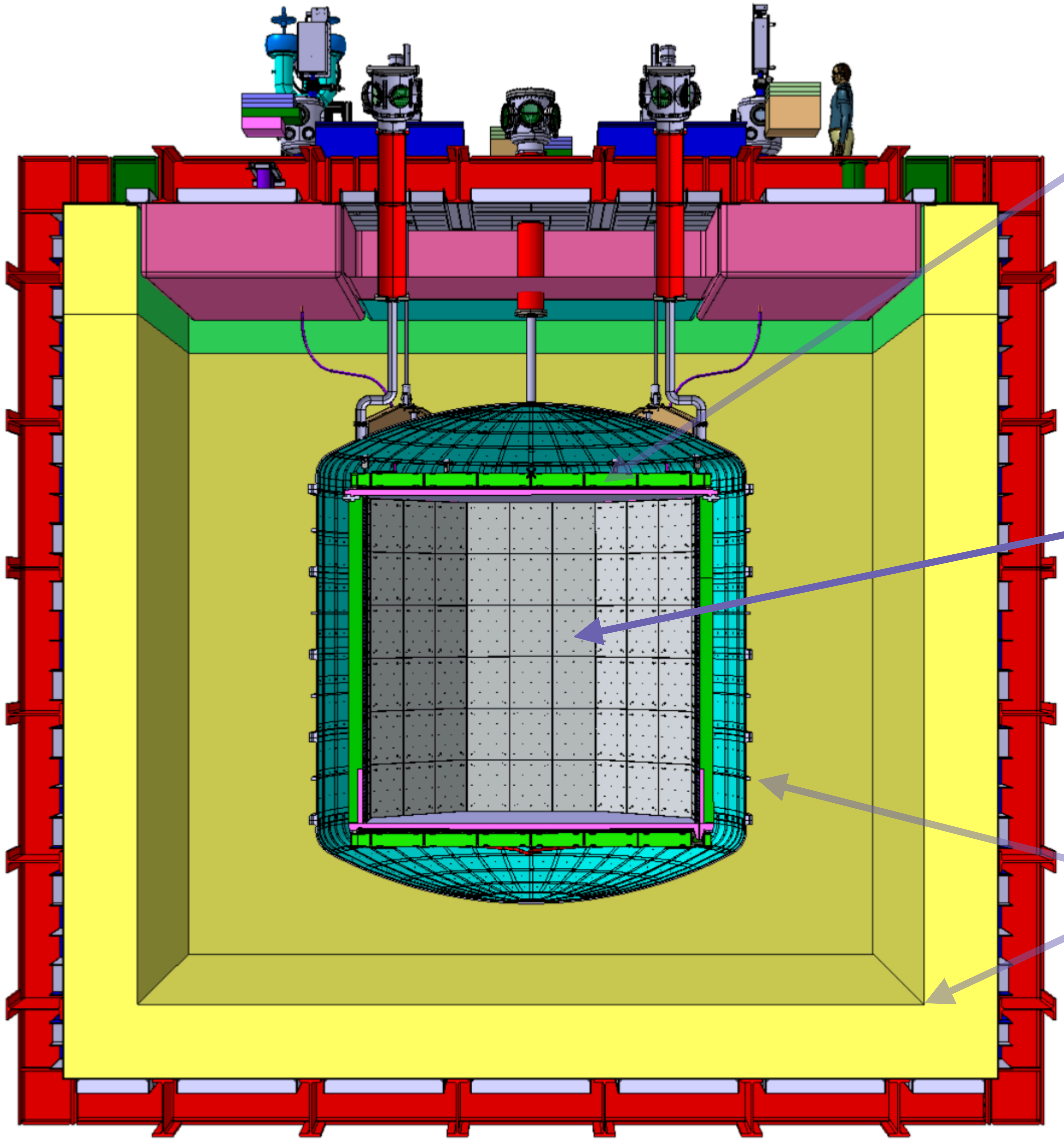
Cosmogenic muons and neutrons

→ Underground detector, instrumented muon veto

Radiogenic neutrons

→ Instrumented neutron veto, fiducialisation, material selection

Further background suppression:
- volume fiducialisation
- understanding of event topology for multi-scatter events



Radioactive contaminants from photosensors

→ Radio assay materials, limited radon exposure

^{39}Ar & ^{85}Kr β decays from LAr bulk

→ Purified UAr, PSD

Radioactive contaminants from detector materials

→ Radio assay materials, surface cleaning, limited radon exposure arXiv:1510.00702

Background source: ^{39}Ar isotope in atmospheric argon

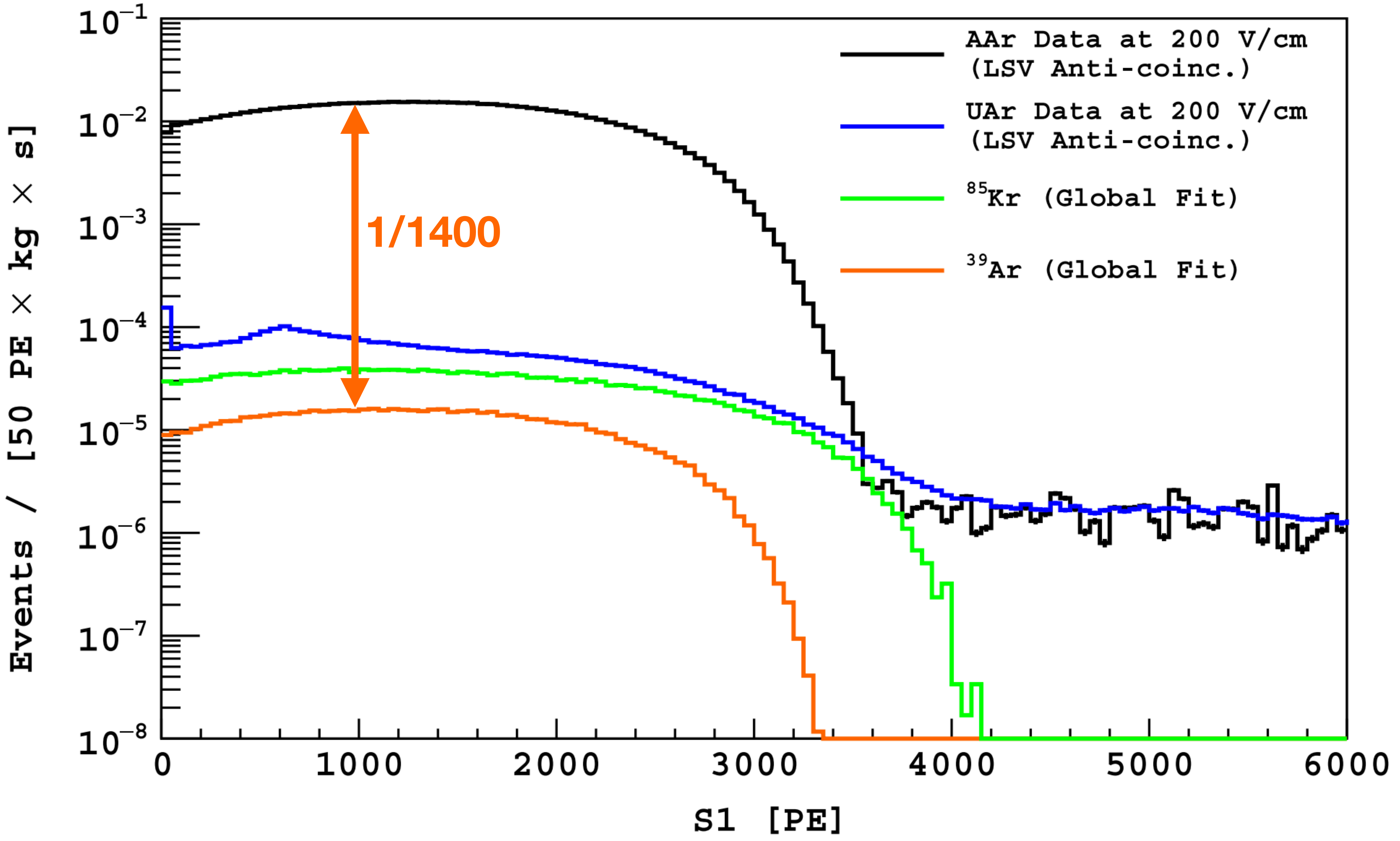
^{39}**Ar radioactivity**

Intrinsic ^{39}Ar β-decay in AAr: a primary background for argon based detectors

—> Activity determines dark matter detection threshold at low energies

Underground sources of argon (UAr): reduced ^{39}Ar activity (since cosmogenically activated)

- **AAr: 1 Bq/kg —> UAr: 0.73 mBq/kg**

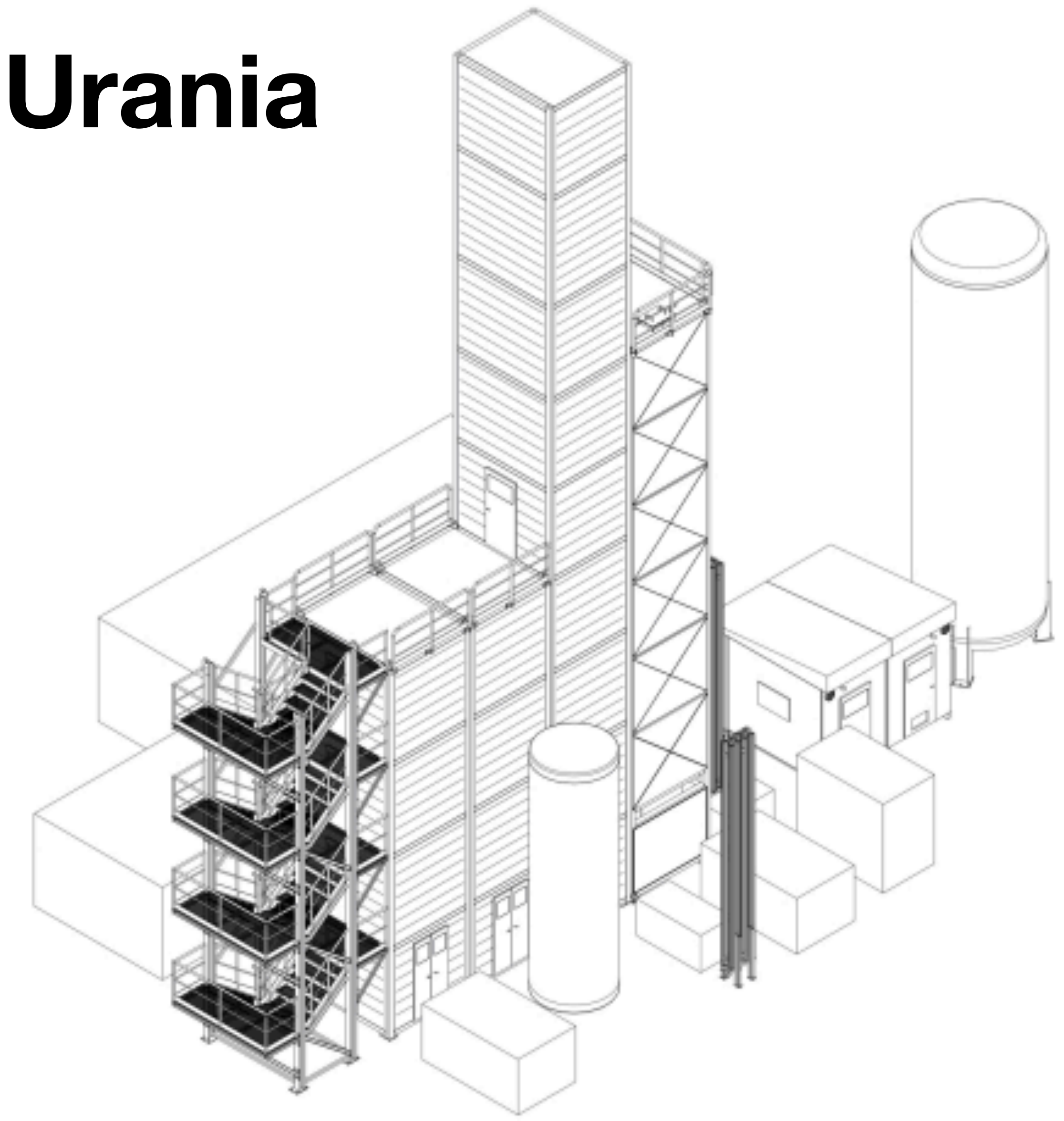


DarkSide-50 pioneered the use of UAr
—> measured reduction of 1400 $\pm$ 200 in ^{39}Ar activity
—> DarkSide-20k will further purify its sources of UAr in dedicated facilities

Underground Argon: extraction and purification

UAr is depleted in intrinsic ^{39}Ar isotope

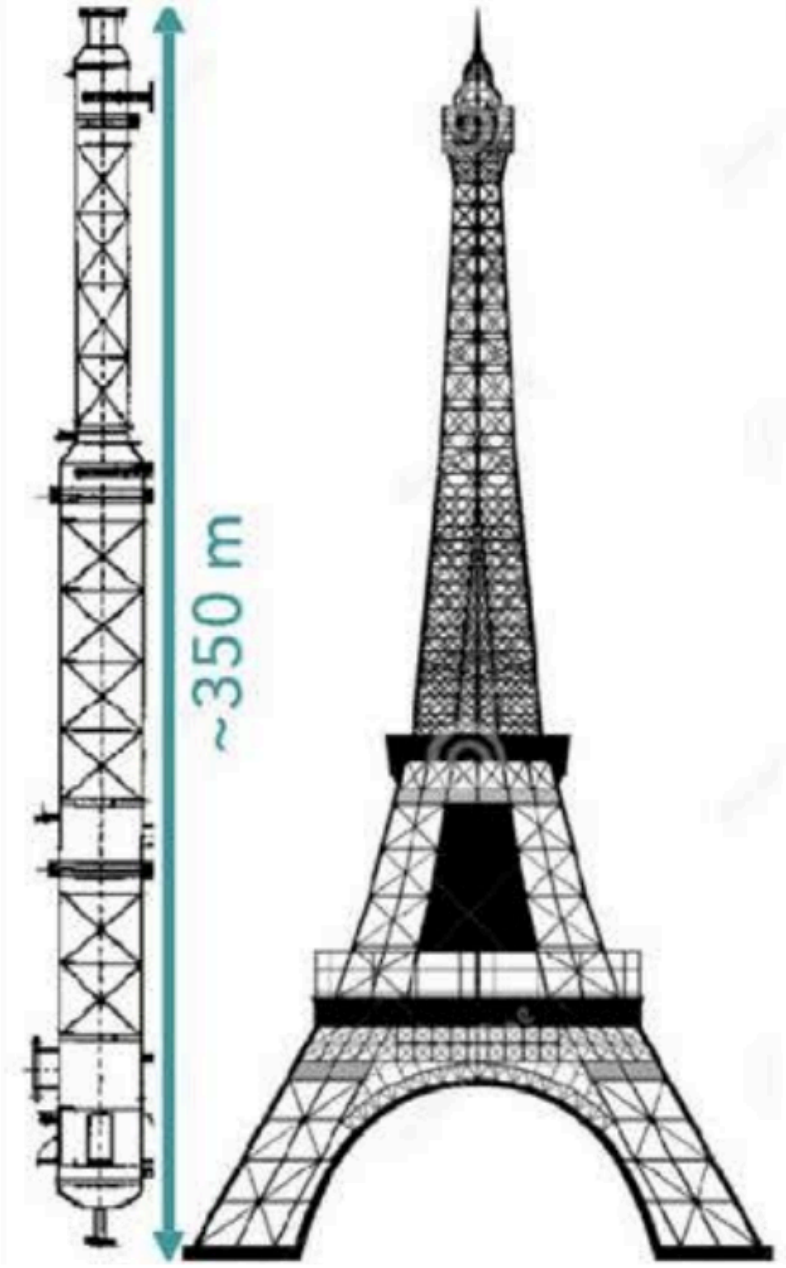
Urania



UAr **extraction plant** in Cortex, Colorado

- Extraction rate of ~330 kg/day with 99.99% purity (arXiv:2301.09639)

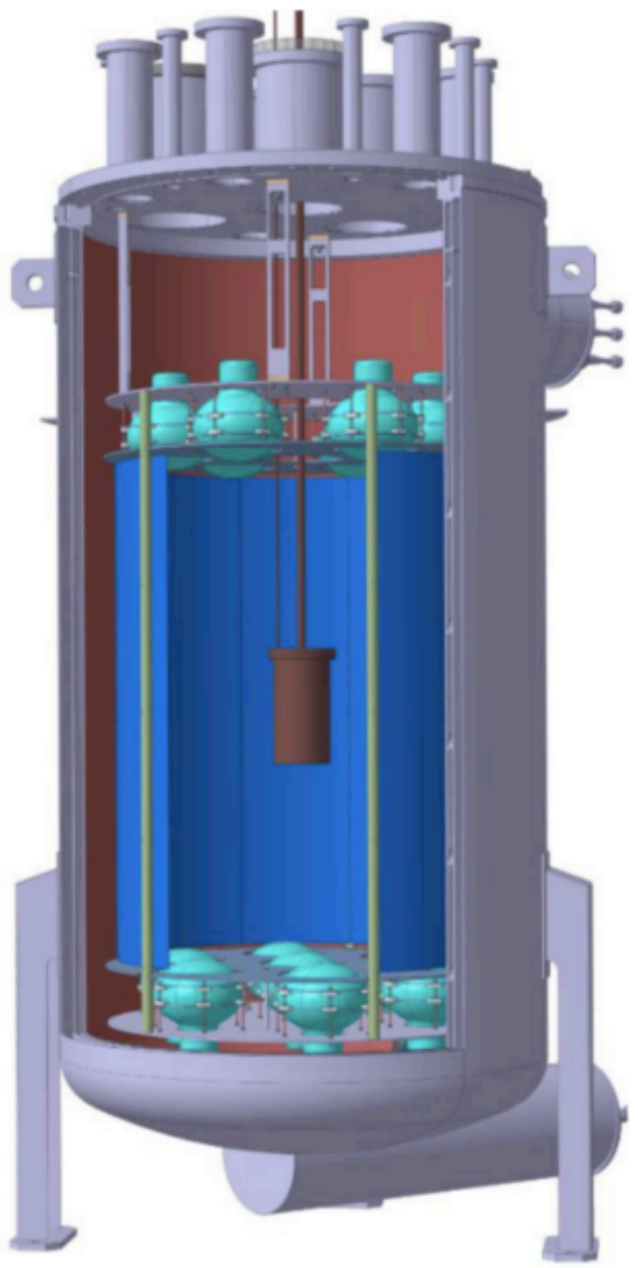
Aria



~350 m tall UAr **purification column** in Sardinia, Italy

- Purification rate of ~1000 kg/day
- x10 reduction in ^{39}Ar per pass with ~10 kg/day

DArT



Quality control of ^{39}Ar activity in Canfranc, Spain

- Dual phase TPC to measure ^{39}Ar depletion factor
- 1.4 kg active mass of UAr
- ^{39}Ar depletion factor sensitivity ~ 6×10^4 (90% C.L: arXiv:2001.08106)

High mass analysis: WIMP sensitivity

Target: **argon nuclei**

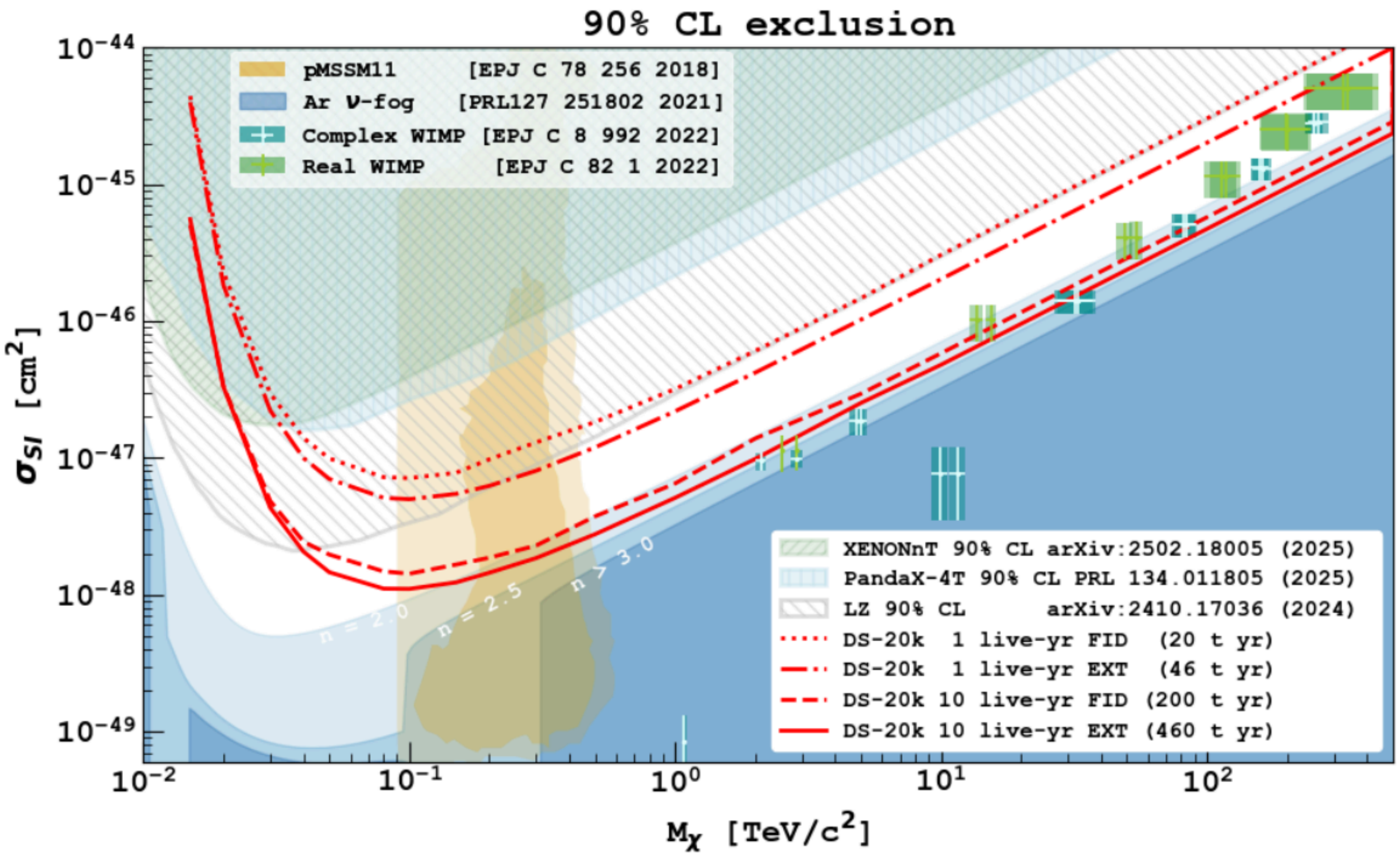
Large exposure

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 keV_{NR}) in total 200 t yr exposure

- **EXT:** background dominated by radiogenic neutrons from photosensors and experimental hall



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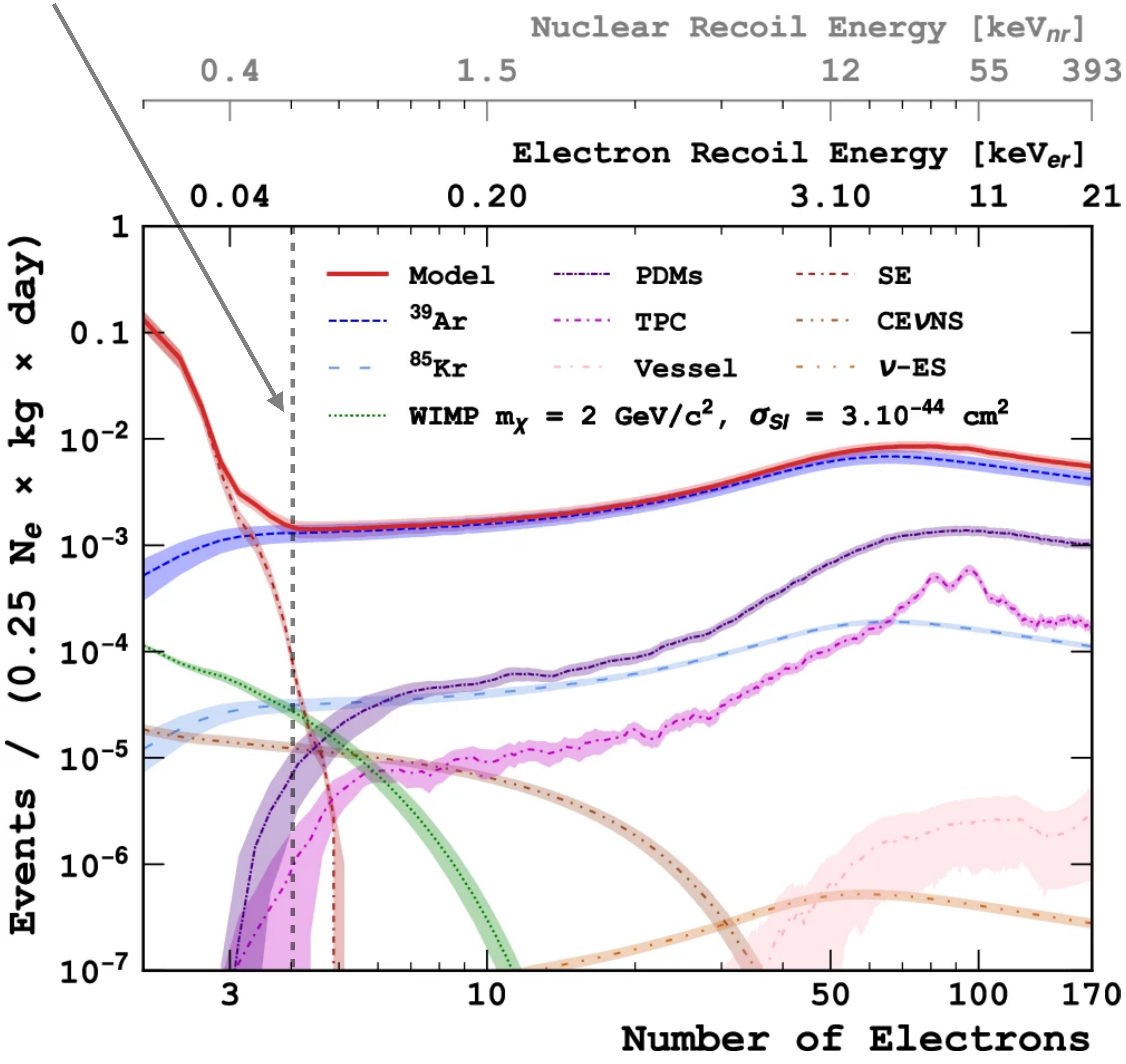
Low mass analysis: DS20k background model

@ $N_e = 4$, SE x18 lower than ^{39}Ar



Drop the requirement for an observable S1

- **S2 only events** where accompanying S1 lies below threshold

—> lower energy recoils, increased low mass sensitivity

BUT increased backgrounds: no PSD possible

- Main background: ERs, mainly from ^{39}Ar
- Pre cuts: 80 Hz —> 51% livetime

Techniques applied to DS-50 —> leading limit in [1.2, 3.6] GeV/c^2 mass range

ROI: $N_e \in$ **[4, 170] (**$N_e \in$ **[2, 170])**

Spurious electrons (SE)

Origin: electrons trapped by impurities and released later
—> extrapolated from DS-50

Sensitivity for many light DM candidates explored…

Low mass analysis: light dark matter sensitivity

DS20k analysis cuts

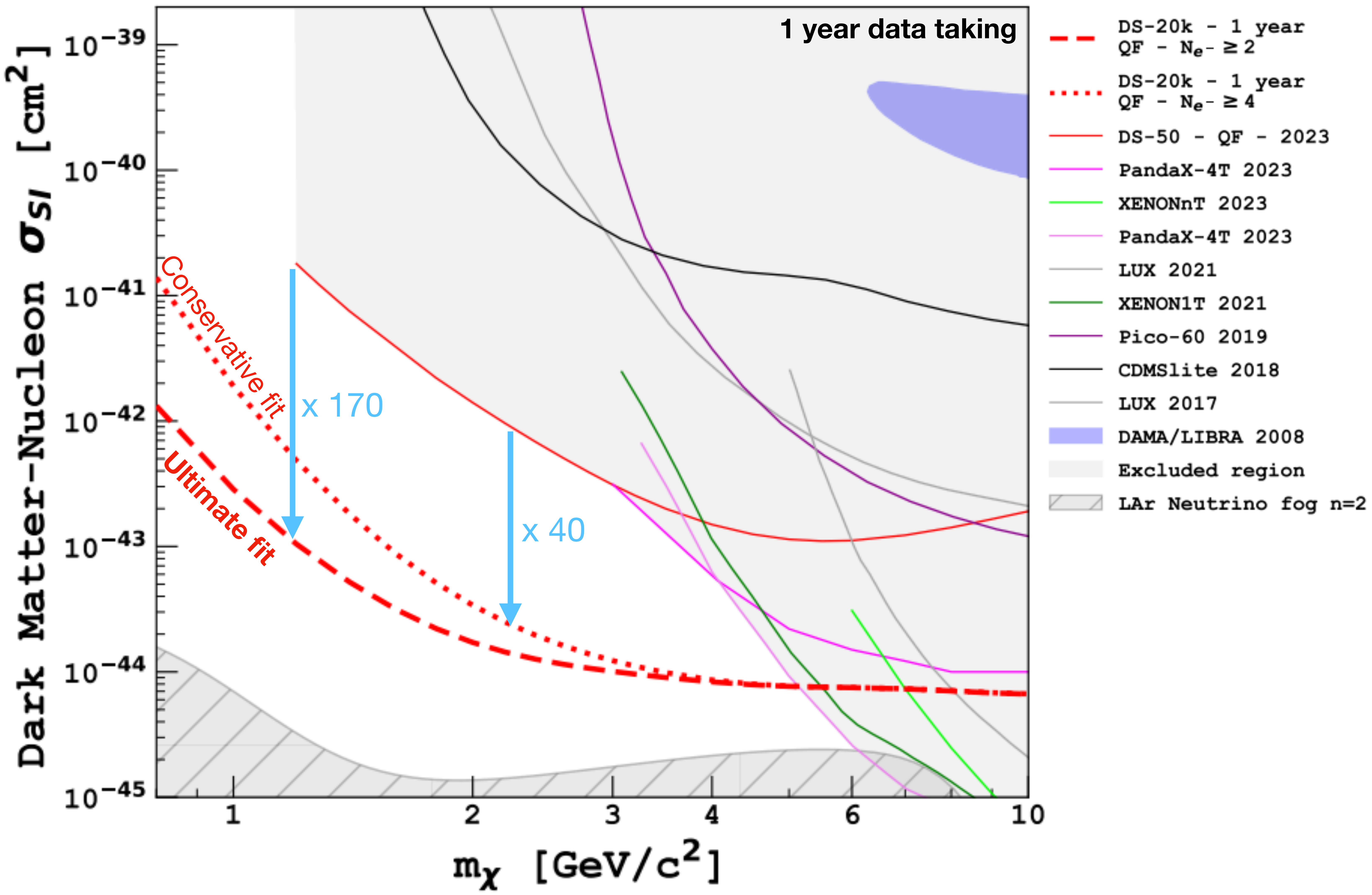
—> single S2 pulse in 3.7 ms drift time
—> remove anomalous low S2 signals (TPC wall α)
—> FV cut: 30 cm from TPC walls (34 t)

Two fit scenarios

Conservative: fit from $N_e = 4$ (~independent of SE modelling)

Ultimate: fit from $N_e = 2$ (assuming good control of spectral shape of SE in DS20k)

Scales with $\sqrt{exposure}$
—> DS20k will reach neutrino fog around $m_\chi \approx$ 5 GeV/c^2 after 10 yrs



>1 order of magnitude improvement over DS-50 ((arXiv:2207.11966))

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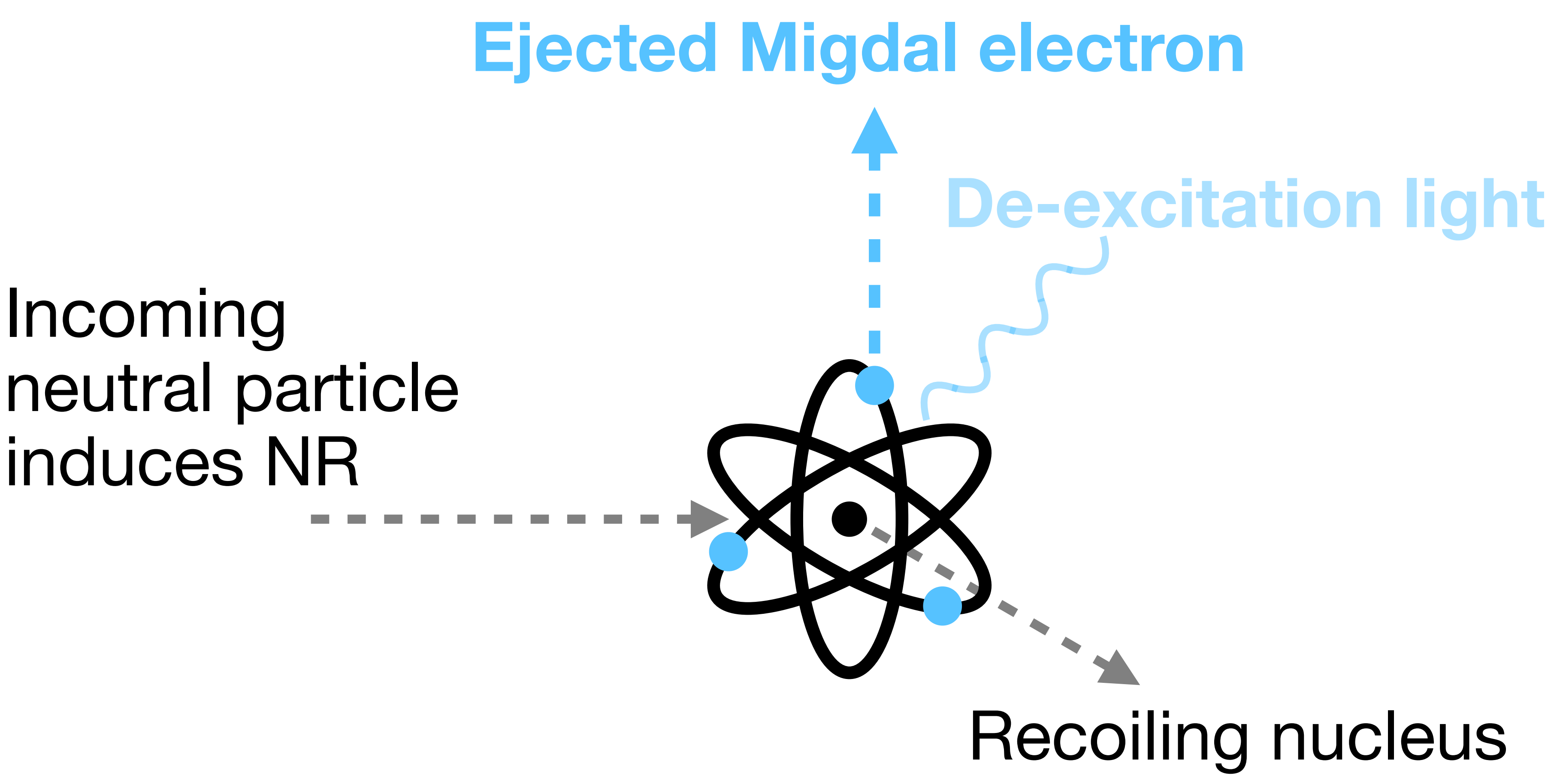
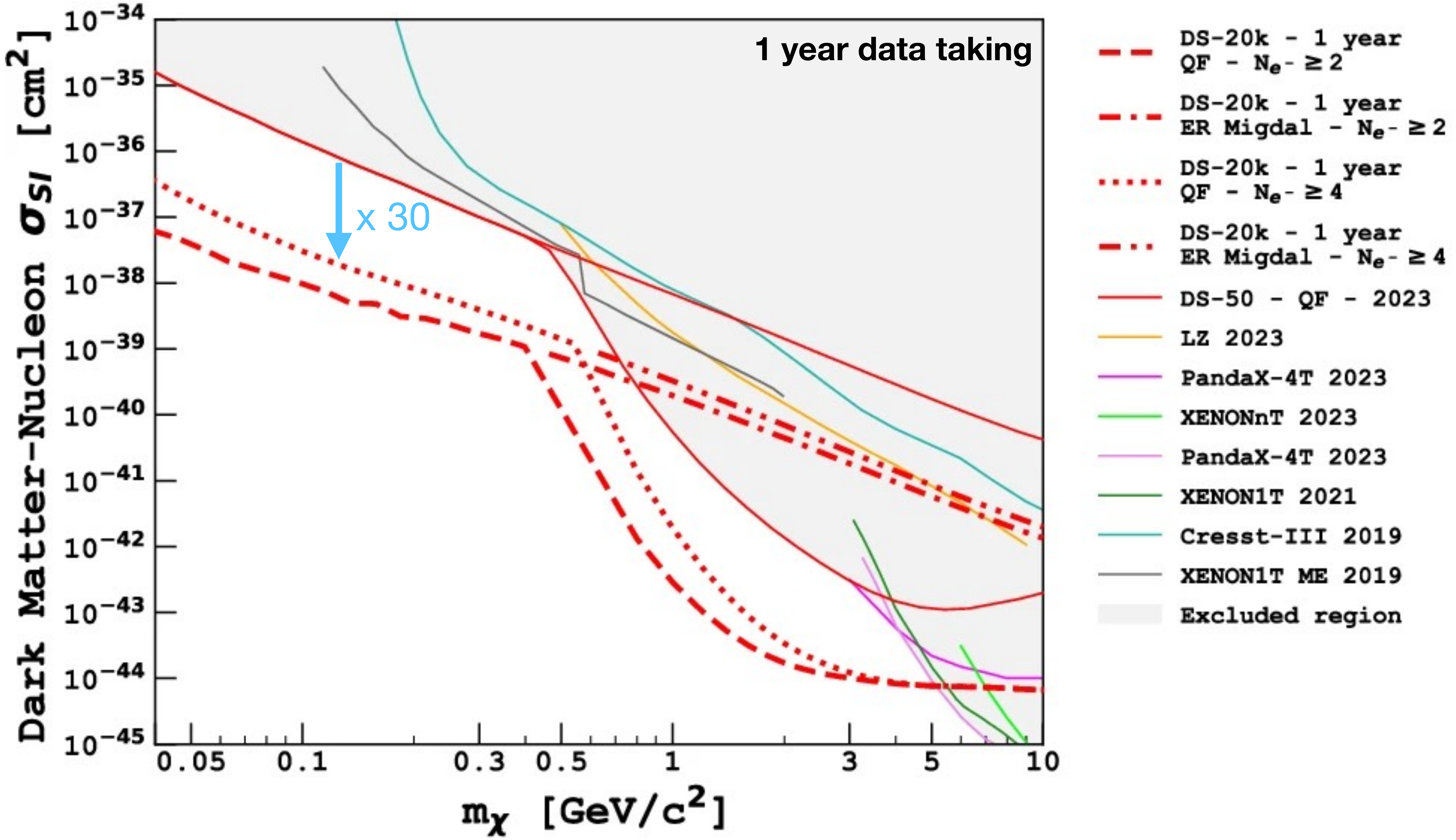
Low mass analysis: light dark matter sensitivity



Migdal effect

- possible atomic effect
- electron released in NR
  - extra ER component increases the probability of exceeding detection threshold
    —> wider range of WIMP masses can be accessed



With Migdal effect: best limits from 40 MeV/c^2 - 5 GeV/c^2

>1 order of magnitude improvement over current experiments

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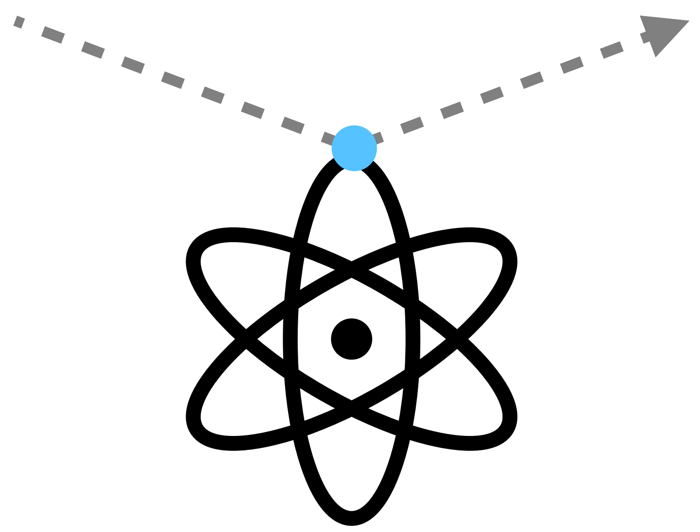
Low mass analysis: light dark matter sensitivity

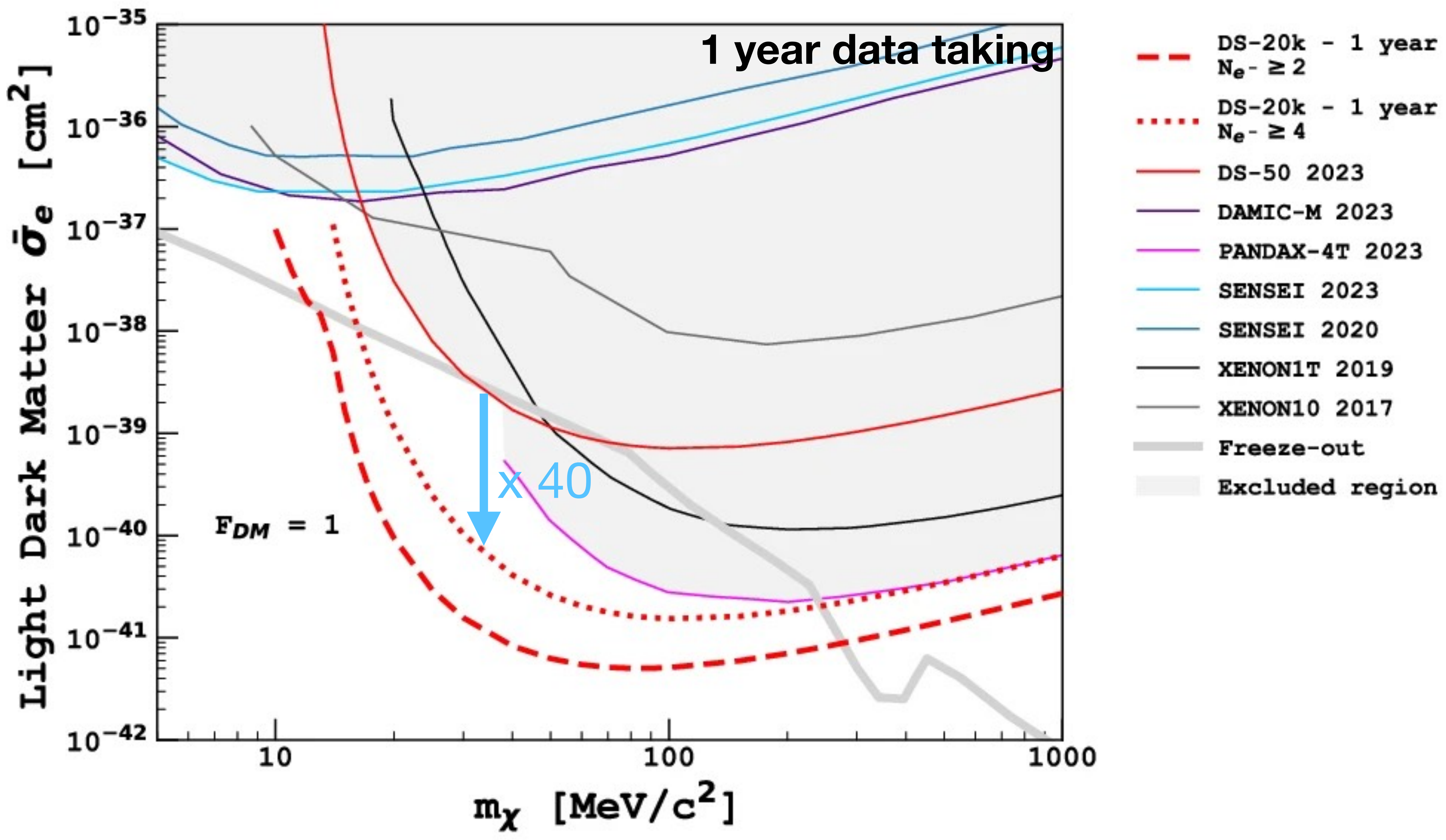


Elastic scatter of light dark matter from bound electrons

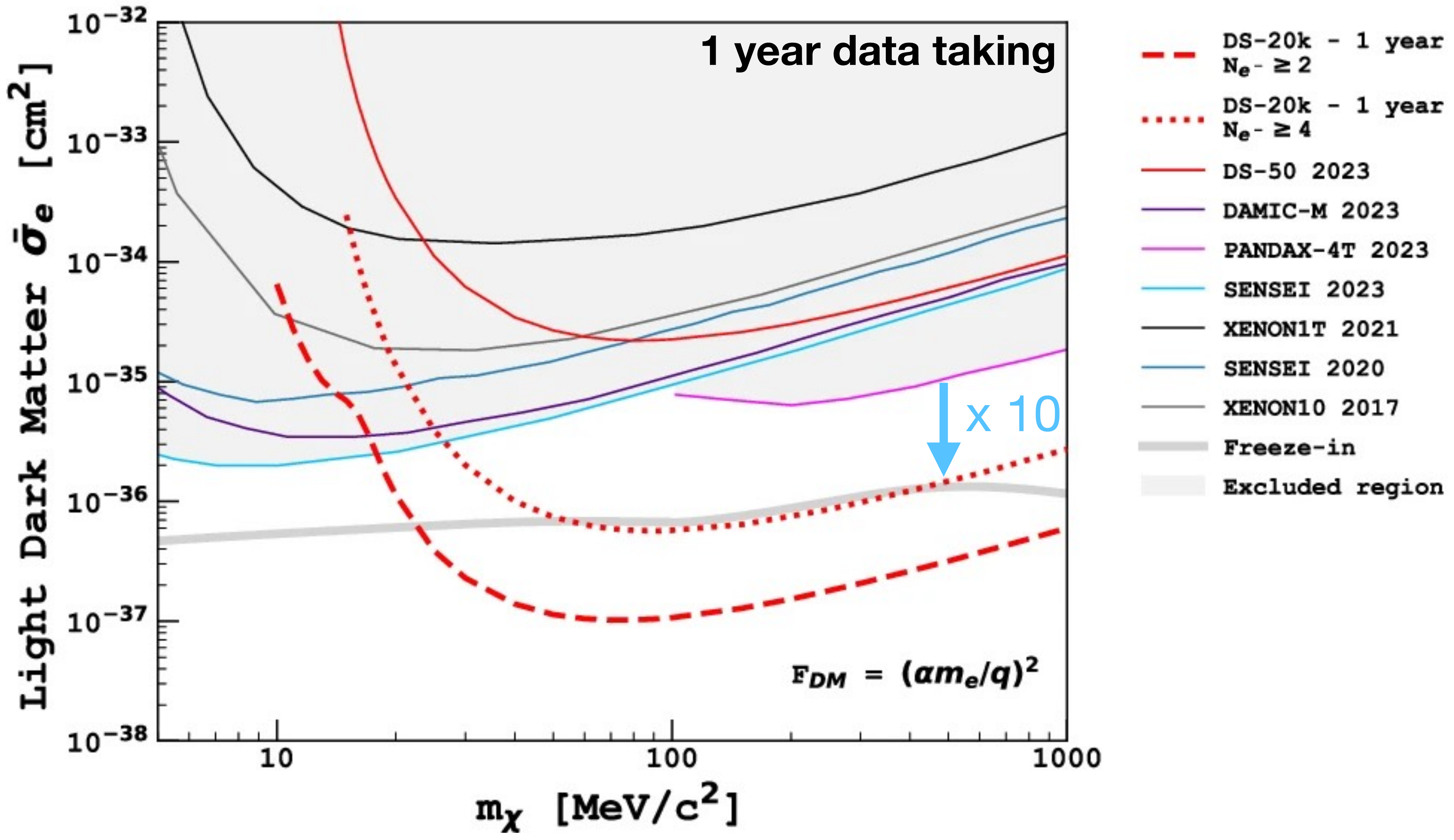
Light dark matter = sub-GeV fermion or scalar boson

Mediator can be heavy (—> F~1) or light (—> F~1/q^2)

Heavy mediator



Light mediator



>1 order of magnitude improvement over current experiments

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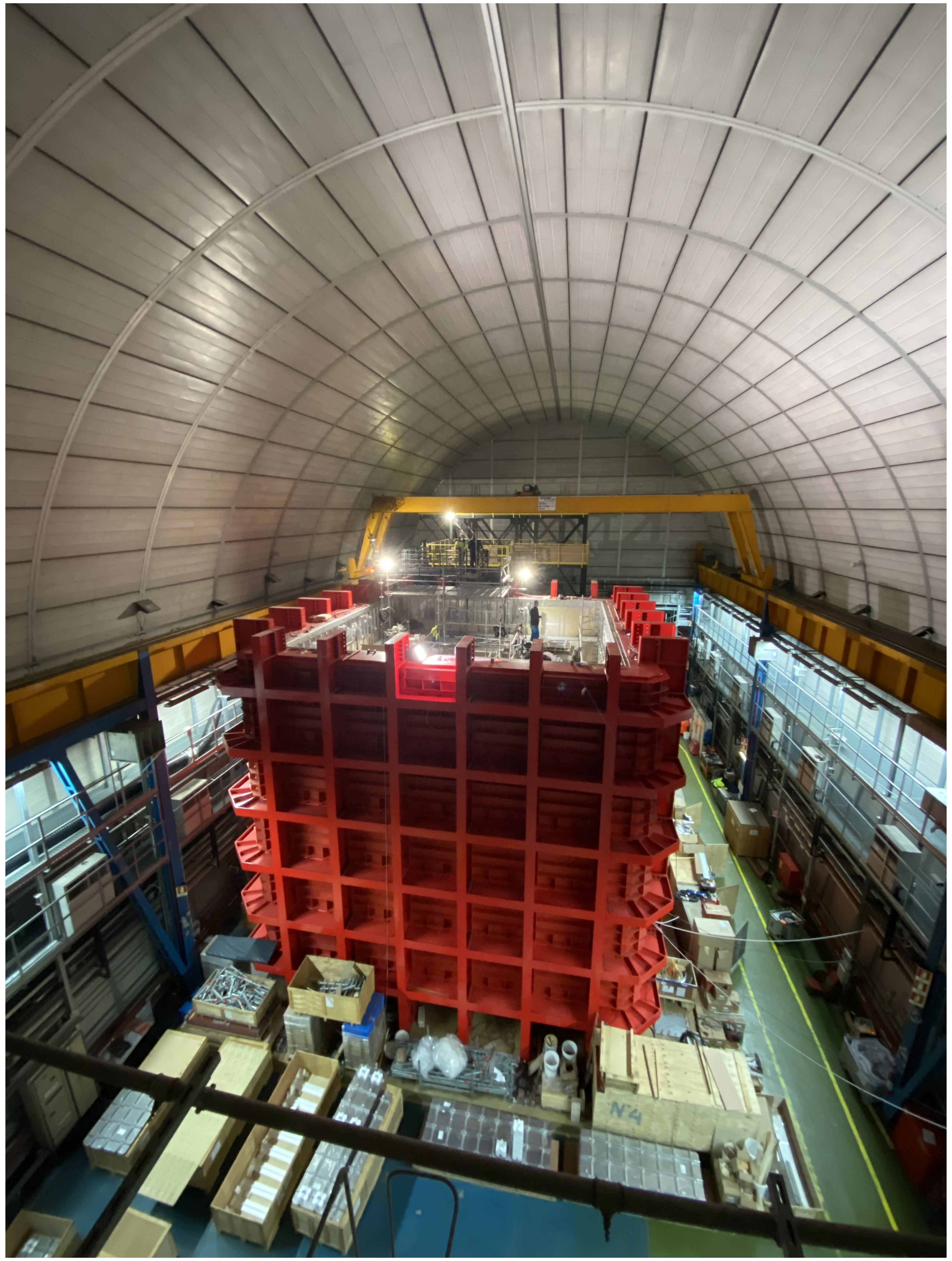
Summary

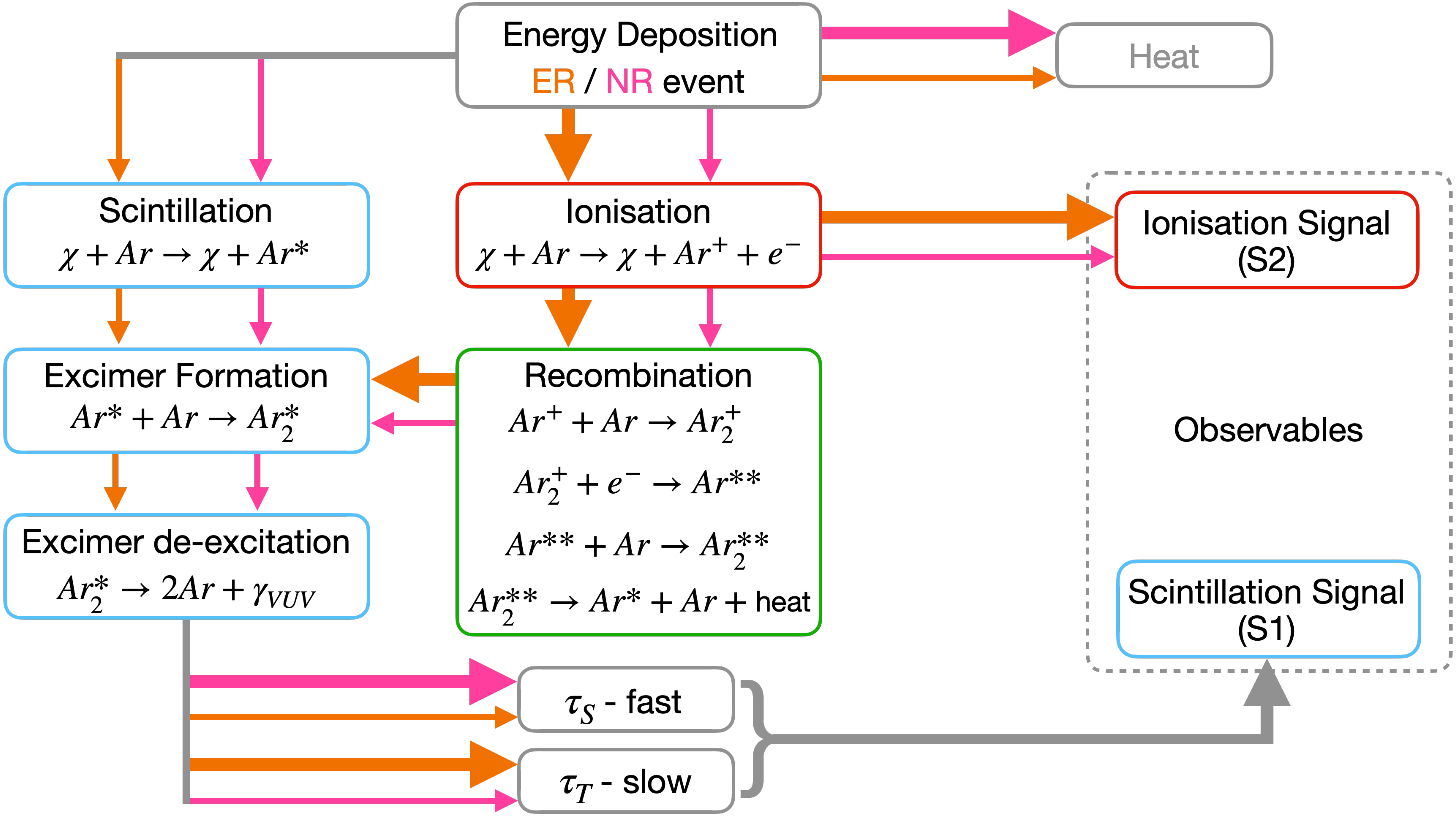
- DarkSide-20k currently under construction at LNGS
- Leading the field with **several novel technologies:**
  - UAr procurement plants set to further increase radio-purity of DS-50s UAr
  - SiPM technology used cryogenically to instrument ~26 m^2 of the detector
- High-mass WIMP search **fully complementary** to existing ongoing Xe-based detectors
- Low energy analysis strengthens physics reach of DarkSide-20k **—> leading role below 5 GeV/c^2**
- Expect to probe **> 1 order of magnitude of uncharted parameter space within 1 year** for variety of dark matter particles
- Data taking set to start in 2027…



Thank you

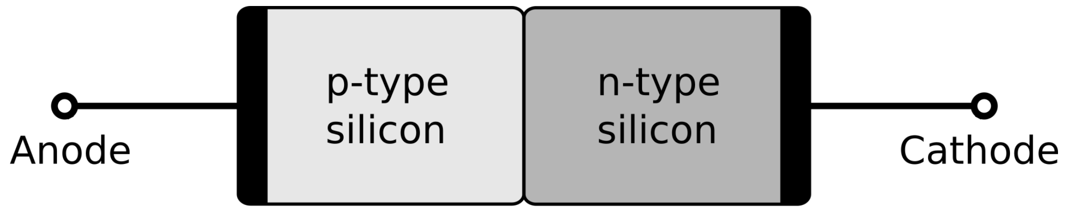
Back up

Energy loss in LAr: electron recoils vs. nuclear recoils



Beyond PMTs: novel Silicon Photomultiplier technology

SiPM: array of SPADs (p-n junction semiconductors) operating in Geiger mode

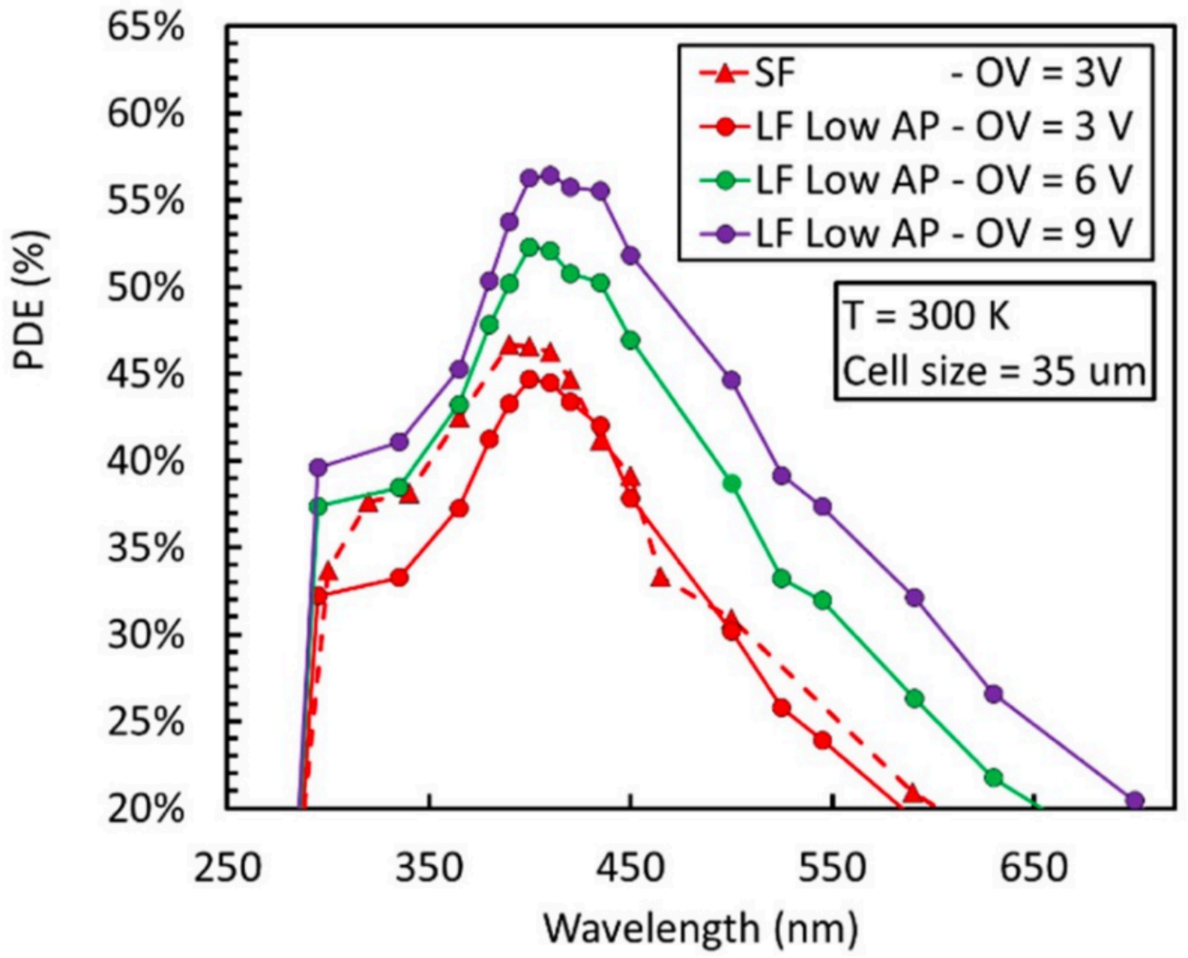


PMTs

SiPMs

Why SiPMs?

- Stable cryogenic operation
- Increased single photon resolution
- Higher photo-detection efficiency
  - PDE > 40% @ λ = 420 nm (LAr scintillation @ 128 nm shifted with TPB)



- **10 x lower radiogenic background**
- Low operating voltage
- Simple robust electronics
  - Application specific front-end
- Low cost
- Modular, scalable architecture
- Fast timing, low jitter
  - Enables precise event reconstruction

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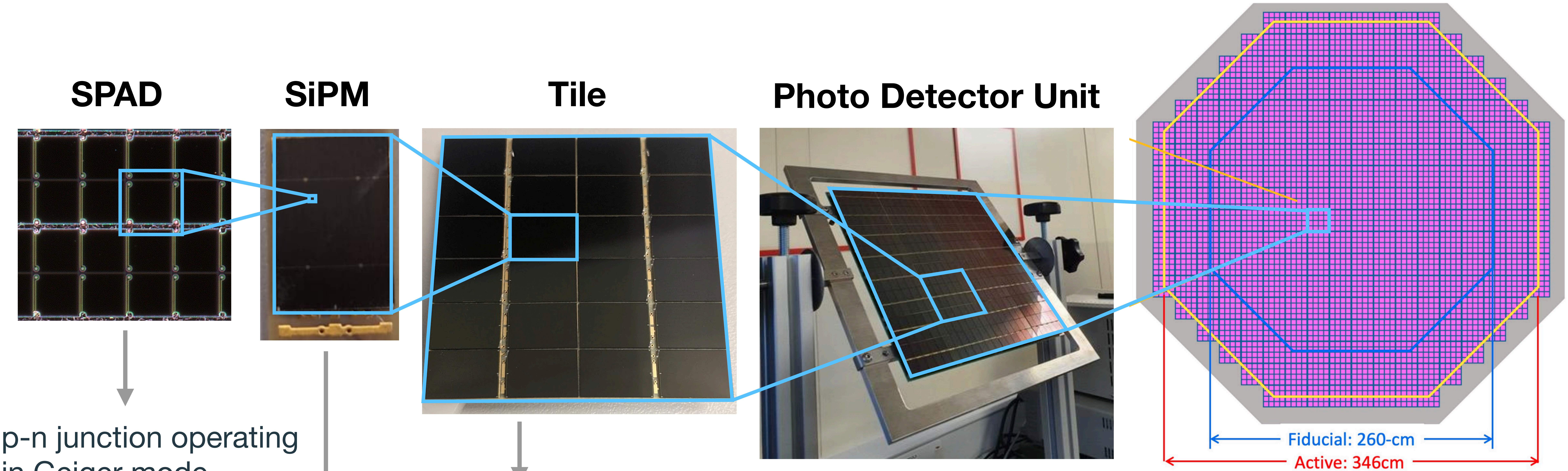
Detector readout: from SiPMs to PDUs

TPC optical plane



p-n junction operating in Geiger mode. Custom technology developed with FBK.

1 SiPM = ~94,000 SPADs

SiPM area: 8 x 12 mm^2

1 tile = 24 SiPMs

$\sum$ 24 SiPM signals = 1 tile channel

Tile area: 5 x 5 cm^2

1 PDU = 16 tiles

$\sum$ 4 tile signals = 1 DAQ channel

Fewer cables = reduced material budget

PDU area: 20 x 20 cm^2

518 PDUs = TPC
120 PDUs = inner veto
32 PDUs = outer veto

DarkSide-20k: TPC

Active UAr mass: 51.1 tonnes
Fiducial UAr mass: 20 tonnes

Dual-phase TPC

Octagonal shape: 3.5 m diameter

Drift length: 348 cm

Drift field: 200 V/cm

Extraction field: 2.8 kV/cm

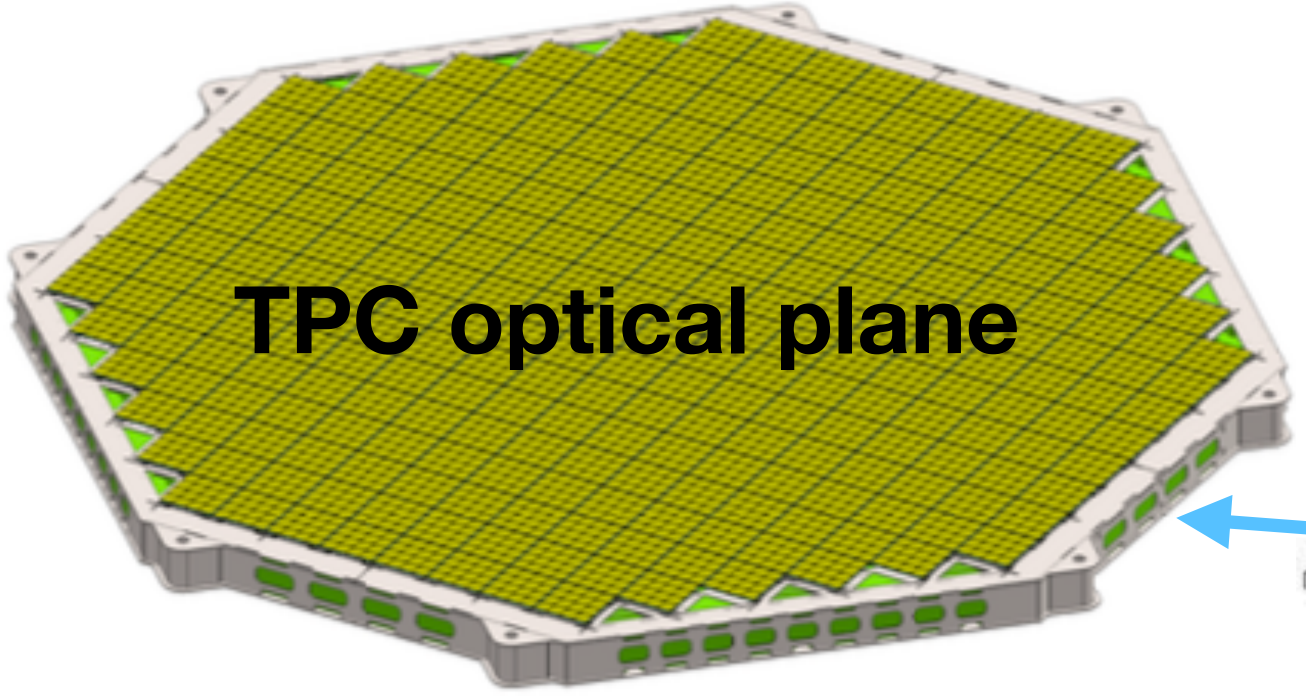
Luminescence field: 4.2 kV/cm

Cathode voltage: -73.38 kV

Spatial resolution: xy < 5 cm, z < 1 mm

ESR reflector & TPB wavelength shifter for increased light yield

Stainless steel wire grid

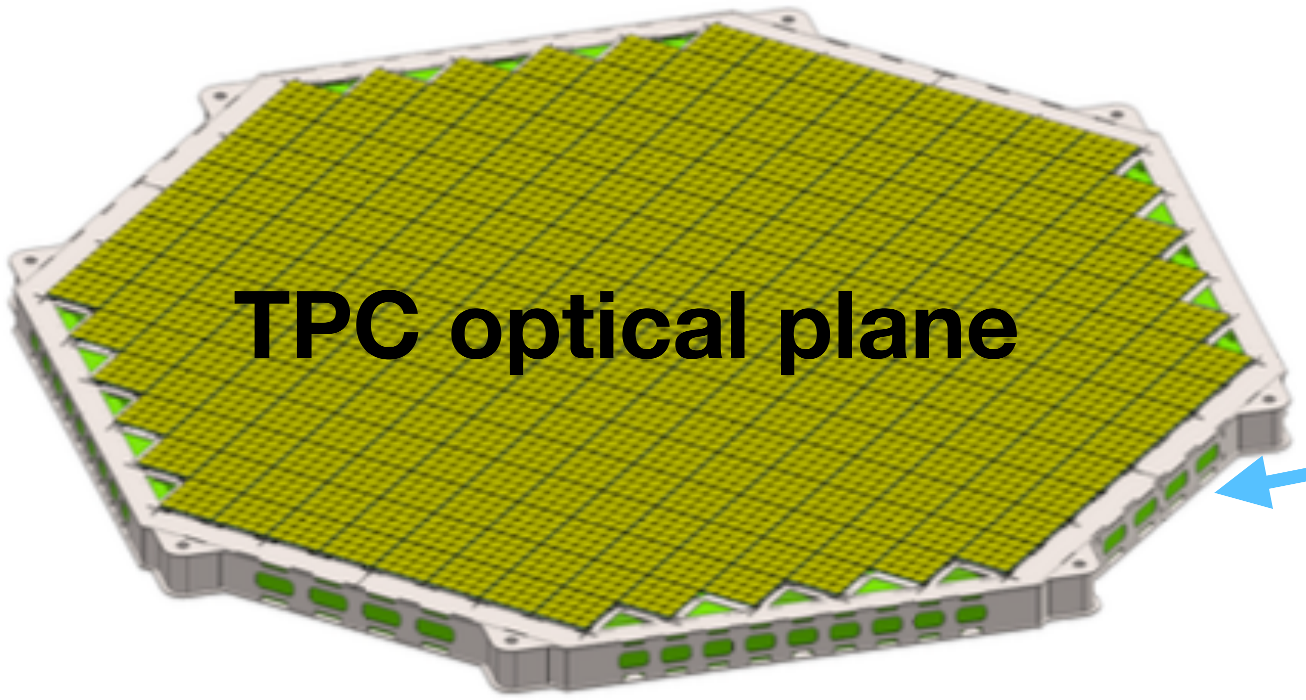


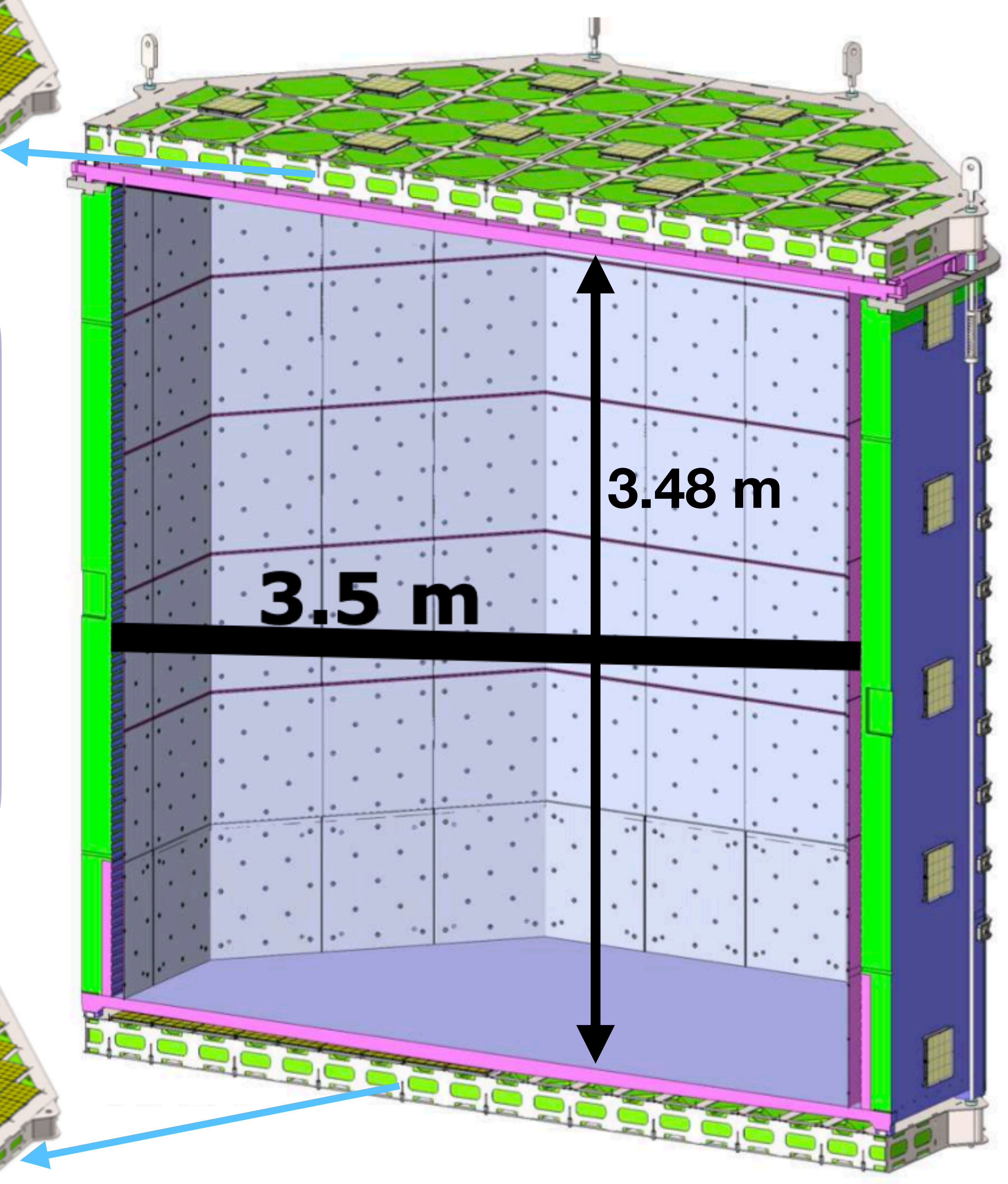
Optical planes

20.8 m^2 photosensor coverage (198,912 total SiPMs: 518 PDUs)

Light yield: 10 PE/keV

S2 yield: > 20 PE/e^-





DarkSide-20k: neutron veto

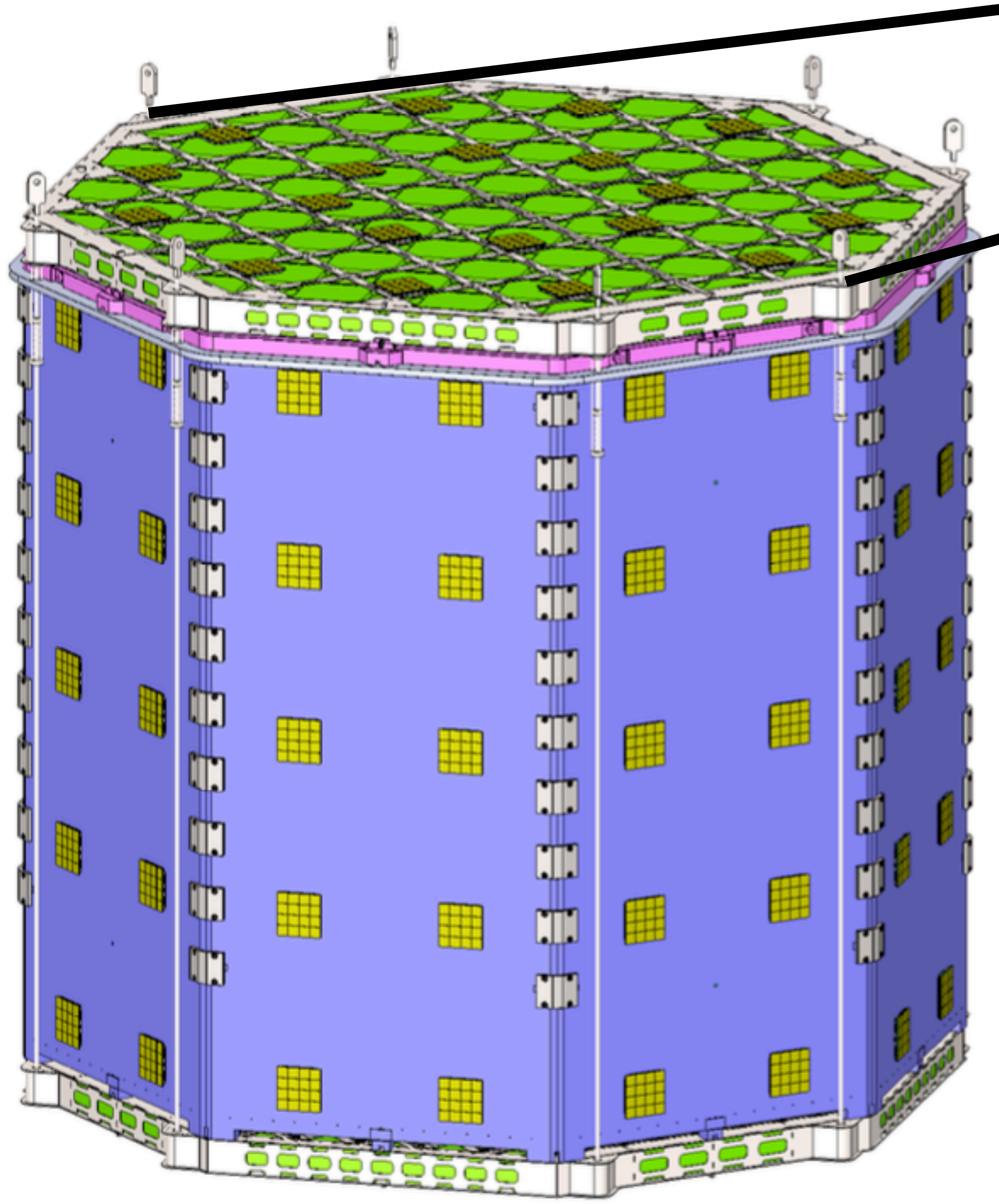
Neutron Veto

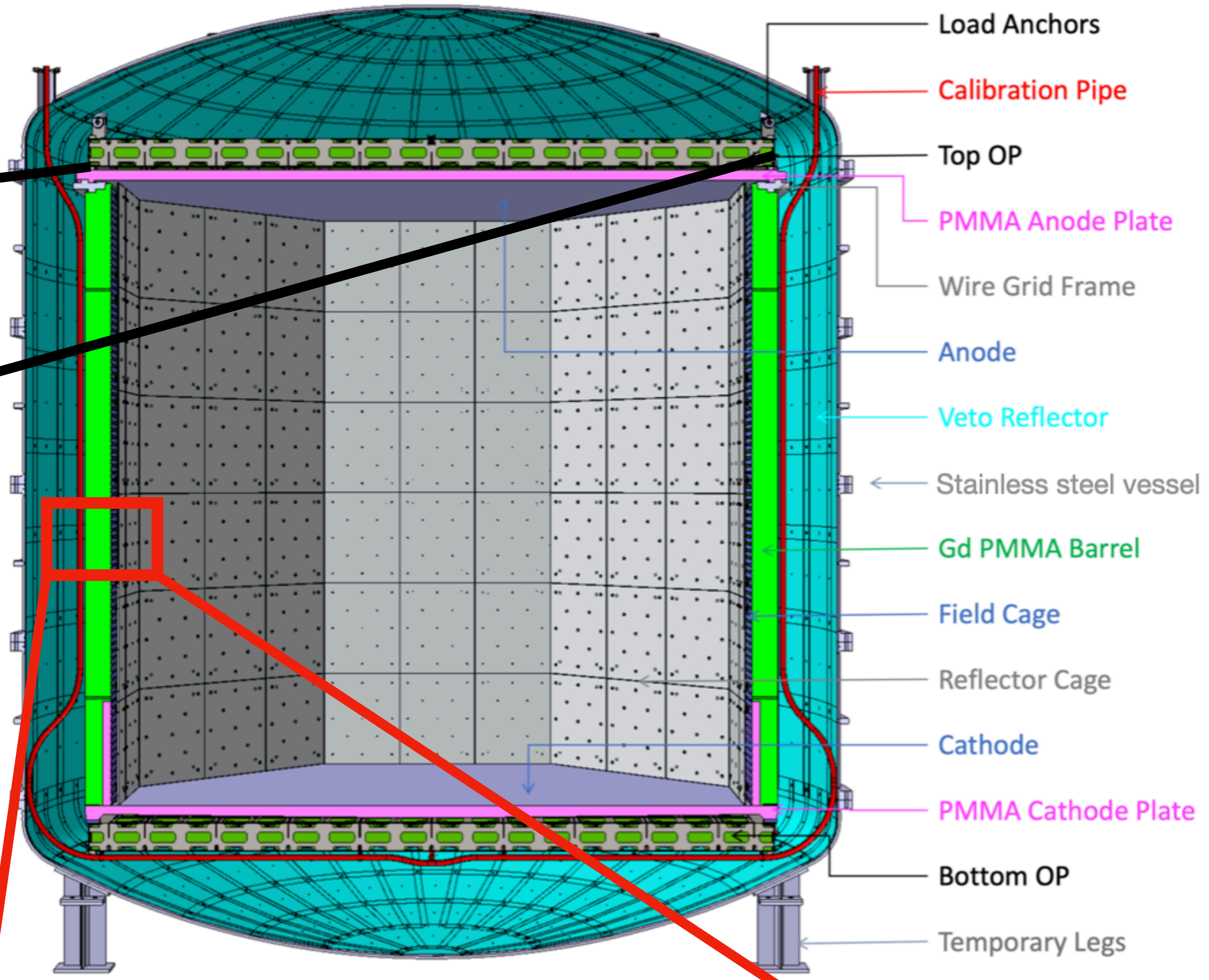
Novel technology of integrated TPC and veto system: 4π acrylic (hydrogen) coverage and 40 cm argon buffer

4.8 m^2 photosensor coverage (120 PDUs) around TPC walls

Light yield: 2 PE/keV

ESR reflector & PEN wavelength shifter for increased light yield

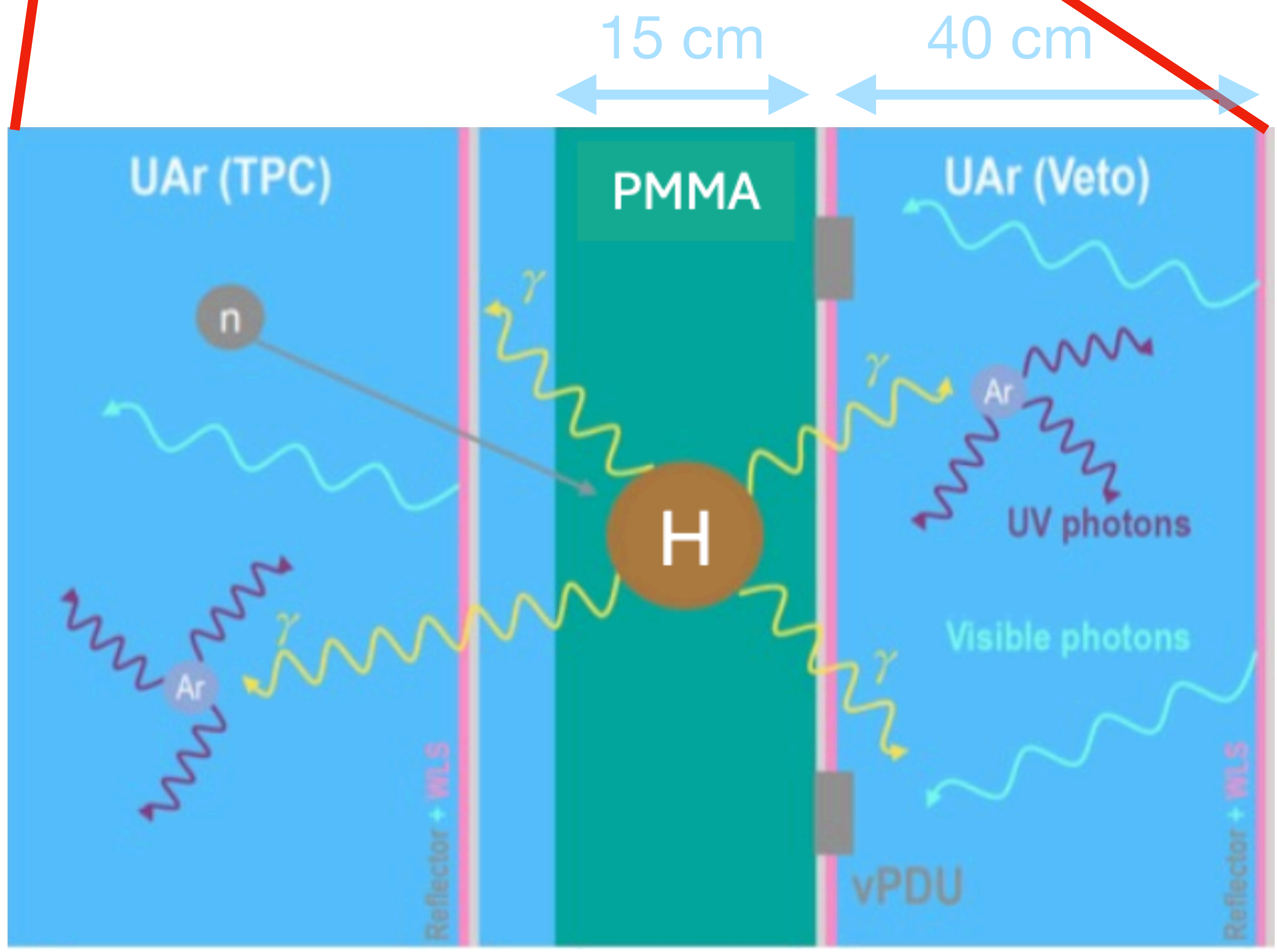




Neutron identification criteria

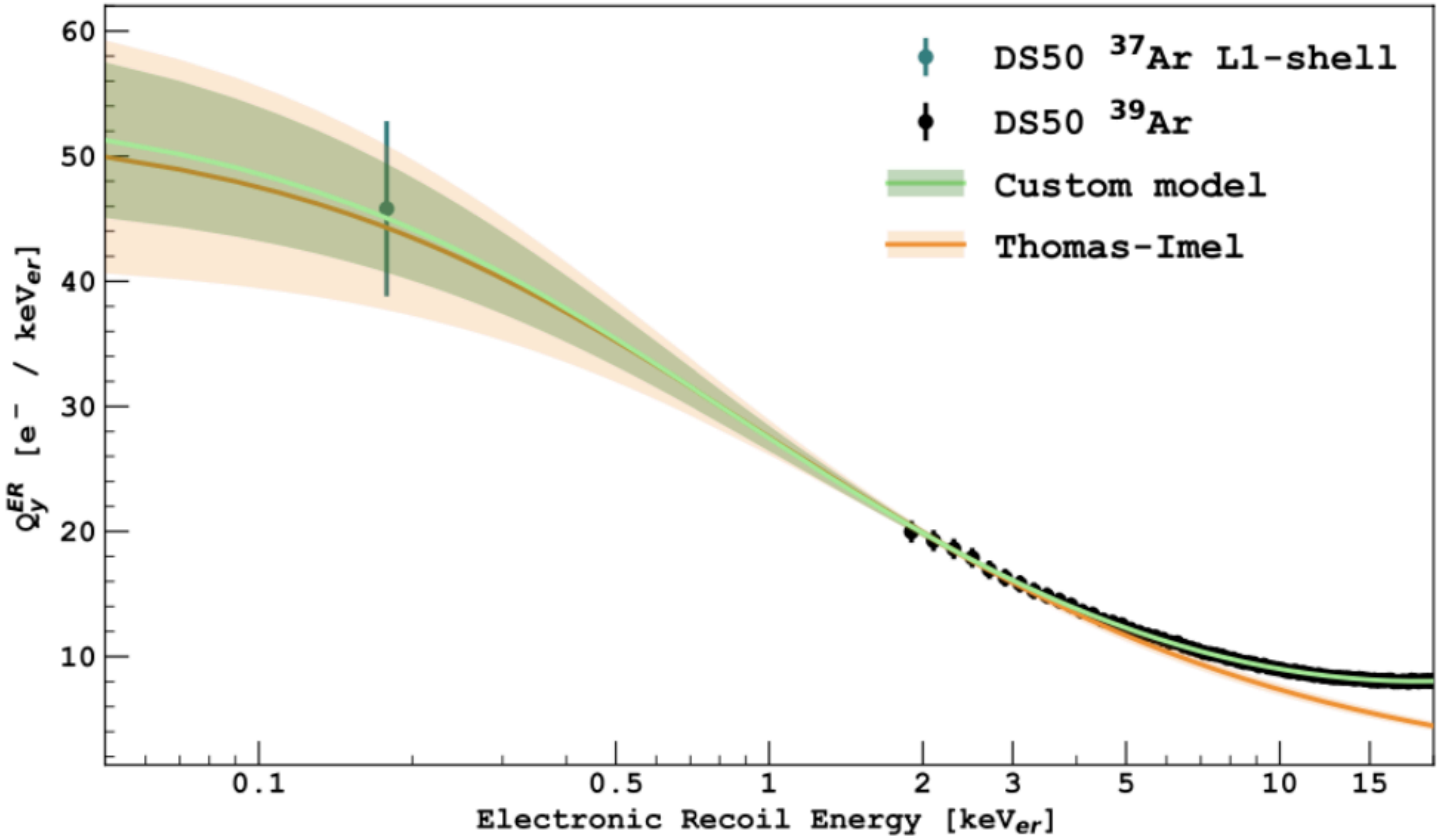
- Single NR: $30 < E_{NR} < 200$ keV
- Radial-z position cuts: FV = 20 tonnes
- $E_{TPC} > 50$ keV, or $E_{Veto} > 200$ keV
- Event window: 800 μs

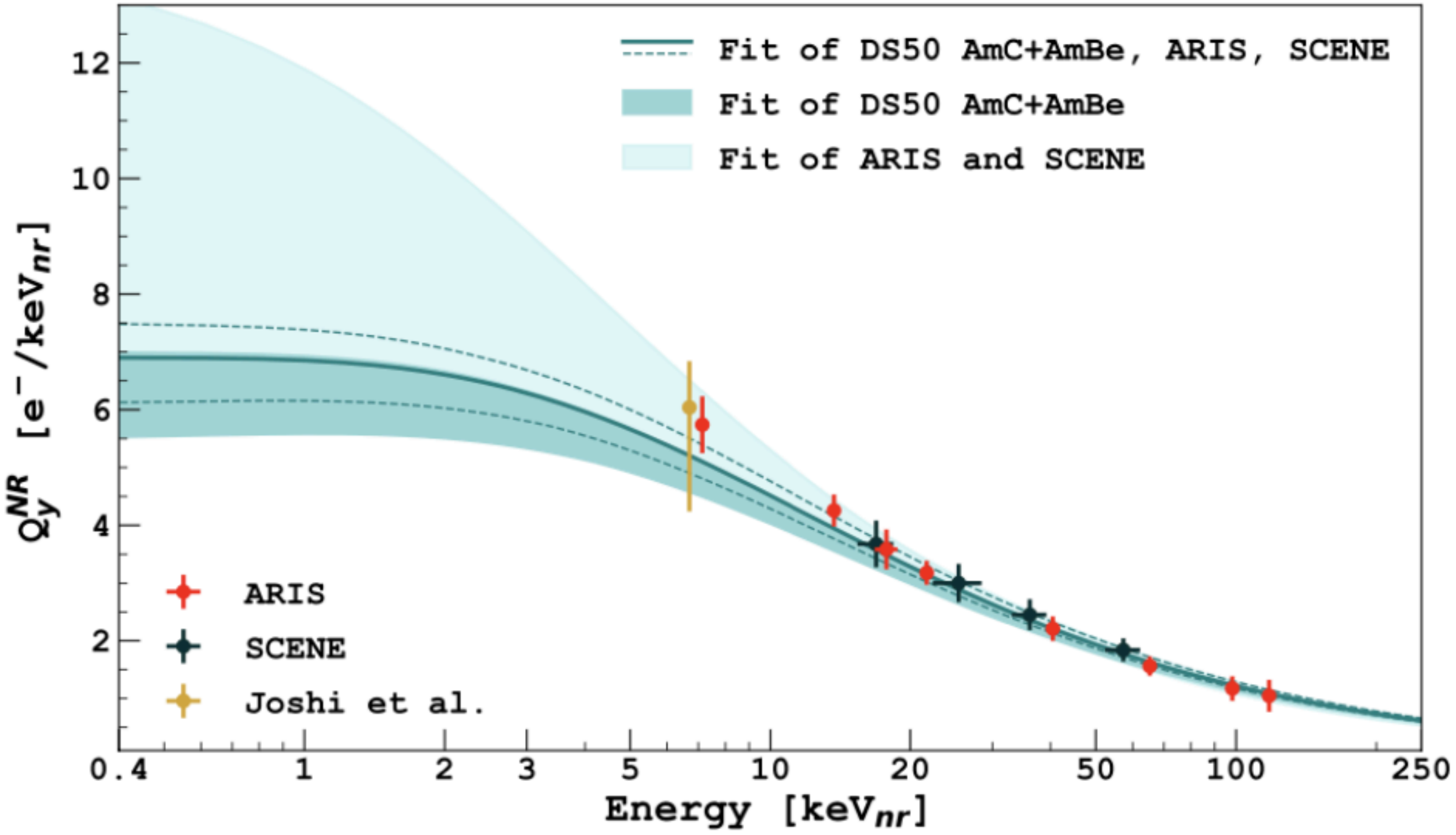
2.1 MeV γ produced by neutron capture on H interact in TPC/veto
- scintillation light detected by photosensors in TPC/veto



< 0.35 WIMP-like neutron events in full 200 tonne year exposure

LAr ionisation response: low energy





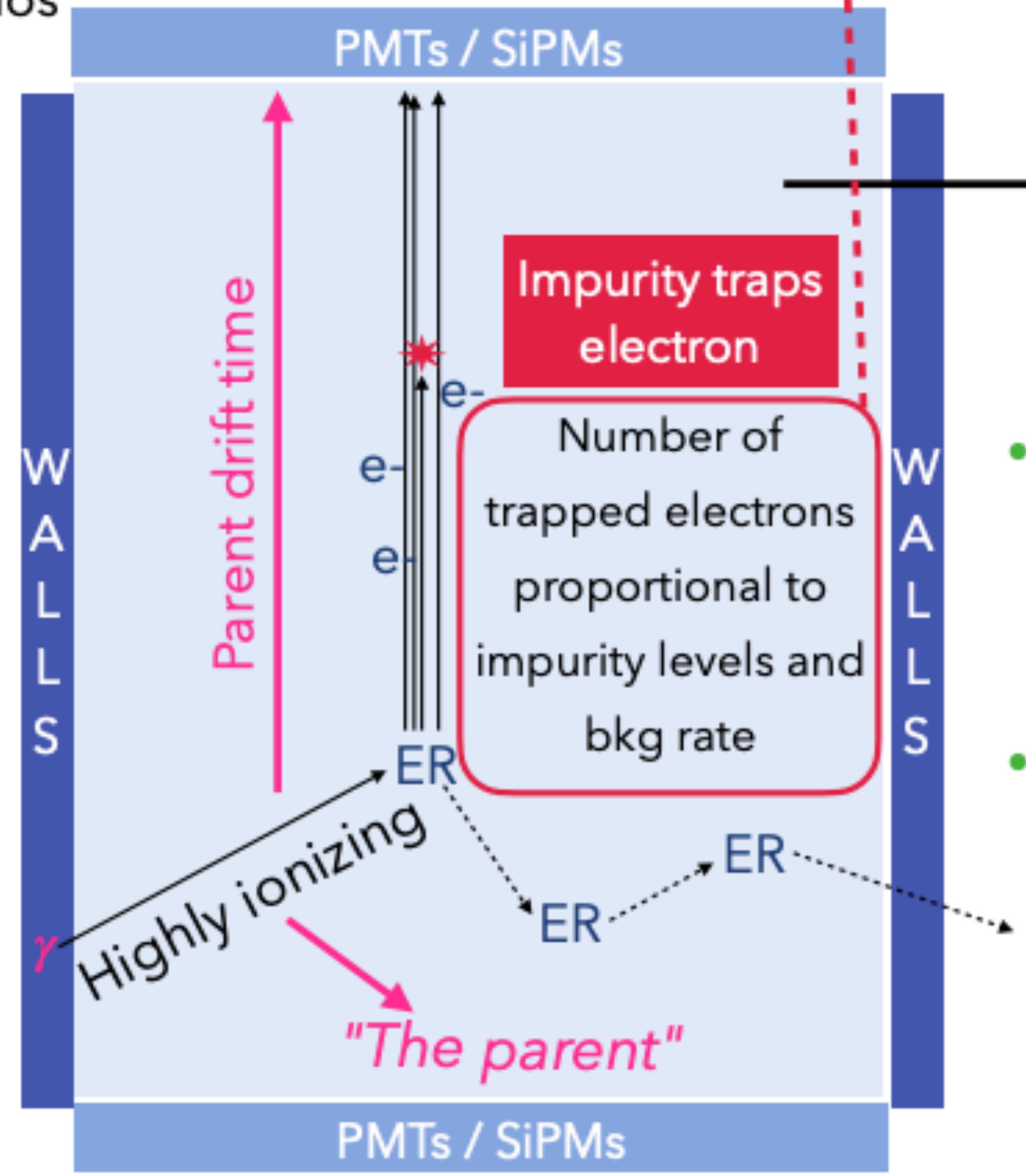
At low energies: limited understanding of quenching, recombination, and ionisation processes which results in large uncertainties in LAr ionisation response.

Suppressing QF: non-physical but more conservative.

Including QF: binomial model.

Spurious electron background

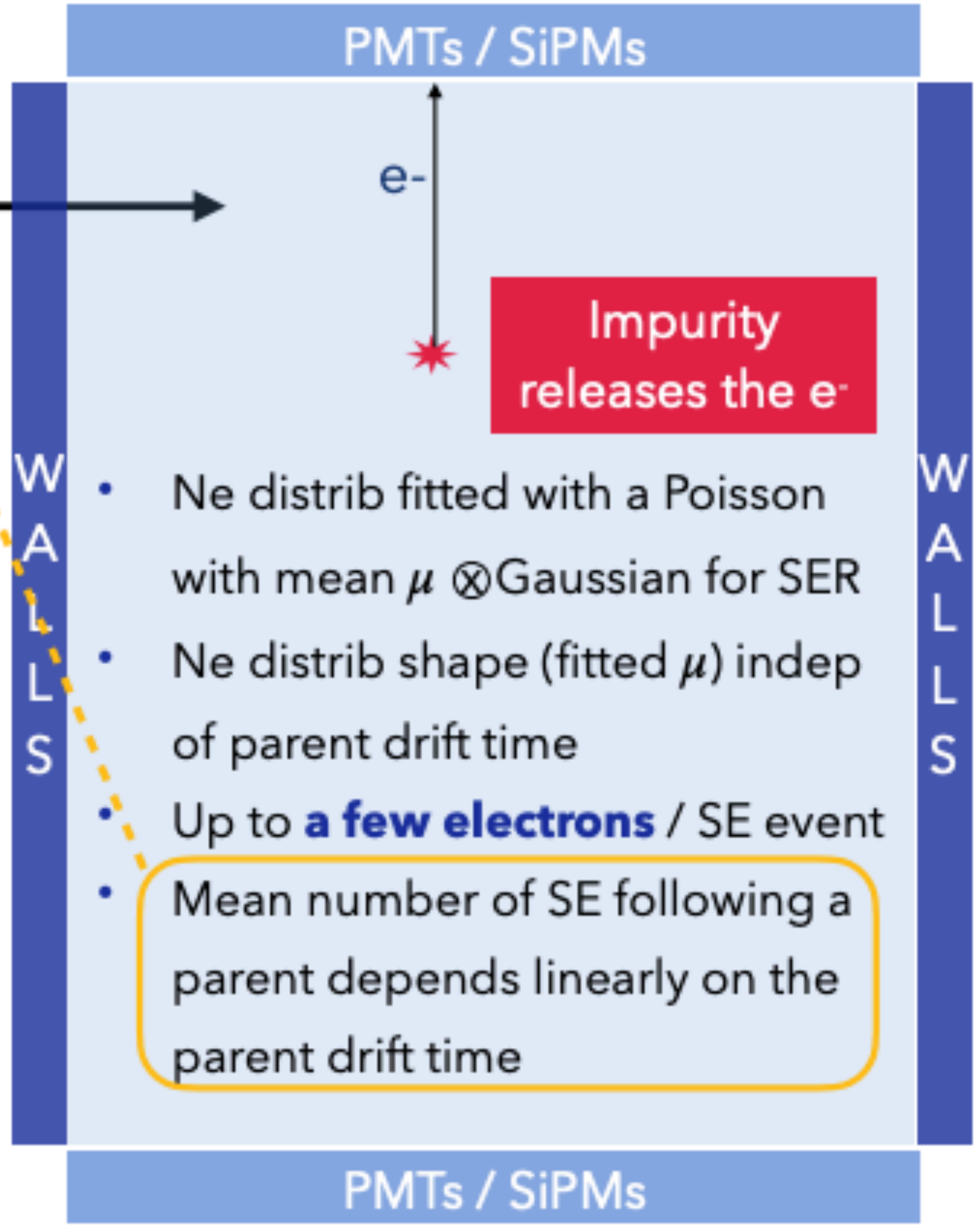
- **Extrapolated** from DarkSide-50 data
- **DS20k rate** = DS50 rate scaled with bkg rate and max. drift time ratios



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



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Low mass analysis: systematic uncertainties

	Source uncertainty	Affected components
Amplitude	5% on the exposure	All
	15% on ^{39}Ar activity	^{39}Ar
	15% on ^{85}Kr activity	^{85}Kr
	20% on SE normalization	SE
	10% on activity from PDMs	PDMs
	10% on activity from the vessel	Vessel
	10% on activity from the TPC	TPC
	10% on neutrinos normalization	Neutrinos
Shape	atomic exchange and screening	^{39}Ar
	atomic exchange and screening	^{85}Kr
	1% on the ^{39}Ar-decay *Q*-value	^{39}Ar
	0.4% on the ^{85}Kr-decay *Q*-value	^{85}Kr
	SE modelling	SE
	ER ionization response	All backgrounds but CEνNS, SE
	NR ionization response	WIMP, CEνNS

Low mass analysis: dark matter signal models

Rates

LDM:

e^- in a given orbital (n, l)

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

ALPs:

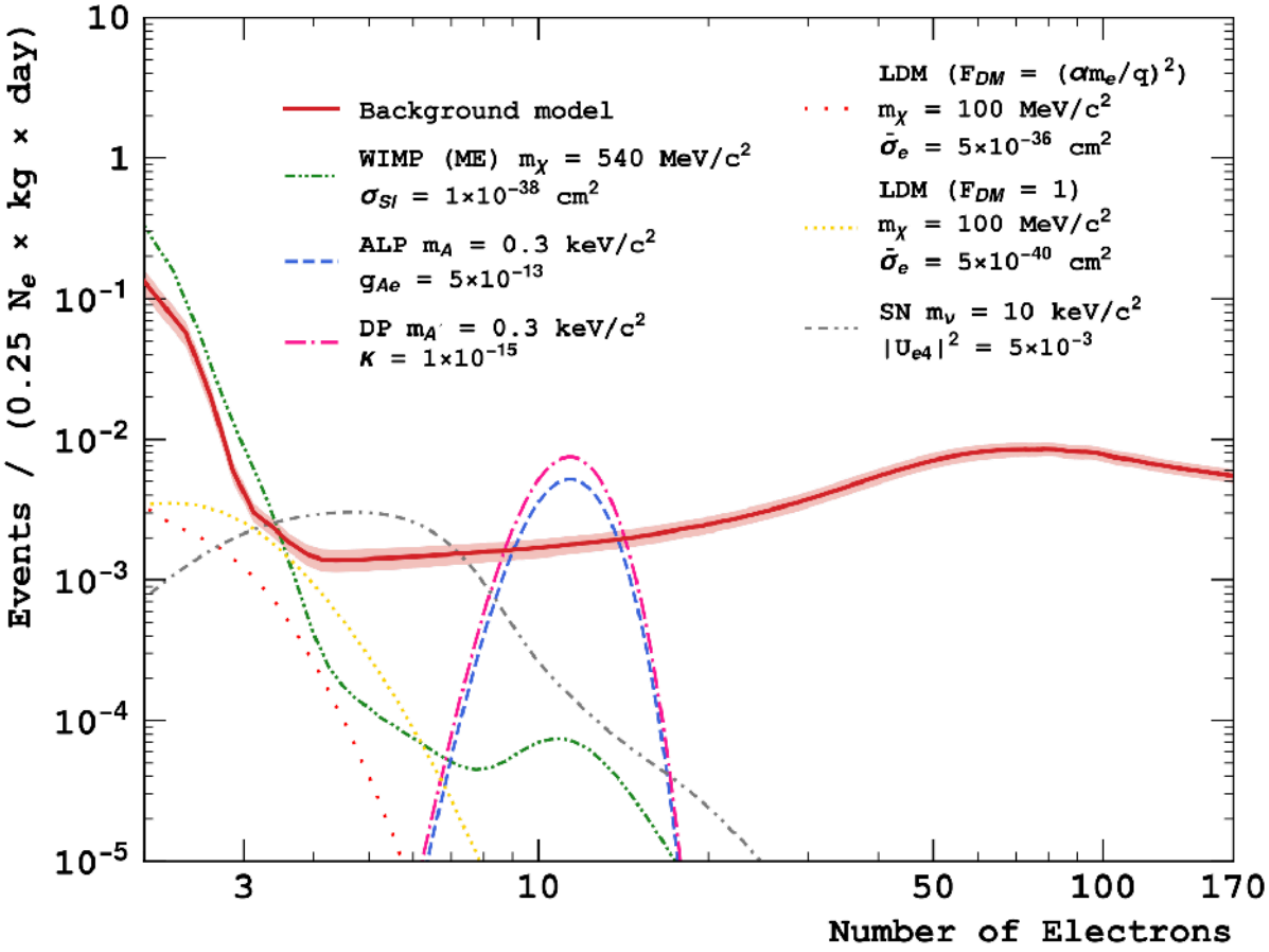
$$R = N_T \frac{\rho_{DM}}{m_A} \times \frac{3m_A^2 g_{Ae}^2}{16\pi\alpha m_e^2} \sigma_{pe}(m_A c^2) c$$

DP:

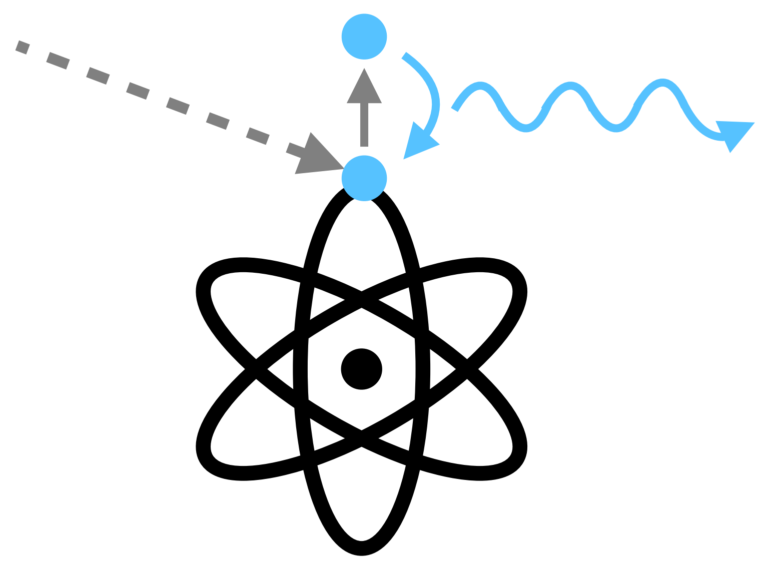
$$R = N_T \frac{\rho_{DM}}{m_{A'}} \times \kappa^2 \sigma_{pe}(m_{A'} c^2) c$$

Sterile neutrinos:

$$\frac{dR}{dE_{er}} = N_T \frac{\rho_{DM}}{m_\nu} \times \sum_{nl} 2(2l+1) \int \frac{d\sigma_{nl}}{dE_{er}} \left(v, m_\nu, |U_{e4}|^2\right) f(v)\ v\ dv$$

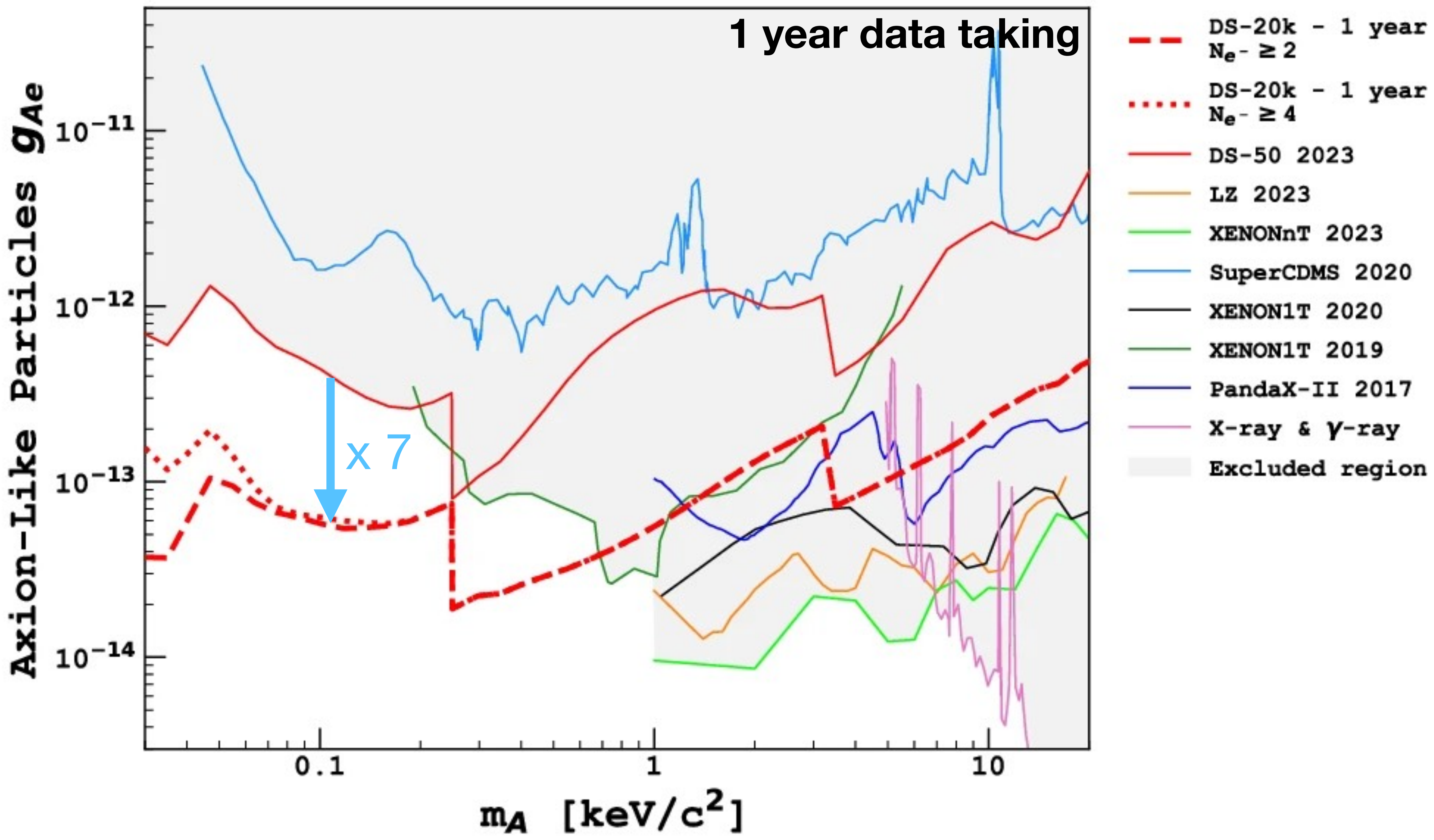


Low mass analysis: light dark matter sensitivity

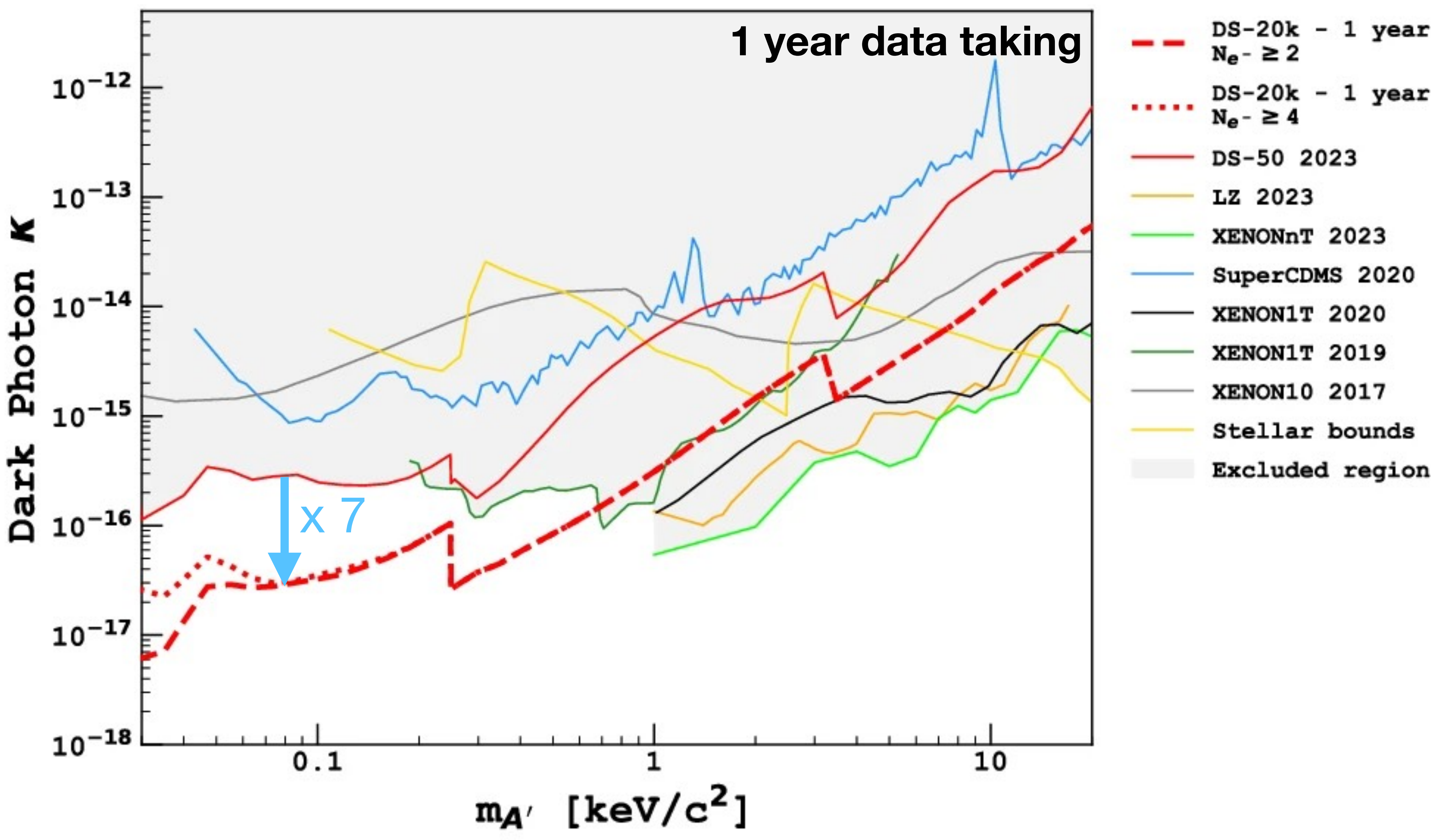


Absorption by shell electrons of axion-like particles or vector-boson DM
—> monoenergetic signal at particle's rest mass

ALP: pseudo scalar particle
g_{A_e}: ALP-electron coupling



DP: vector-boson particle
κ: kinetic mixing between DP and SM photons



~5x improvement over current experiments

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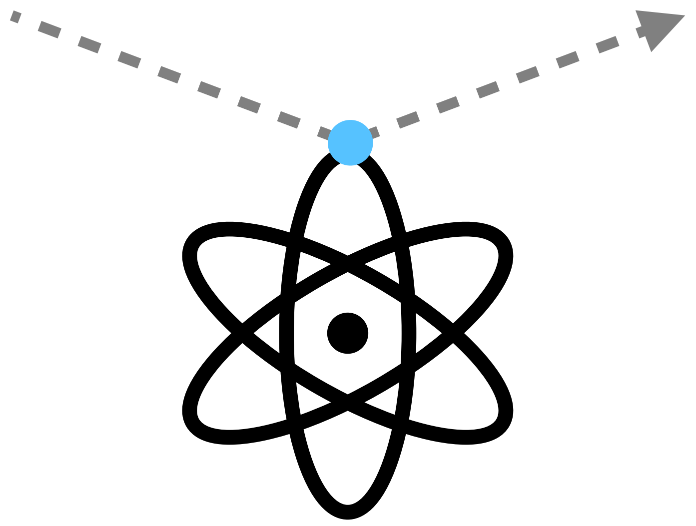
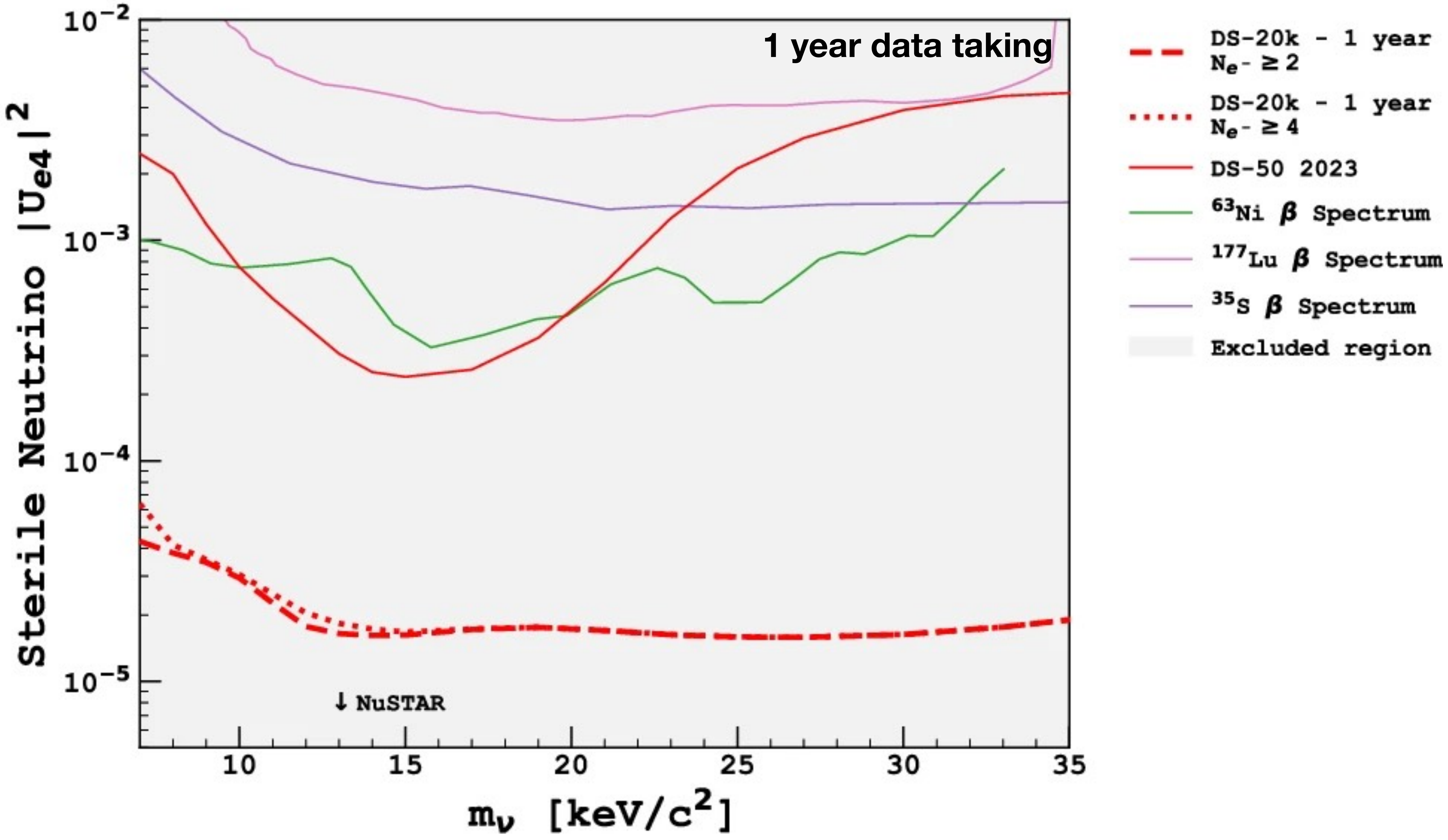
Low mass analysis: light dark matter sensitivity



Inelastic scatter of sterile νs from bound electrons

Possible mixing with active neutrinos
—> PMNS-like matrix element

Best direct limits in 1 year but phase space already rejected by NuSTAR indirect measurements



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Supernova ν: sensitivity

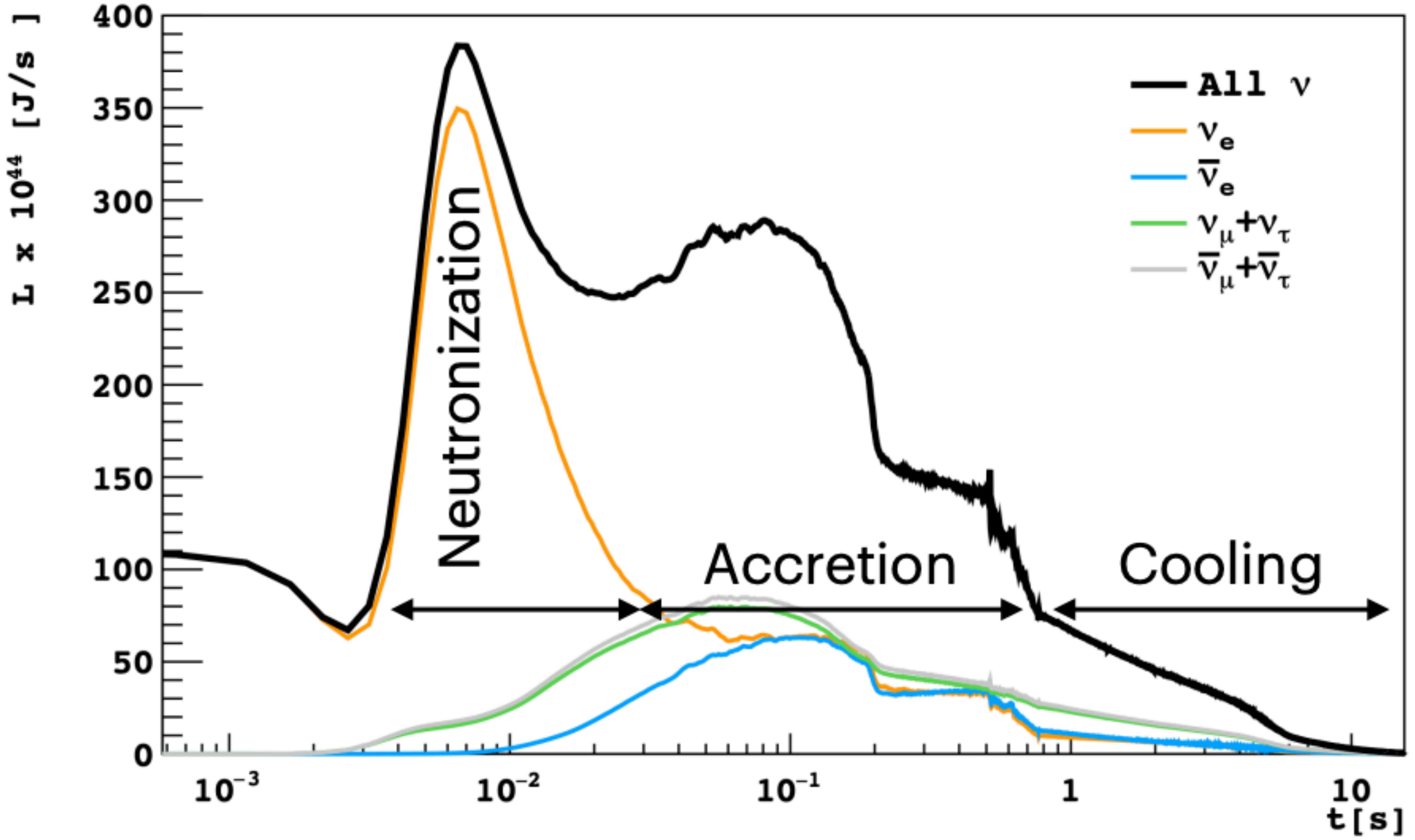
Supernovae can provide constraints on neutrino absolute mass, and mass ordering

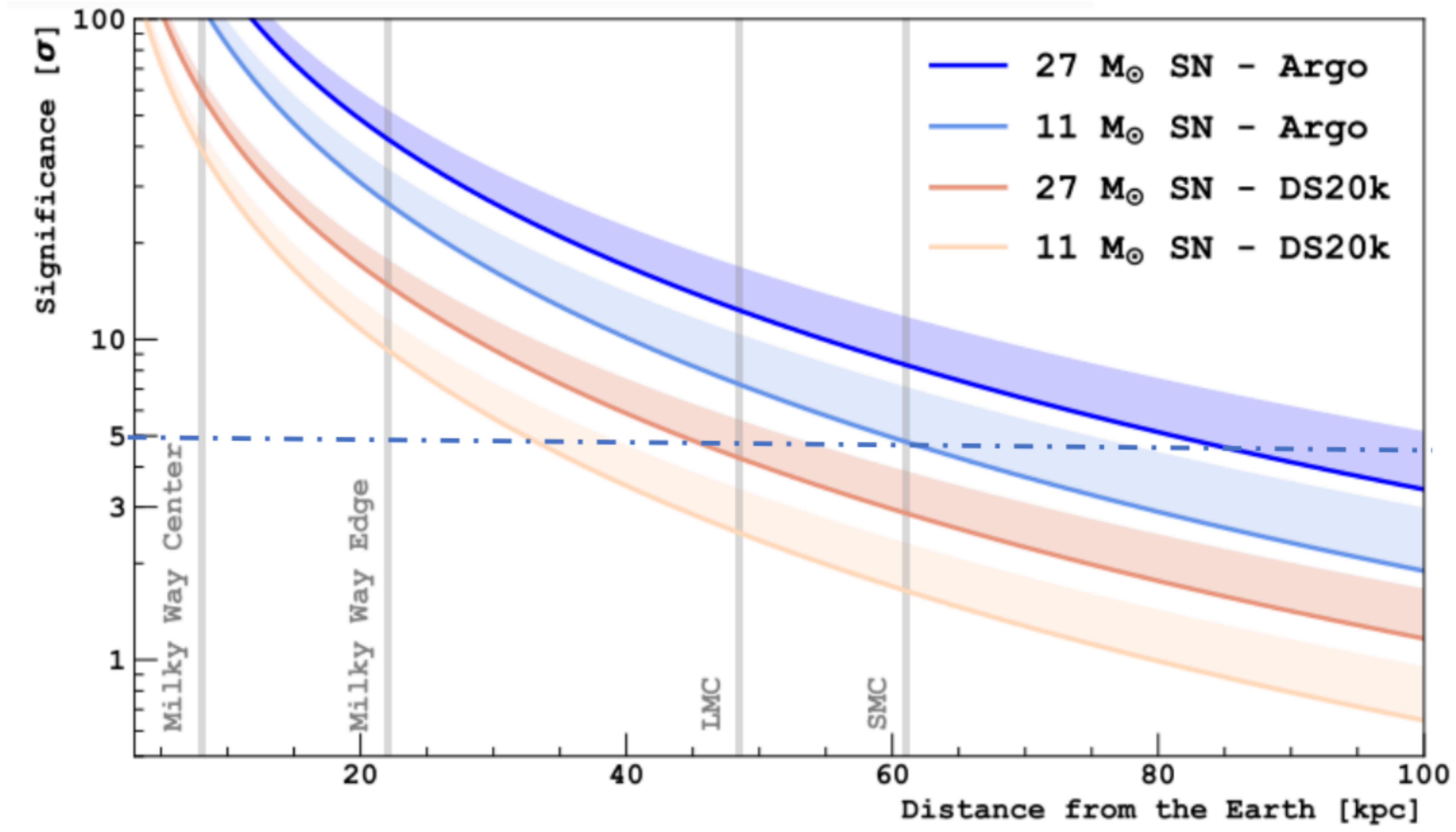
Water Cherenkov and scintillator detectors are most sensitive to $\bar{\nu}_e$ inverse beta decay and ν_e elastic scattering

- DUNE: mostly sensitive to ν_e via charge current interaction

DS20k: sensitive to all flavour (anti)neutrinos via CEνNS

- S2 only analysis
- Inferred background from DS-50
- Potential to discover supernova bursts throughout our galaxy





[JCAP 03, 043 (2021)]