SOUP 2024

NOBLE LIQUID DETECTORS, PART 2

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CONTENTS, PART 2

- Applications to direct dark matter detection and experiments
    - Brief review of direct detection principles
    - Argon DM detectors: ArDM, Darkside-50, DEAP-3600, DarkSide-20k
    - Xenon DM detectors: XMASS, XENON, LZ, PandaX, DARWIN/XLZD
- Applications to neutrino physics and experiments
    - Brief motivation and open questions in neutrino physics
    - DUNE (LAr)
    - EXO-200, nEXO (LXe)
- Summary

Slides courtesy of L. Baudis and R. Calabrese

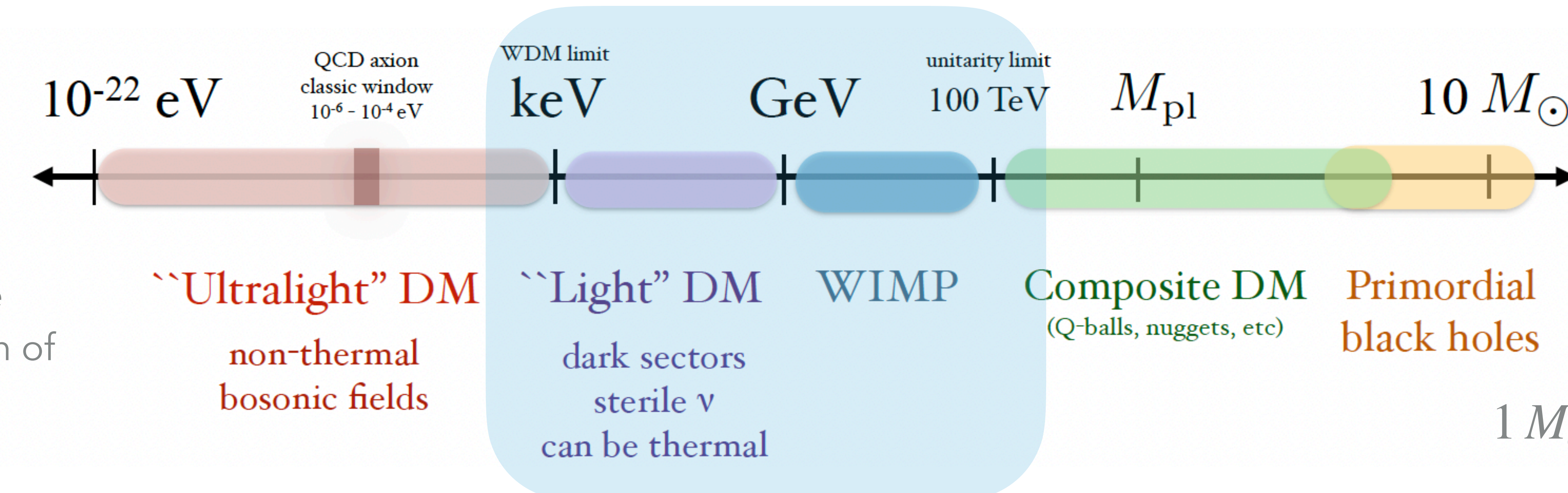
NL DETECTORS

DARK MATTER

WHAT IS DARK MATTER?

A spectrum spanning 80 orders of magnitude

(de Broglie wavelength of galaxy)

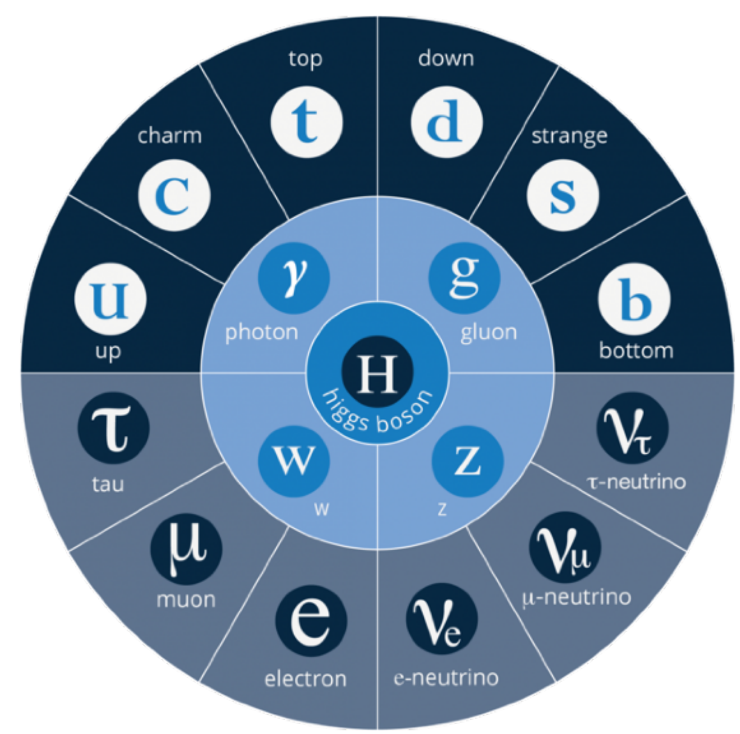


$1\ M_\odot = 10^{57}$ GeV

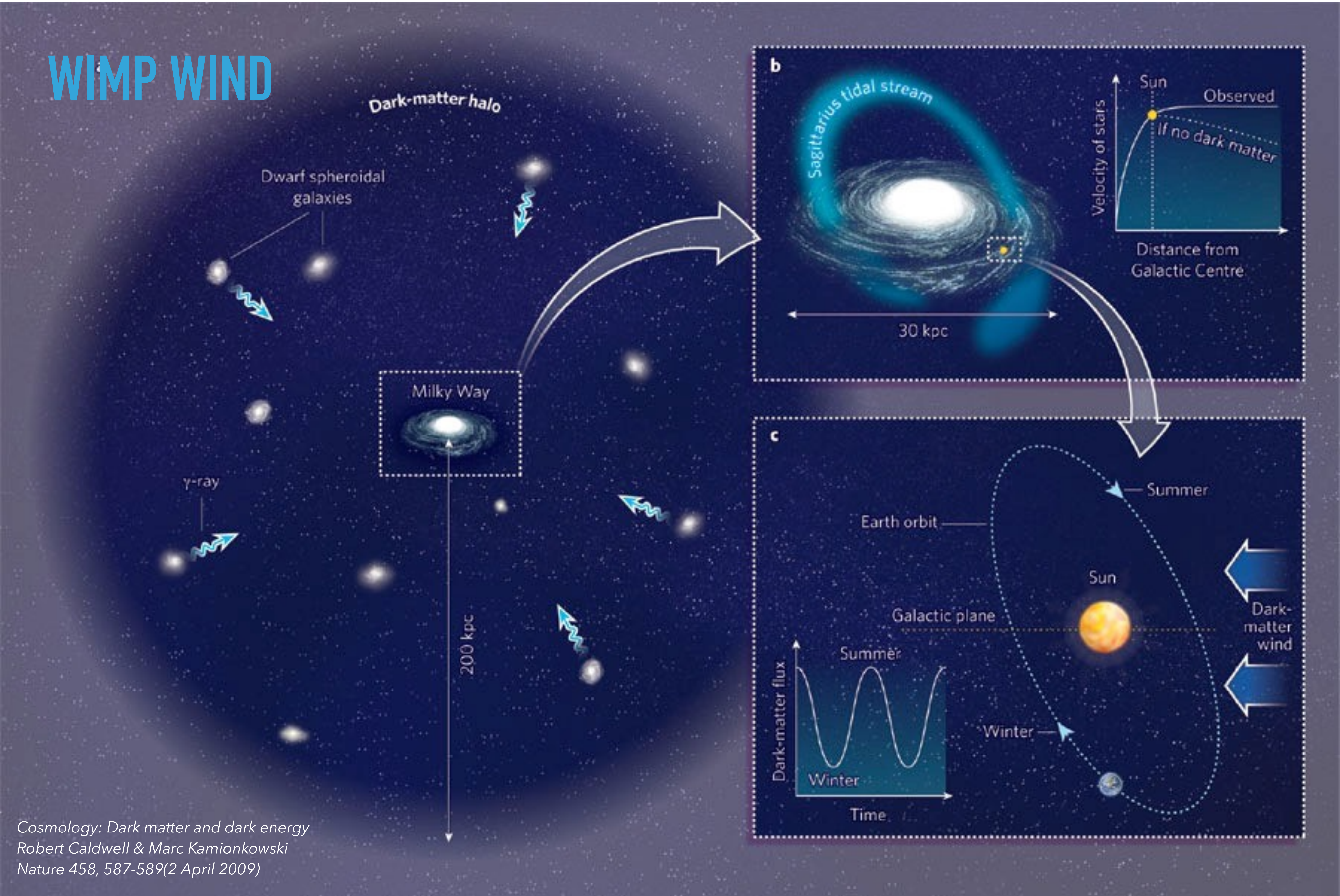
WIMP paradigm: a good place to start looking

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



WIMP WIND



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”

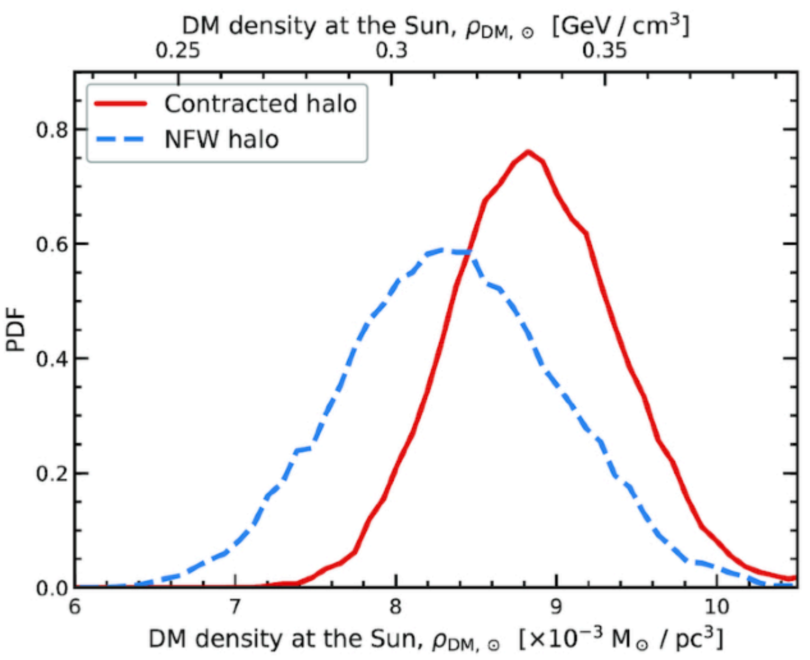
$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \times \int dv\, f(v)\, v\, \frac{d\sigma_\chi}{dE_R}$$

- ρ_χ galactic dark matter halo local density
- v relative velocity wrt terrestrial detector

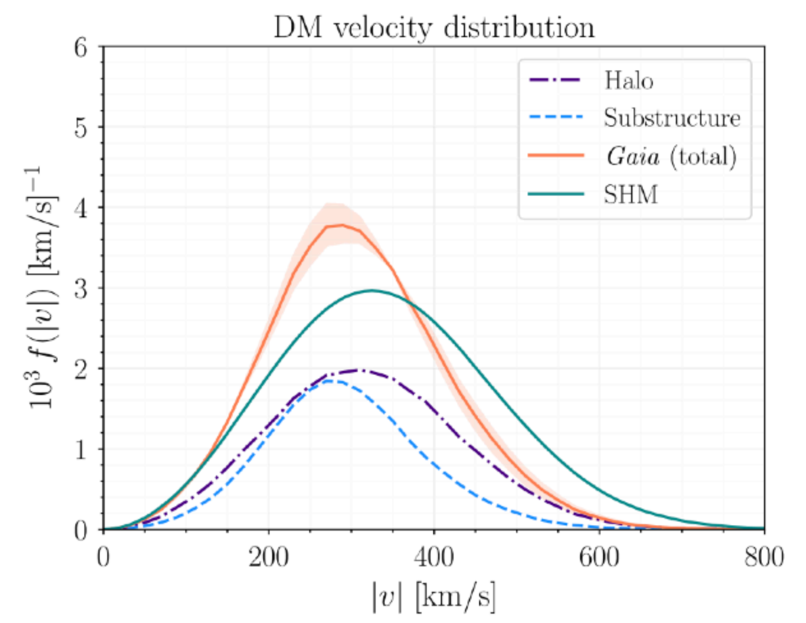
} Astrophysics

- σ_χ elastic scattering off target nuclei → Particle physics

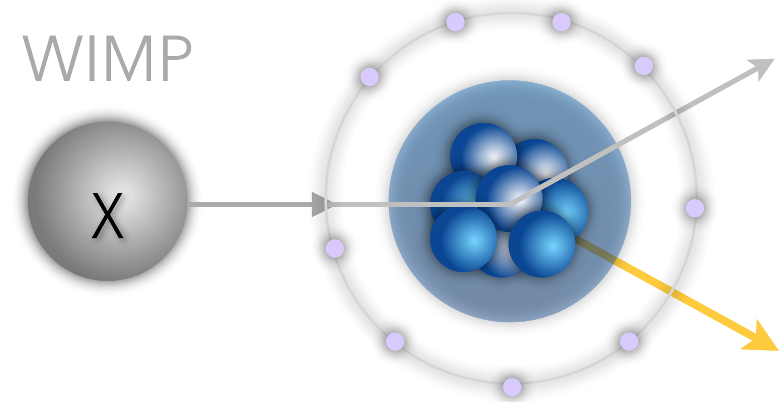
M. Cautun et al, MNRAS 2020



Buch et al, PRD101, 2020



WIMP–NUCLEON SCATTERING



- Non-relativistic scattering $v/c \simeq 10^{-3}$

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

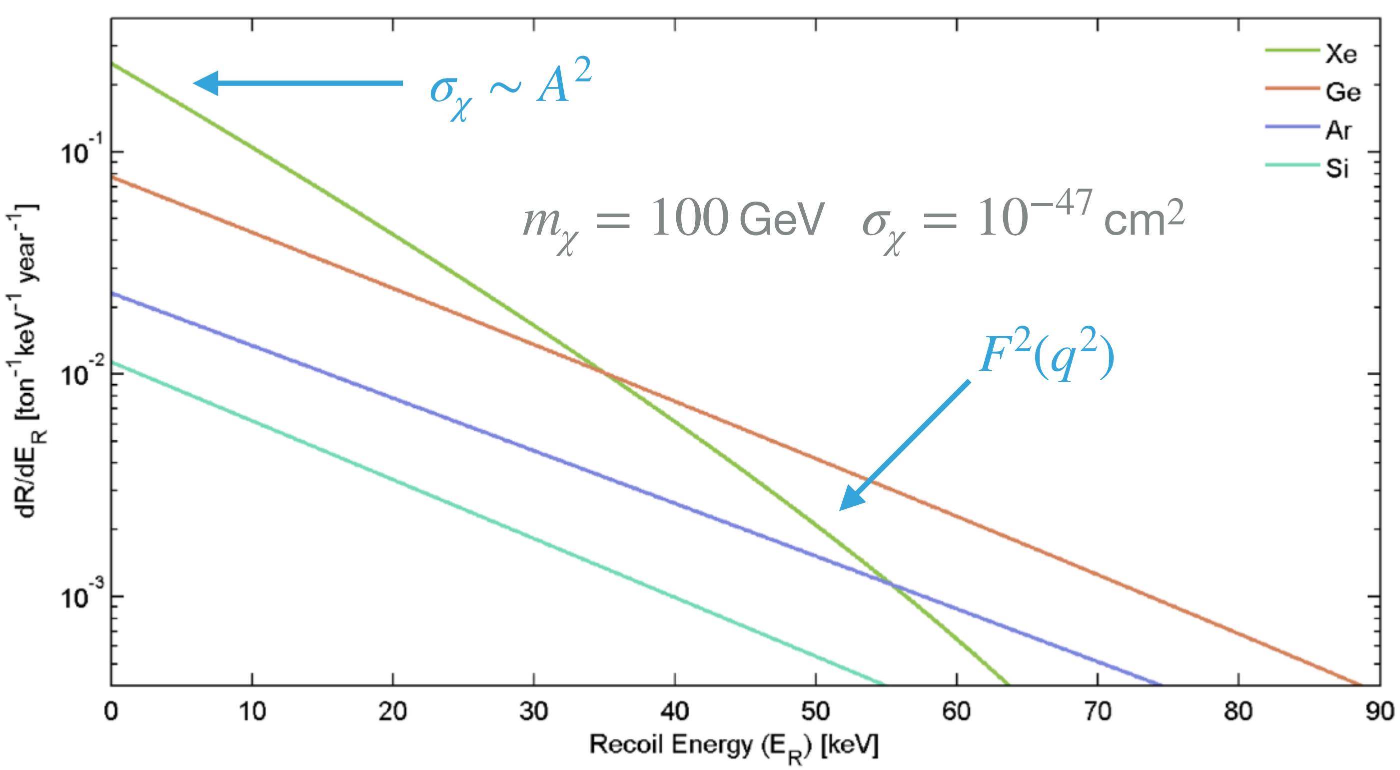
$$\phi = \frac{\rho_\chi}{m_\chi}\langle v \rangle \simeq \frac{10^5}{\text{s cm}^2} \times \left(\frac{100\ \text{GeV}}{m_\chi}\right)$$

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

$$R_0 \simeq 0.135 \cdot \frac{\text{events}}{\text{ton} \cdot \text{yr}} \cdot \frac{1}{A} \cdot \left(\frac{100\ \text{GeV}}{m_\chi}\right) \cdot \left(\frac{\langle \sigma_{\chi-N} \rangle}{10^{-43}\ \text{cm}^2}\right)$$

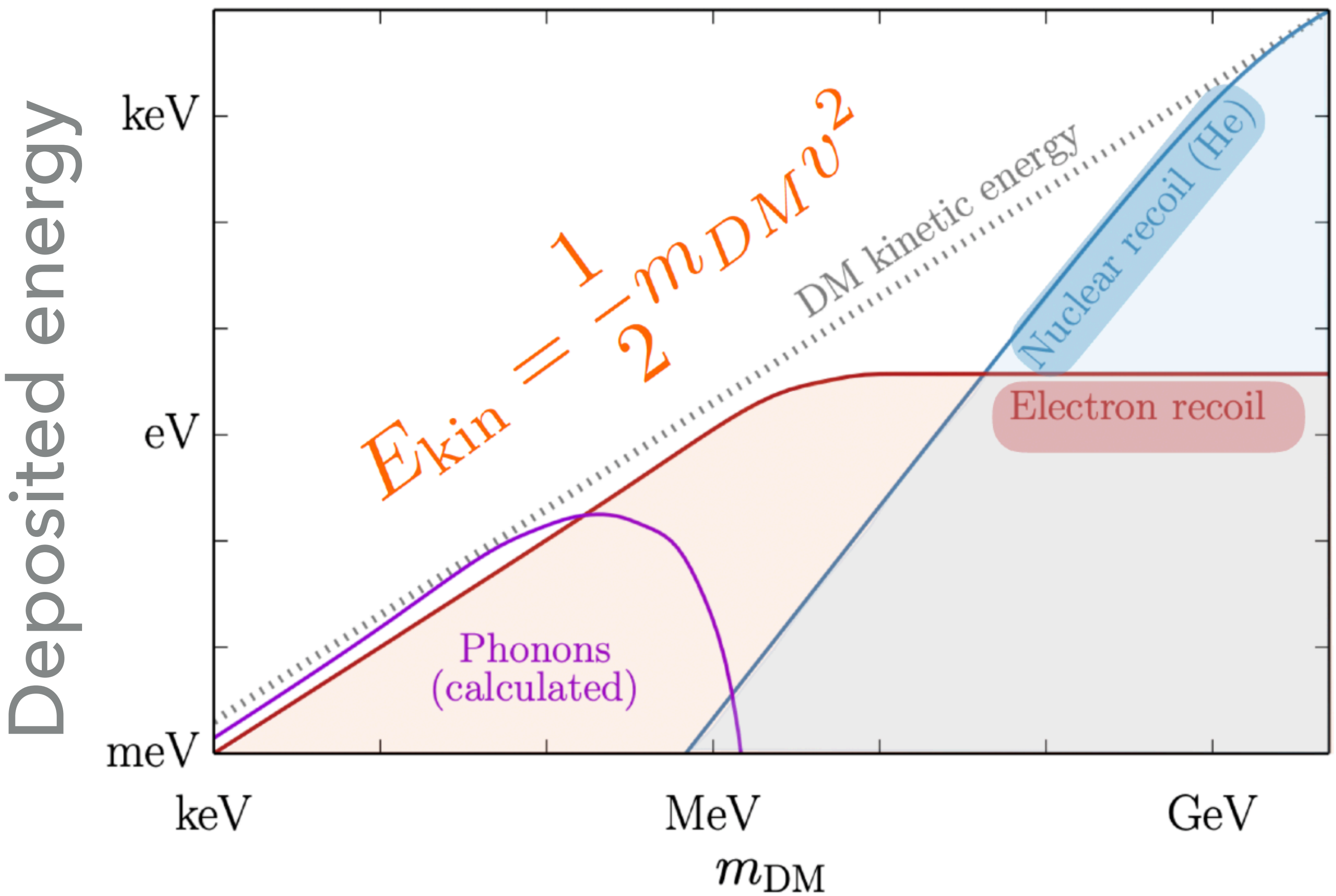
$F^2(q^2)$ Form factor
$S(E_R)$ seasonal modulation
I Interaction type

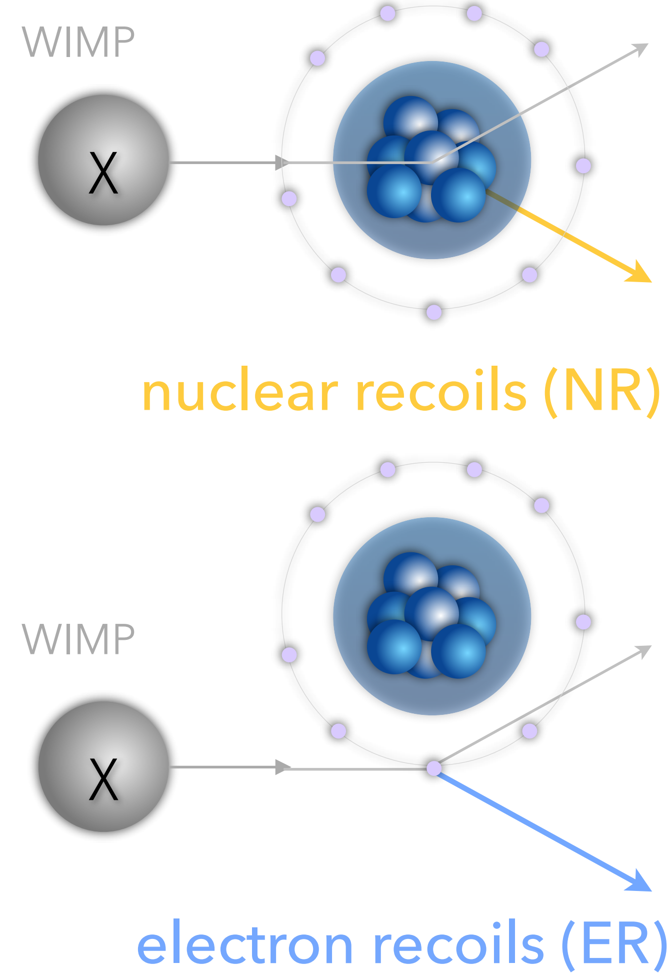
- Contact interaction independent of momentum exchange (nucleus as a particle, with charge and spin)
  - ➡ standard SI/SD description
  - ➡ nuclear form factors generally included



DARK MATTER KINEMATICS

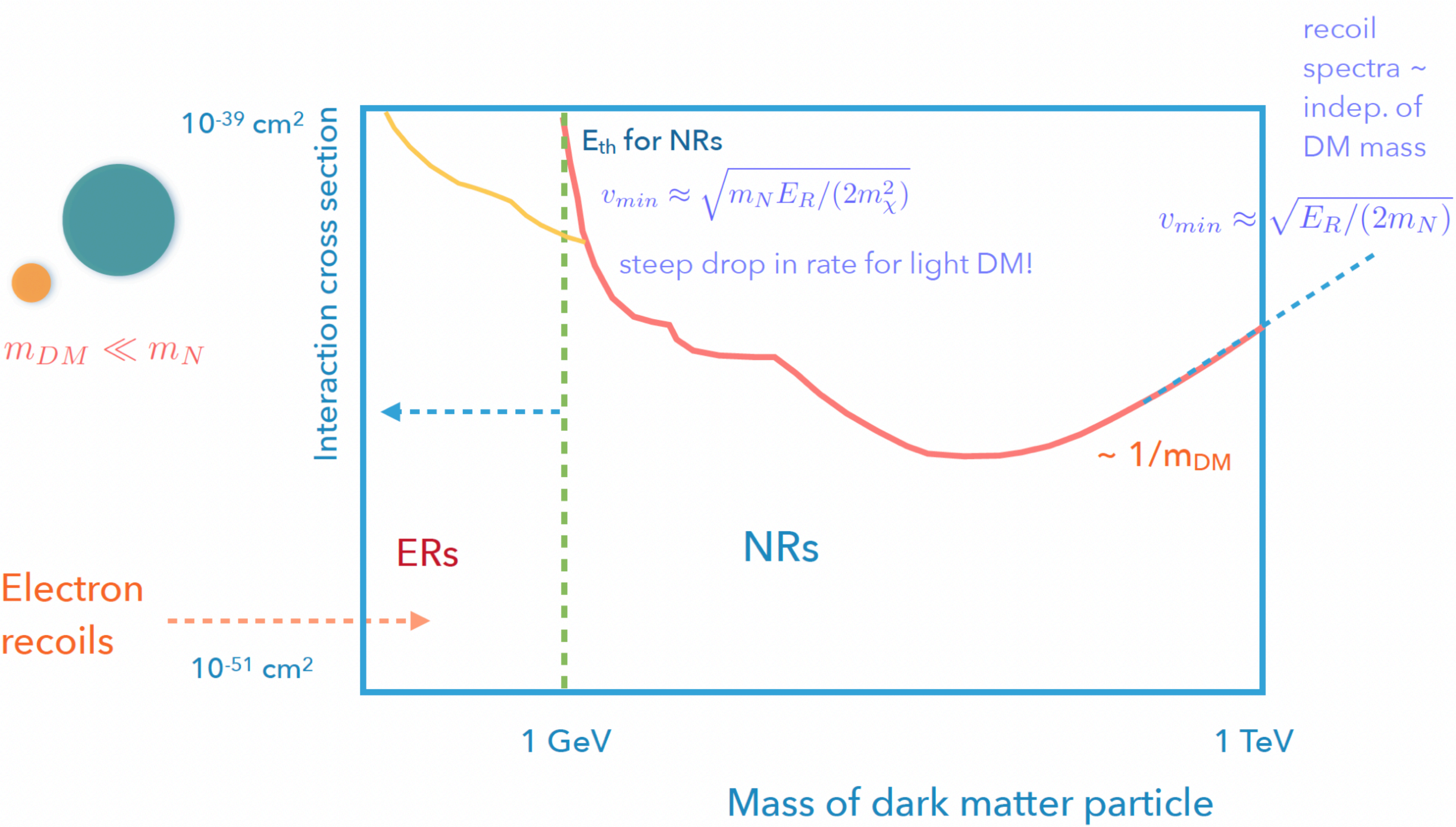
$$E_{\text{kin}} = \frac{1}{2} m_{\text{DM}} v_{\text{DM}}^2 \sim 1 \text{ eV} \left(\frac{m_{\text{DM}}}{1 \text{ MeV}} \right)$$



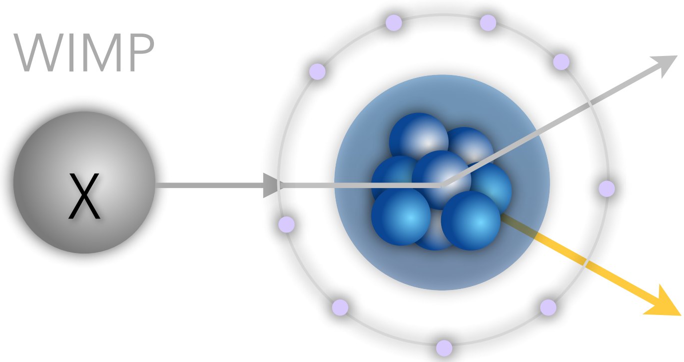


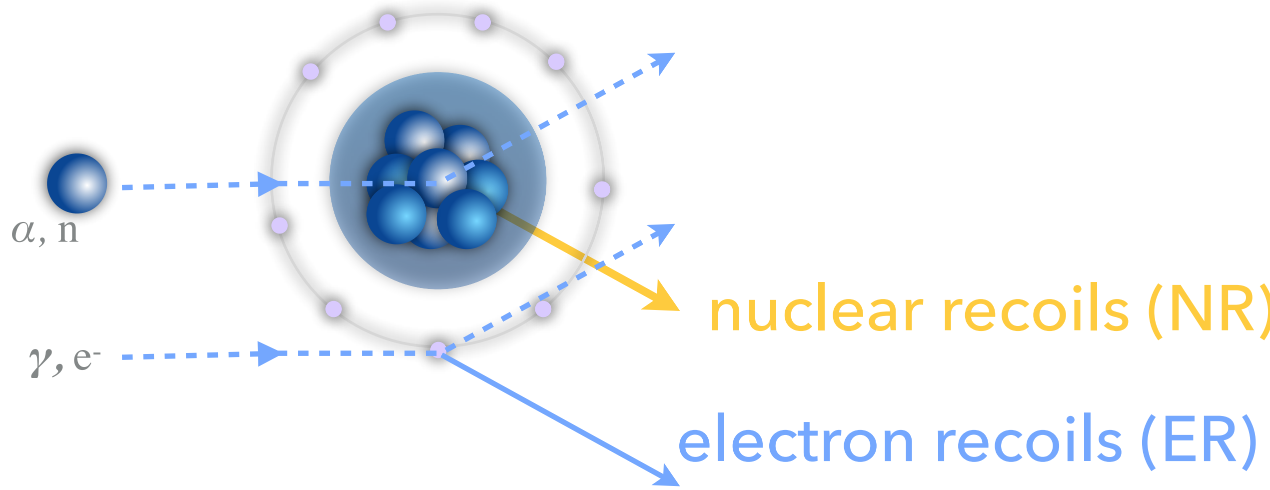
arXiv:1904.07915

INTERACTION CROSS SECTION VS WIMP MASS



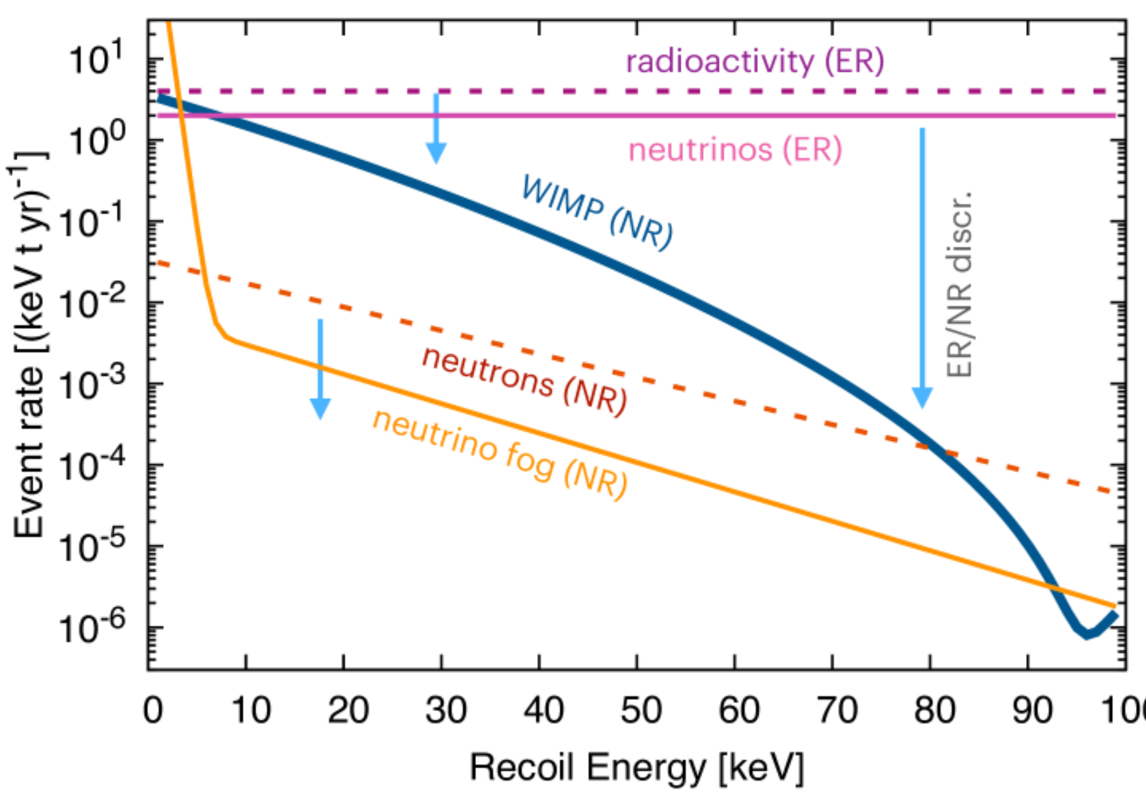
EXPERIMENTAL CHALLENGE





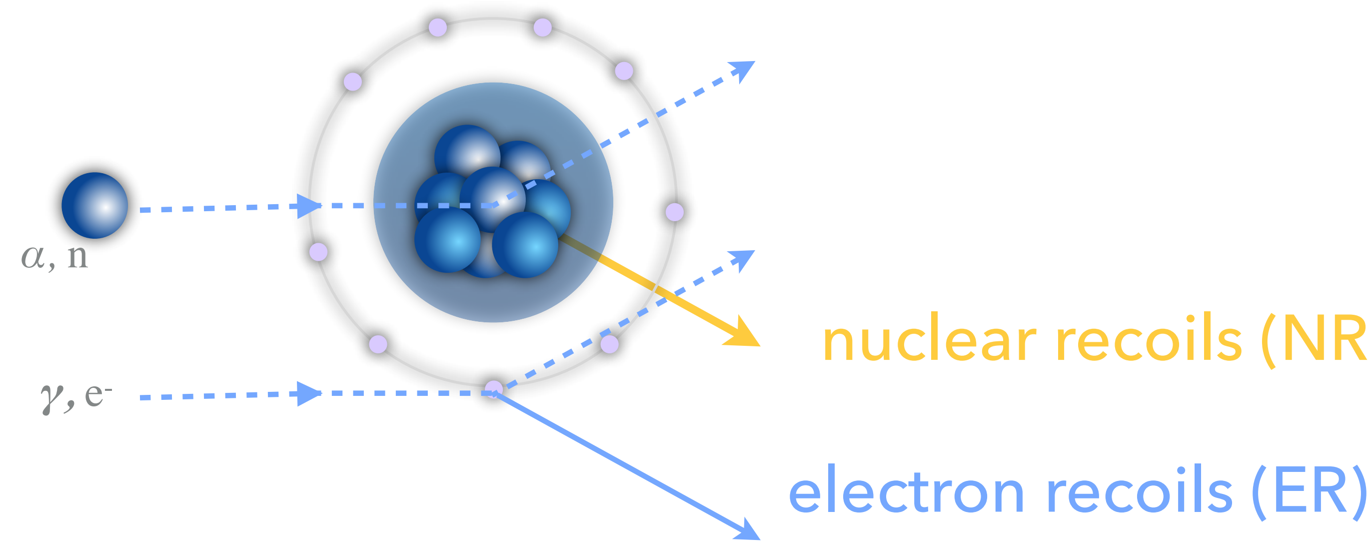
- To observe a signal which is:
  - very small: low recoil energies < 100 keV
  - very rare: <1 event/(kg y) at low masses and < 1 event/(t y) at high masses
  - buried in backgrounds with > 10^6 higher rates:
    - Muon-induced neutrons: NRs
    - Cosmogenic activation of materials/targets: ERs
   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

arXiv:2404.19524v1

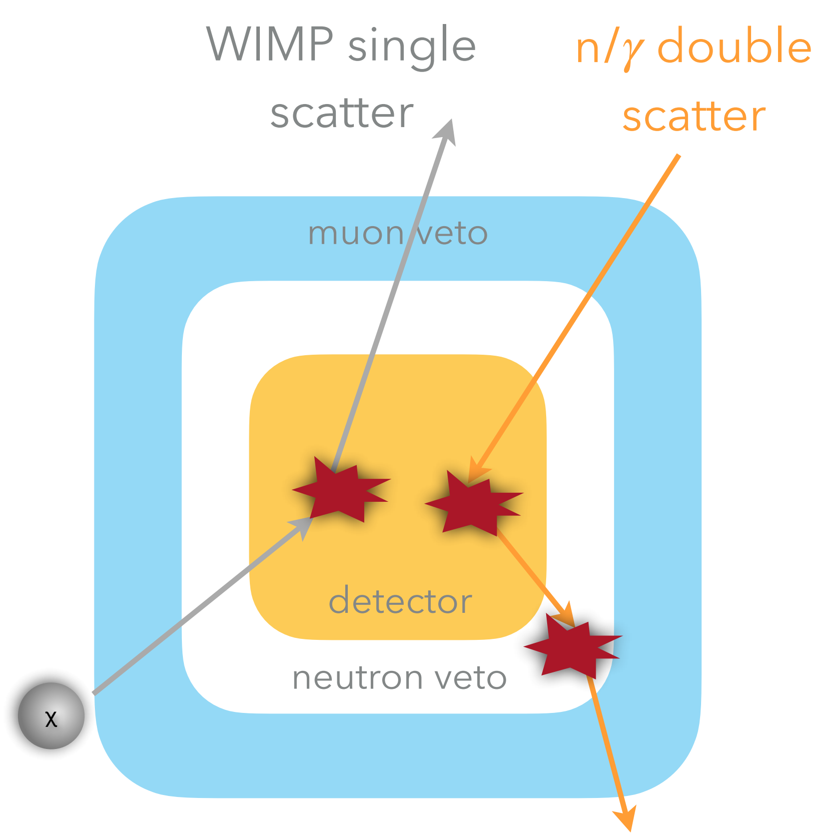


DEFEATING BACKGROUNDS

- **Background reduction:**
  - Go underground
  - Clean environment
  - Material screening & selection
- **Background discrimination**
  - Active veto shield
  - ER/NR identification

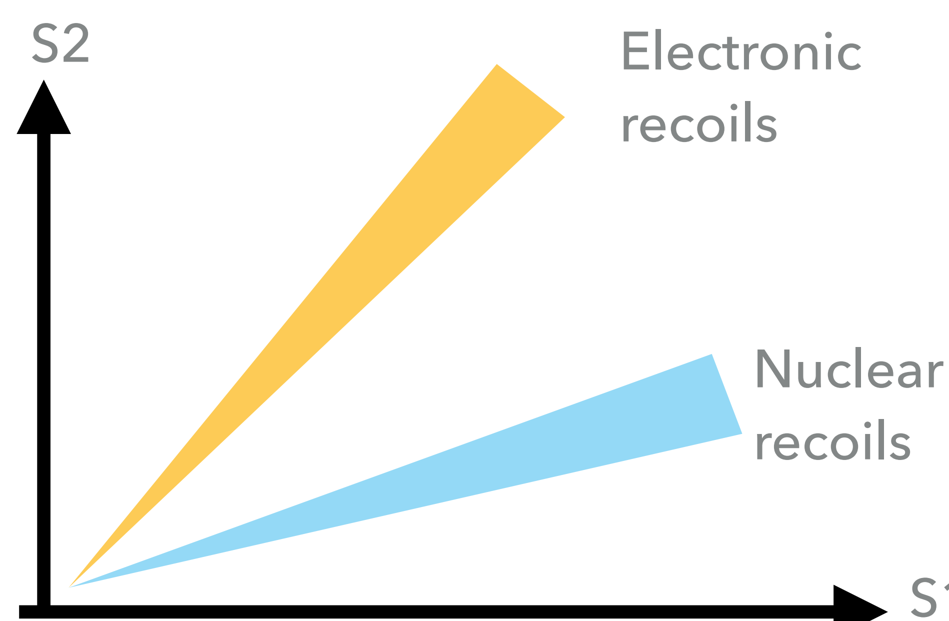


Active veto shield



ER/NR identification:

Signal split in two components which respond differently to NR/ER



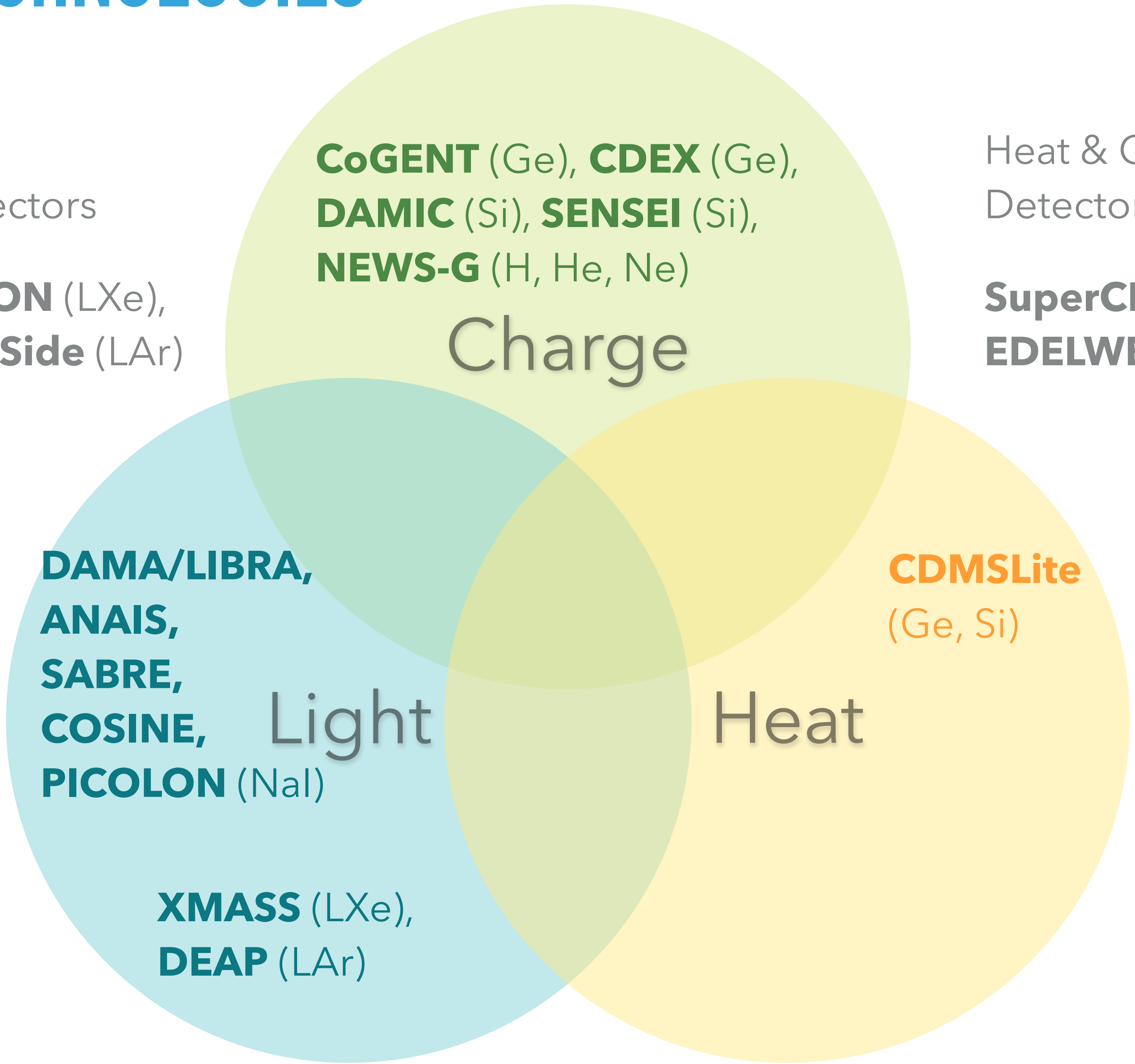
DETECTOR TECHNOLOGIES

Light & Charge Detectors

PandaX (LXe), **XENON** (LXe), **LUX/LZ** (LXe), **DarkSide** (LAr)

Heat & Charge Cryogenic Detectors

SuperCDMS (Ge, Si), **EDELWEISS** (Ge)



Total Energy

PICO (C_3F_8, CF_3I)

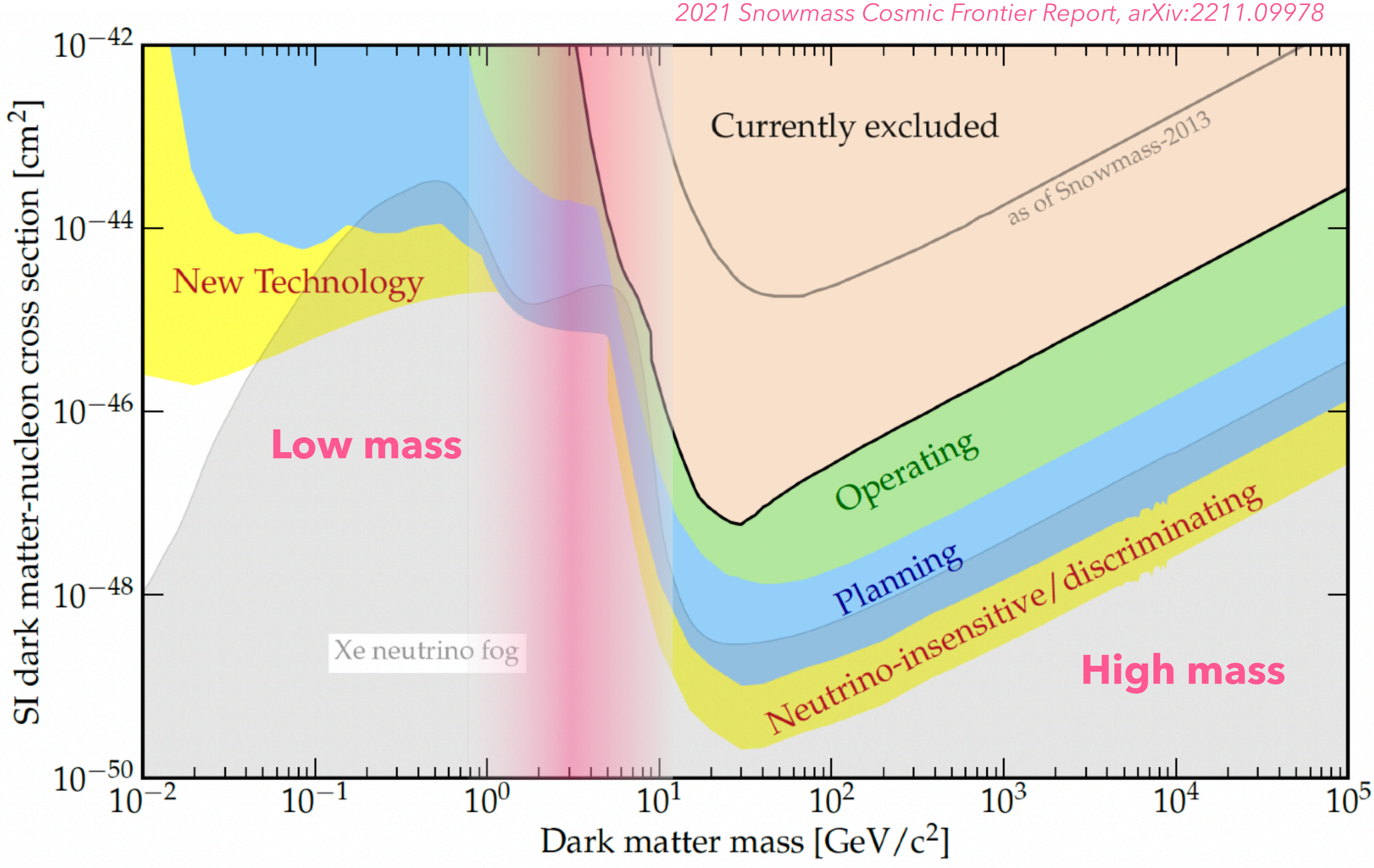
Light & Heat Cryogenic Detectors

CRESST ($CaWO_4$), **COSINUS** (NaI)

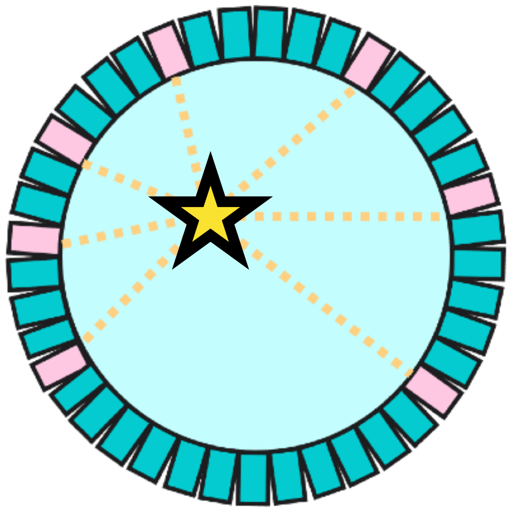
WIMP NUCLEON SI INTERACTION EXCLUSION LIMITS LANSCAPE

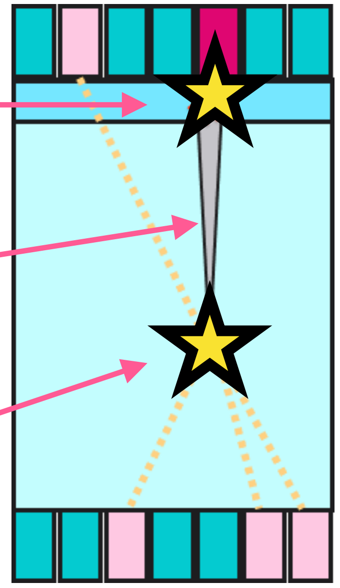
- To improve sensitivity:
  - larger exposure M × T and lower background
- To extend sensitivity at low mass WIMPs:
  - lower energy threshold
- Minimum of the curve:
  - depends on target nuclei

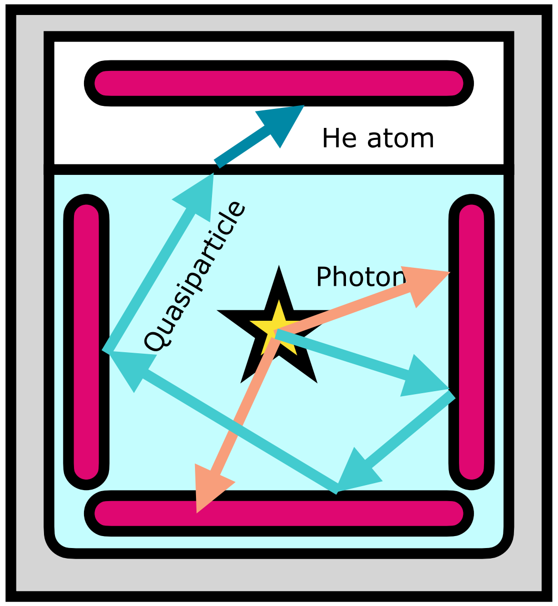
2021 Snowmass Cosmic Frontier Report, arXiv:2211.09978



NOBLE LIQUID DM DETECTORS







Single phase, light readout

- High light yields, simple geometry, no E-fields
- Scintillation with PMTs
- LAr: DEAP-3600
- LXe: XMASS (until 2019)

Dual-Phase TPC with light readout

- Light and charge with PMTs
- 3D position resolution, improved energy resolution, discrimination based on S2/S1
- LAr: DarkSide-50 (until 2019), DarkSide-20k
- LXe: LZ, PandaX-4T, XENONnT

Superfluid ^4He, phonon readout

- R&D phase for light DM
- Signals: phonons and rotons; detect excitations down to ~ 1 meV (via ejection of 4He atom), TES/MMC readout
- HeRALD, DELight

Credit to L. Baudis

DM DETECTORS

XENON

XENON DETECTORS

XENON: lowest background from ER
LZ: best limit for high WIMP masses

XENON 10 (LNGS)
10 kg
ZEPLIN II (Boulby)
ZEPLIN III (Boulby)

2010

XENON 100 (LNGS)
100 kg

LUX (250 kg, SURF),

PANDA-X (500 kg, CJPL)

XMASS (0.8t, Kamioka)

2015

1000 kg

XENON 1T (1t, LNGS)

PandaX-4:(4t, CJPL)

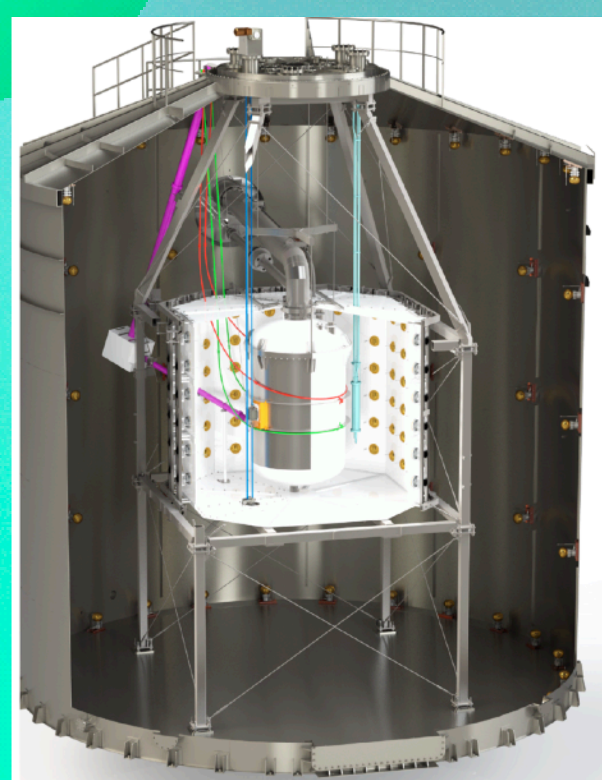
XENONnT: (6t, LNGS)
LZ: (7t, SURF)

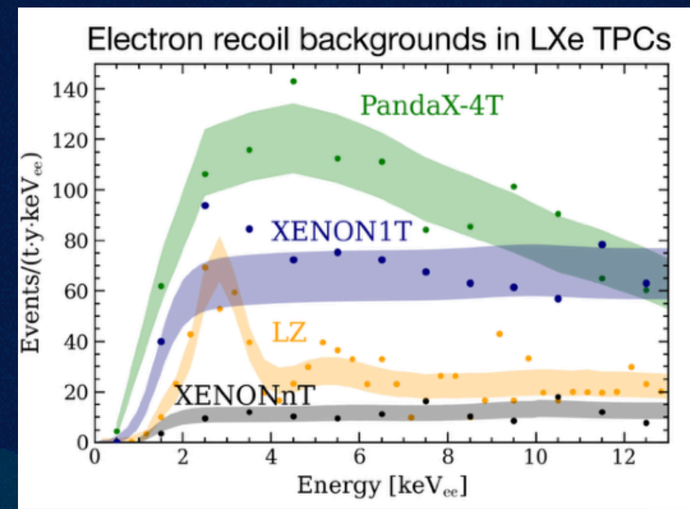
2020

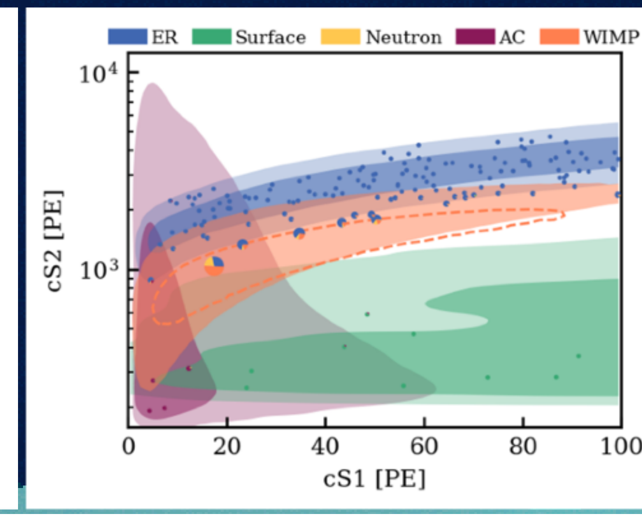
10000 kg

DARWIN/XLZD: (40-60t),
PandaX-20: (20t, CJPL)

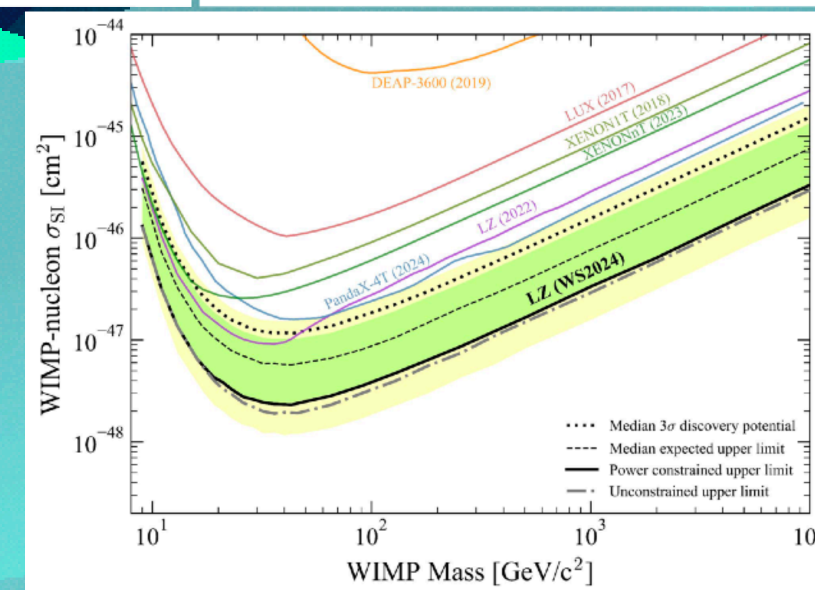
XLZD Consortium formed







Phys. Rev. Lett. 131, 041003

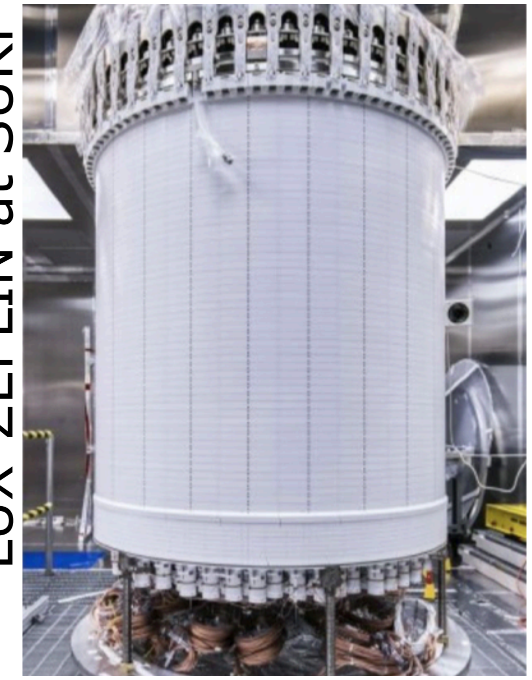


Scott Haselschwardt TEVPA 2024

Credits: Jocelyn Monroe

LXe TIME PROJECTION CHAMBERS

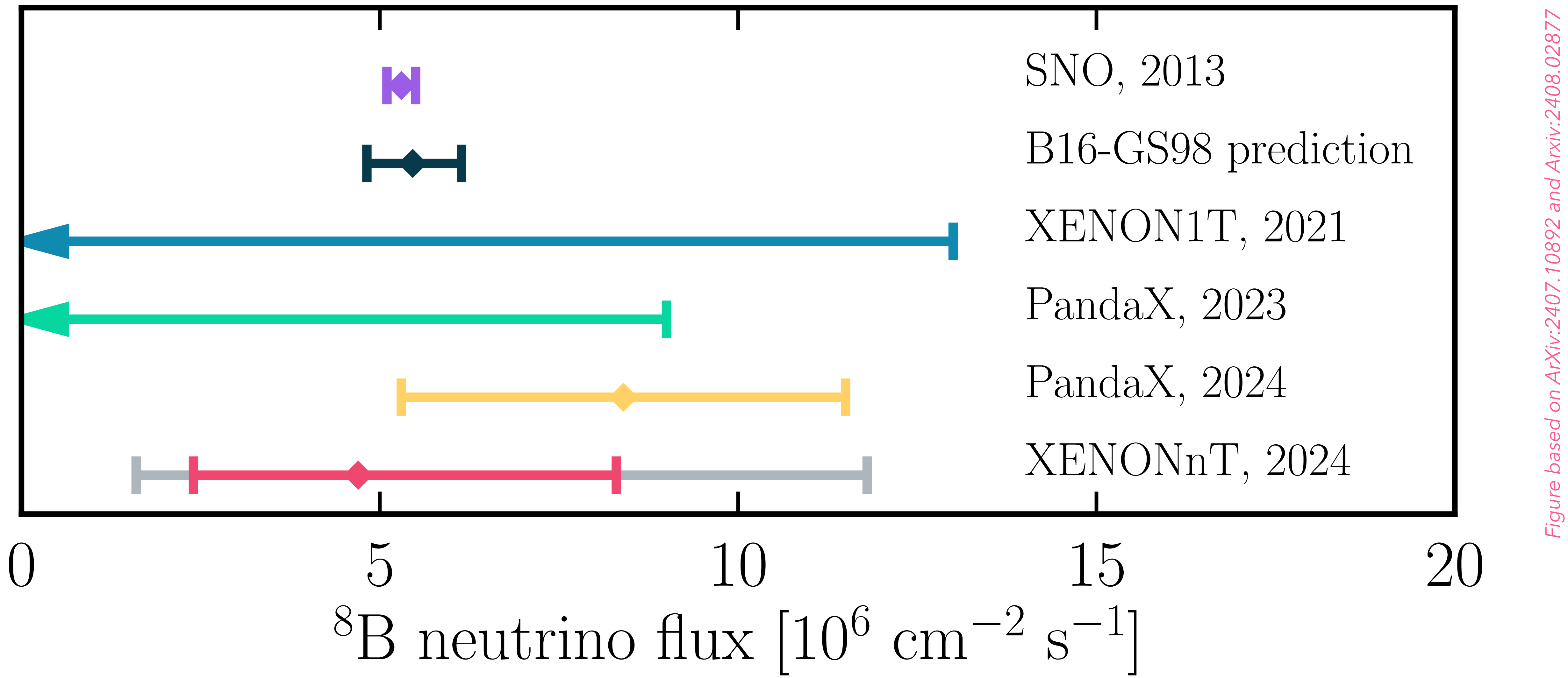
- Detector scales: 10 t (LZ), 6 t (PandaX-4T) and 8.6 t LXe (XENONnT) total Xe mass
- TPCs with 2 arrays of 3-inch PMTs
- Kr and Rn removal techniques
- Ultra-pure water shields, n & μ vetos
- External and internal calibration sources
- Status: running towards the neutrino floor ⇒ first detection of ^{8}B CEVNS


LUX-ZEPLIN at SURF


XENONnT at LNGS


PandaX-4T at Jinping

FIRST MEASUREMENTS OF ^{8}B NEUTRINO FLUX IN PANDAX AND XENONnT

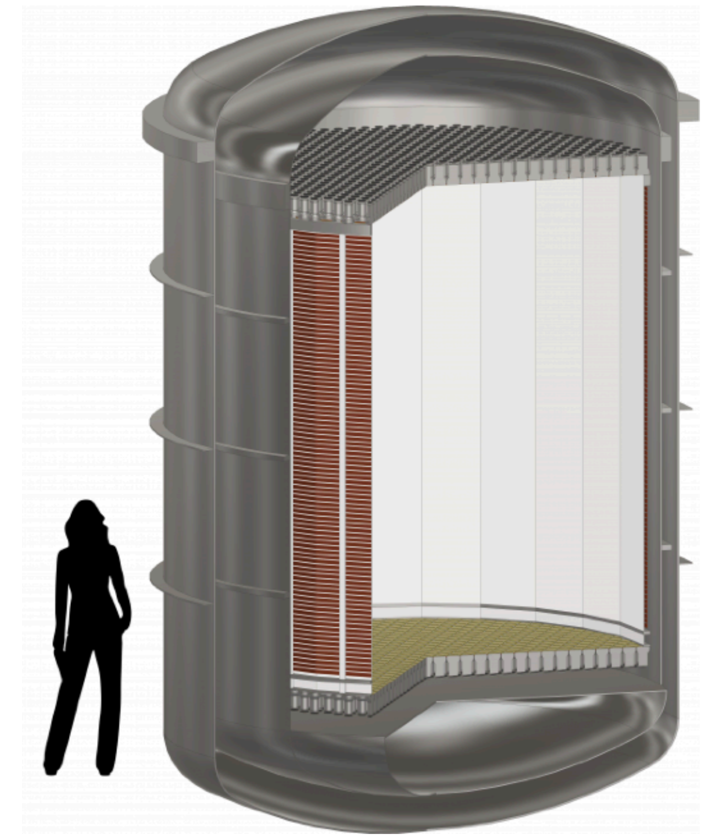


PandaX (Exposure 1.20 (paired) and 1.04 (US2) $\text{tonne} \times \text{yr}$): The data disfavors background-only hypothesis at 2.64σ. The measured ^{8}B neutrino flux is $(8.4 \pm 3.1) \times 10^{6}$ cm^{-2} s^{-1}

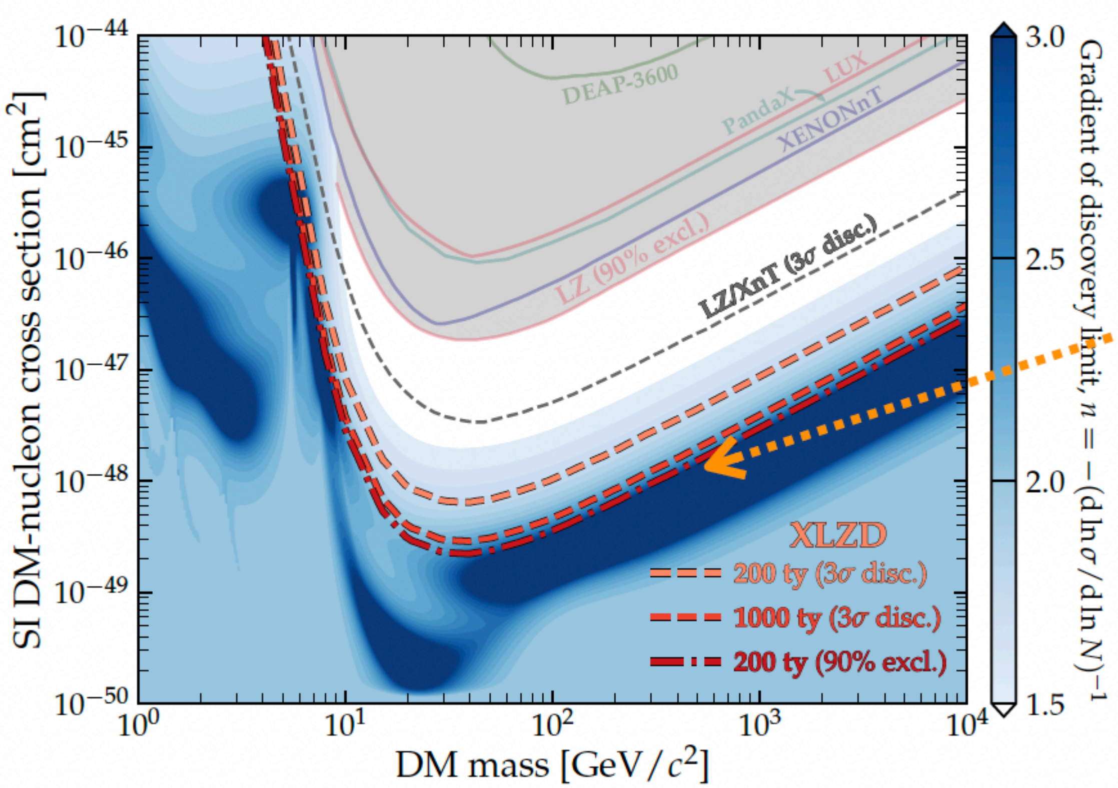
XenonNT (Exposure 3.51 $\text{tonne} \times \text{yr}$): The data disfavors background-only hypothesis at 2.73σ. The measured ^{8}B neutrino flux is $4.7^{+3.6}_{-2.3} \times 10^{6}$ cm^{-2} s^{-1}

FUTURE LXe DETECTORS

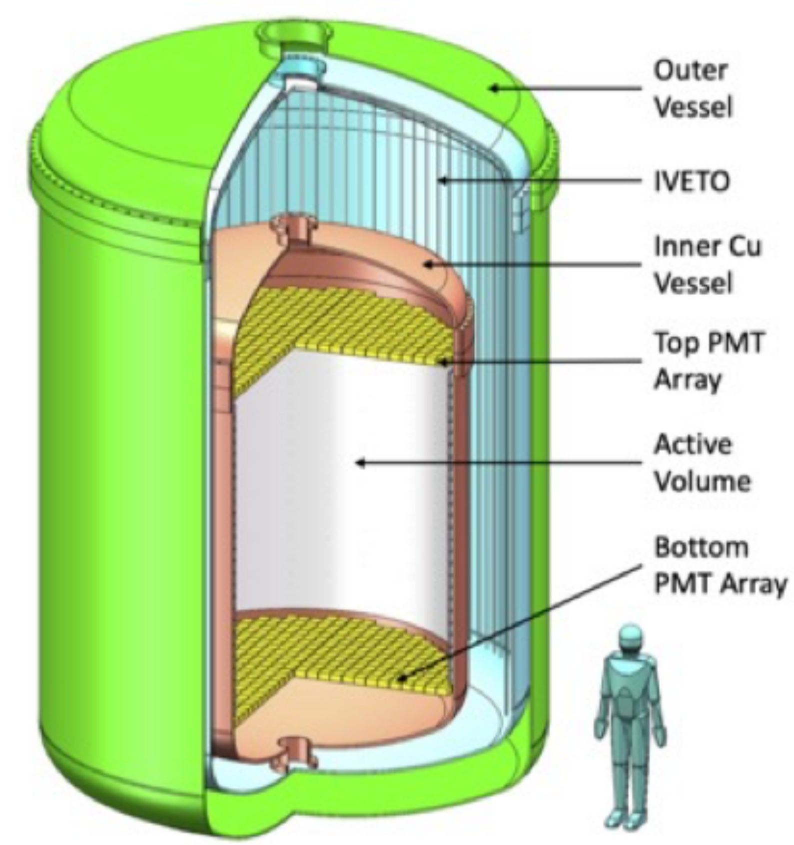
- DARWIN/XLZD
- DARWIN: 50 t LXe (40 t active target) at LNGS; ~1900 3-inch PMTs (baseline design); Gd-doped water n and μ vetoes
- R&D and prototyping in progress
- XLZD: 75 t LXe (60 t active target), several labs are considered
- PandaX-xT: > 30 t active volume at JinPing; 2 arrays of 2-inch PMTs



DARWIN collaboration JCAP 1611 (2016) 017



Systematic limit imposed by CEvES from atmospheric neutrinos



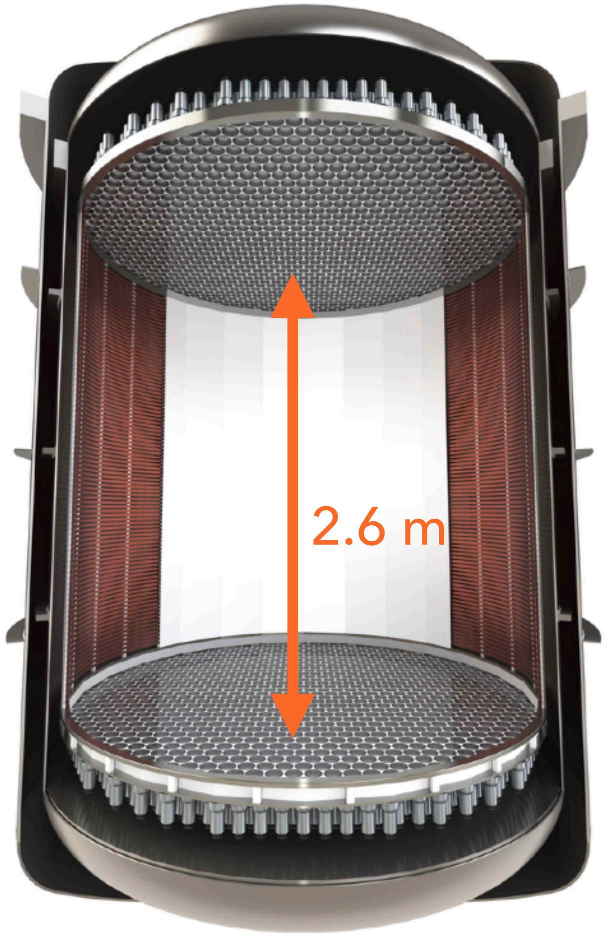
SCALING UP CHALLENGES

- LUX-ZEPLIN and XENONnT: 1.5 m e- drift and ~ 1.5 m diameter electrodes
- DARWIN/XLZD: 2.6 - 3.0 m new challenges
    - Design of electrodes: robustness (minimal sagging/ deflection), maximal transparency, reduced e- emission
    - Electric field: ensure spatial and temporal homogeneity, avoid charge-up of PTFE reflectors
    - High-voltage supply to cathode design, avoid high-field regions
    - Liquid level control
    - Cryogenic purification (222Rn and 85Kr below solar pp neutrino level)
- Electron survival in LXe: > 10 ms lifetime
- Diffusion of the e--cloud: size of S2-signals

LUX-ZEPLIN at SURF

XENONnT at LNGS

DARWIN



DETECTOR DEMONSTRATORS

- Full scale demonstrators in z and in x-y, supported by ERC grants
  - Xenoscope, 2.6 m tall TPC and Pancake, 2.6 m ø TPC in double-walled cryostats
  - Both facilities available to the collaboration/consortium for R&D purposes
  - LowRad to demonstrate large-scale cryogenic distillation at Münster

Vertical demonstrator: *Xenoscope*

L. Baudis et al, JINST 16, P08052, 2021

Horizontal demonstrator: *Pancake*

Test electrodes with 2.6 m Ø

DM DETECTORS

ARGON

ARGON DETECTORS

LAr high mass: background discrimination

10 kg 2010

DarkSide-50
(50 kg, LNGS)

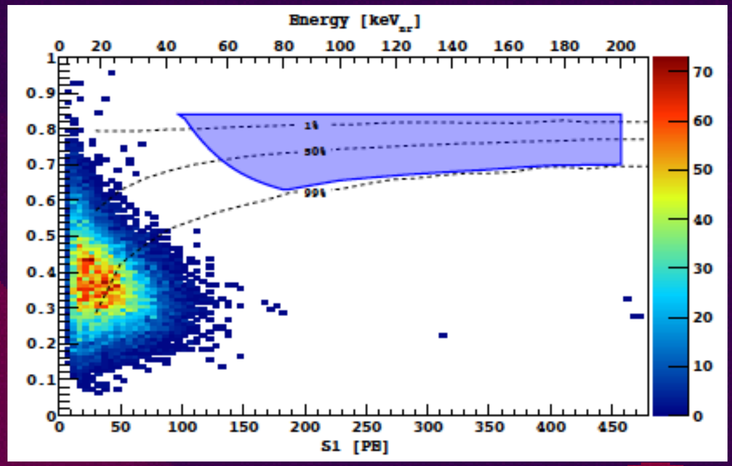
100 kg

ArDM
(1t, LSC)

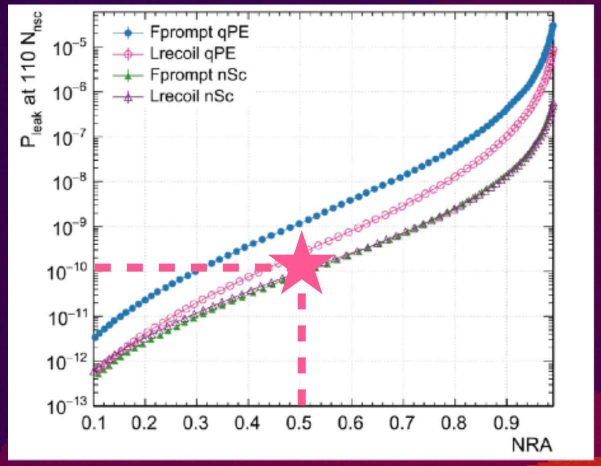
1000 kg 2015

DEAP-3600
(3.6t, SNOLAB)

10000 kg

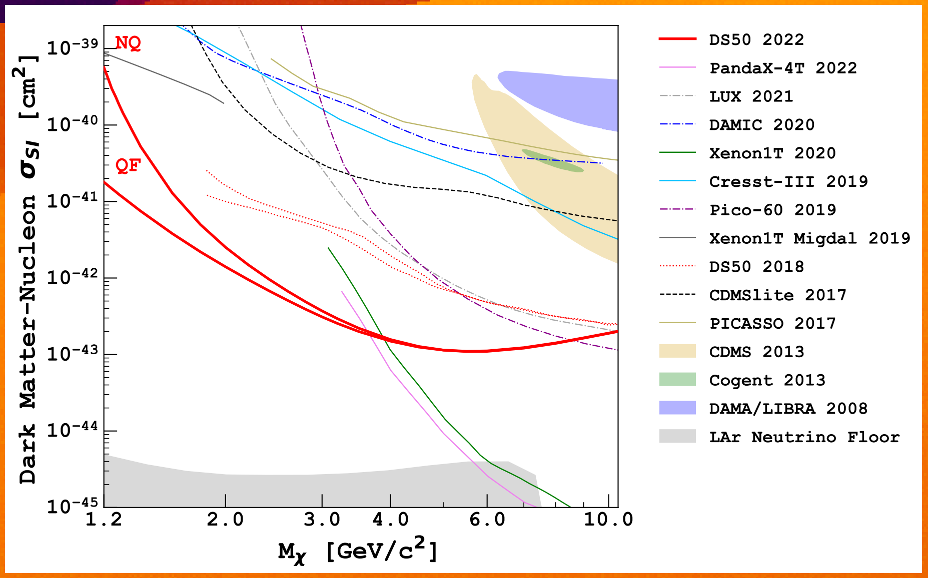


Phys. Rev. D 98, 102006 (2018)

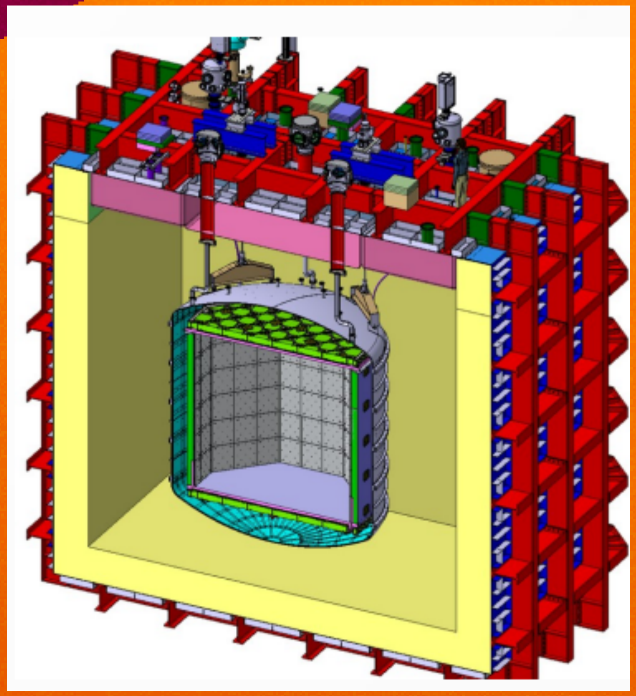


Eur. Phys. J. C 81, 823 (2021)

DS50 low mass:
leading SI limit at
1.2-3.6 GeV/c^2



Phys. Rev. D 107, 063001 (2023)



Global Argon Dark Matter Collaboration formed

2020

DarkSide-20k
(50t, LNGS)

100000 kg

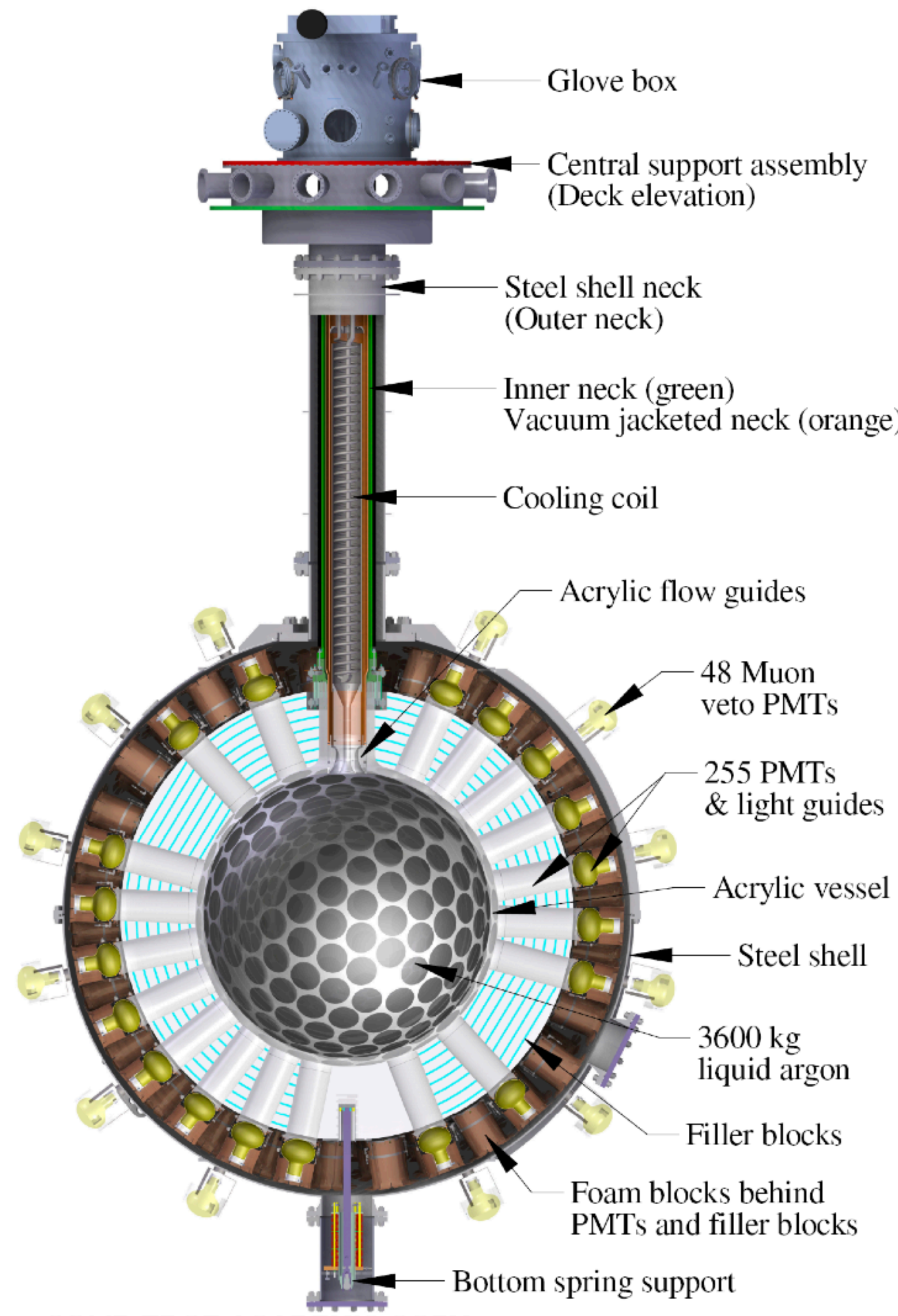
ARGO: 400 t, SNOLAB

Credits: Jocelyn Monroe

LIQUID ARGON: THE DEAP-3600 EXPERIMENT

Single-phase LAr detector, located 2 km underground at SNOLAB

- 3.3 t target (1 t fiducial) in sealed ultra-clean acrylic vessel
- vessel is resurfaced in-situ to remove deposited Rn daughters after construction
- in-situ vacuum evaporated *tetra-phenyl butadiene* (TPB) wavelength shifter (128 nm 420 nm) with ~10 m^2 surface ◉ bonded 50 cm long light guides + PE shield against neutrons
- 255 8-inch PMTs (32% QE, 75% coverage)
- detector immersed in 8 m water shield, instrumented with PMTs to veto muons



LAr TIME PROJECTION CHAMBERS

ArDM @ Canfranc:

850 kg of active LAr

500 kg fiducial

28 8-inch PMTs

DarkSide-50 @ LNGS:

50 kg of LAr (dip in ^{39}Ar)

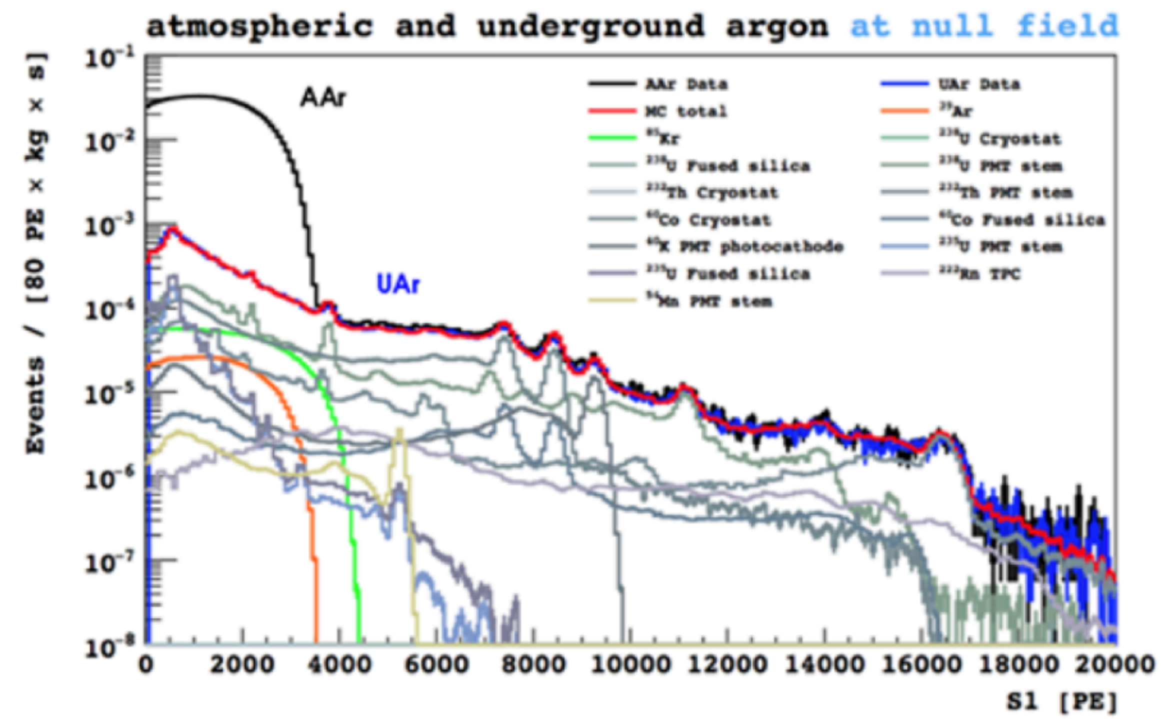
33 kg fiducial

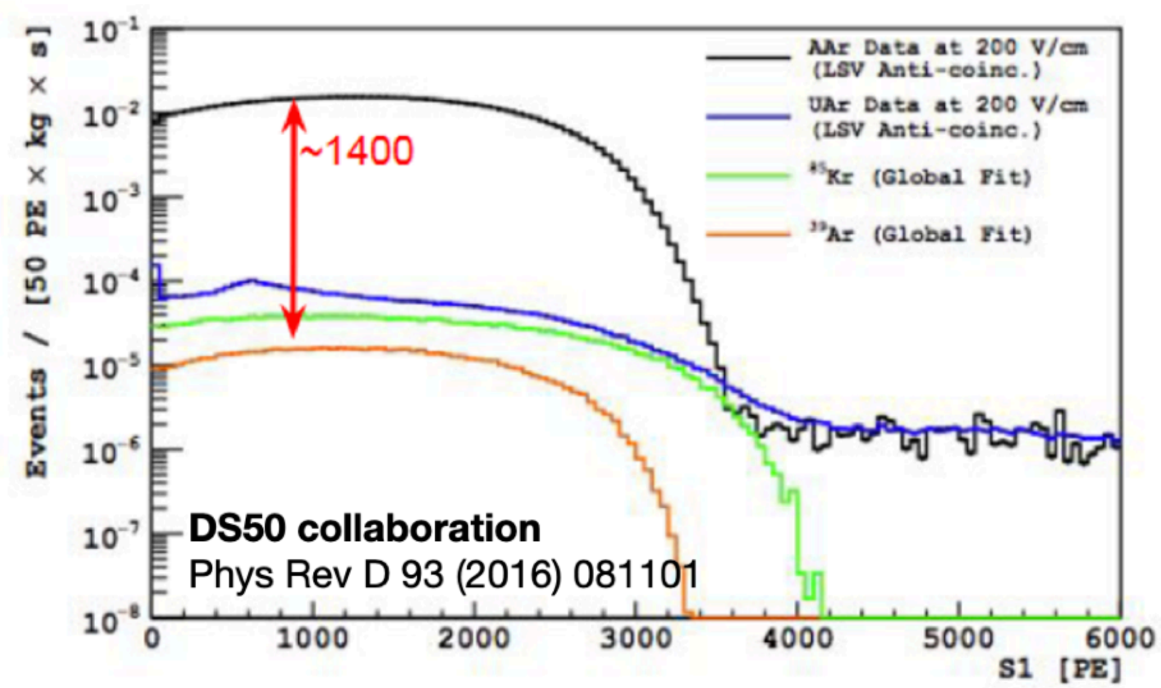
38 3-inch PMTs

Dark Matter search with underground argon

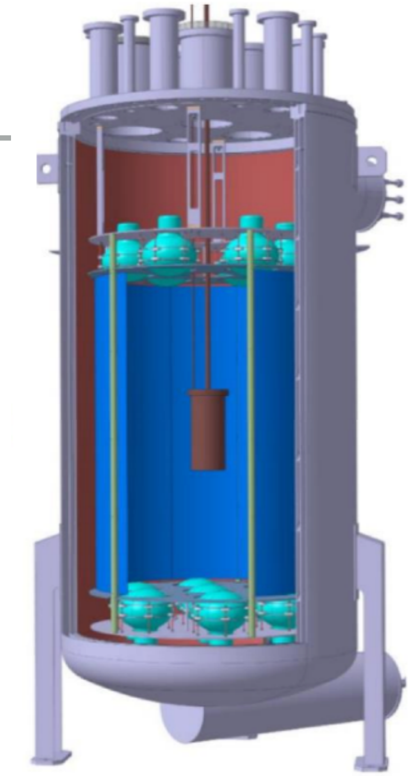
RADIOPURE ARGON FROM UNDERGROUND SOURCES

- $^{39}Ar\ \beta$ decay (Q = 570 keV, half-life 269 yr)
- ~1Bq/kg in atmosferic Ar
- Origin from $^{40}Ar(n,2n)^{39}Ar$ in atmosphere
- Extraction of Ar from underground sources, where such processes are suppressed
- DS50 used 157 kg of UAr
- Depletion factor in ^{39}Ar : 1400 ± 200





LOW RADIOACTIVITY ARGON: URANIA & ARIA



1) UAr extraction at the URANIA plant.

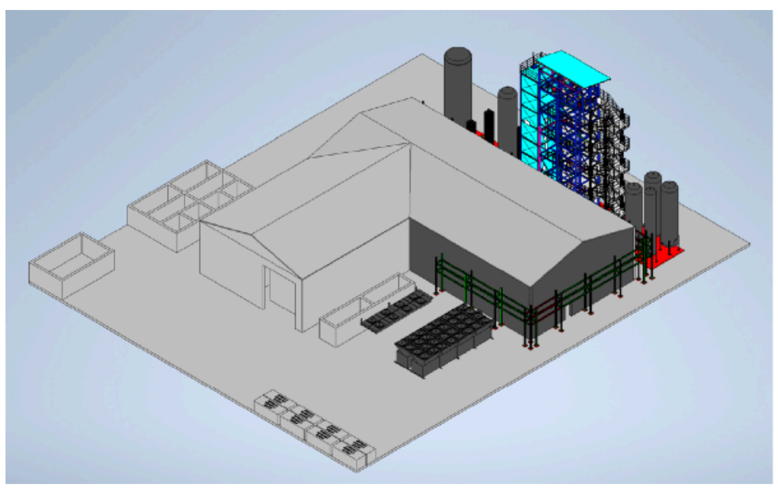
^{39}Ar (β-decay) suppressed by $\sim 10^3$ in underground CO2 reservoir in Cortez, Colorado

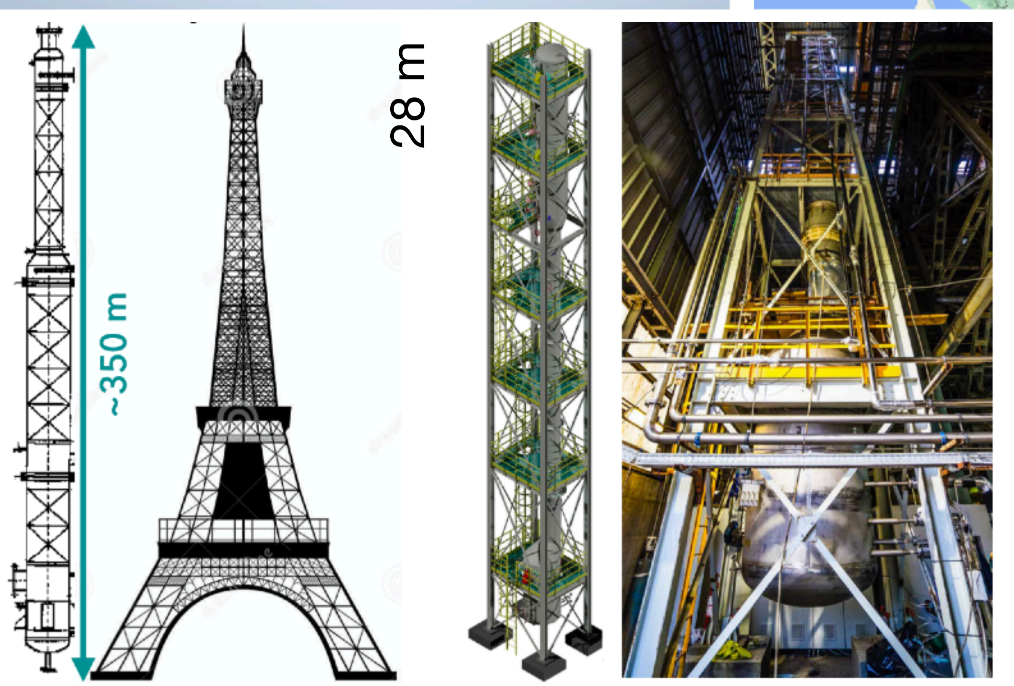
UAr extraction rate: 250-330 kg/day

Expected argon purity at outlet: 99.99%

3) Qualification at Canfranc, DArT in ArDM

A single-phase LAr detector with active volume ~1L, capable of measuring UAr to AAr ^{39}Ar depletion factors of the order of 1000 with 10% precision in weeks *JINST 15 P02024*





Eur. Phys. J. C (2021) 81:359

2) Cryogenic distillation at the ARIA facility

Installed in the shaft of a coal mine

Chemical purification rate: 1 t/day

First module operated according to specs with nitrogen

Run completed with Ar at the end of 2020 *Eur. Phys. J. C (2023) 83:453*

Full assembly about to start

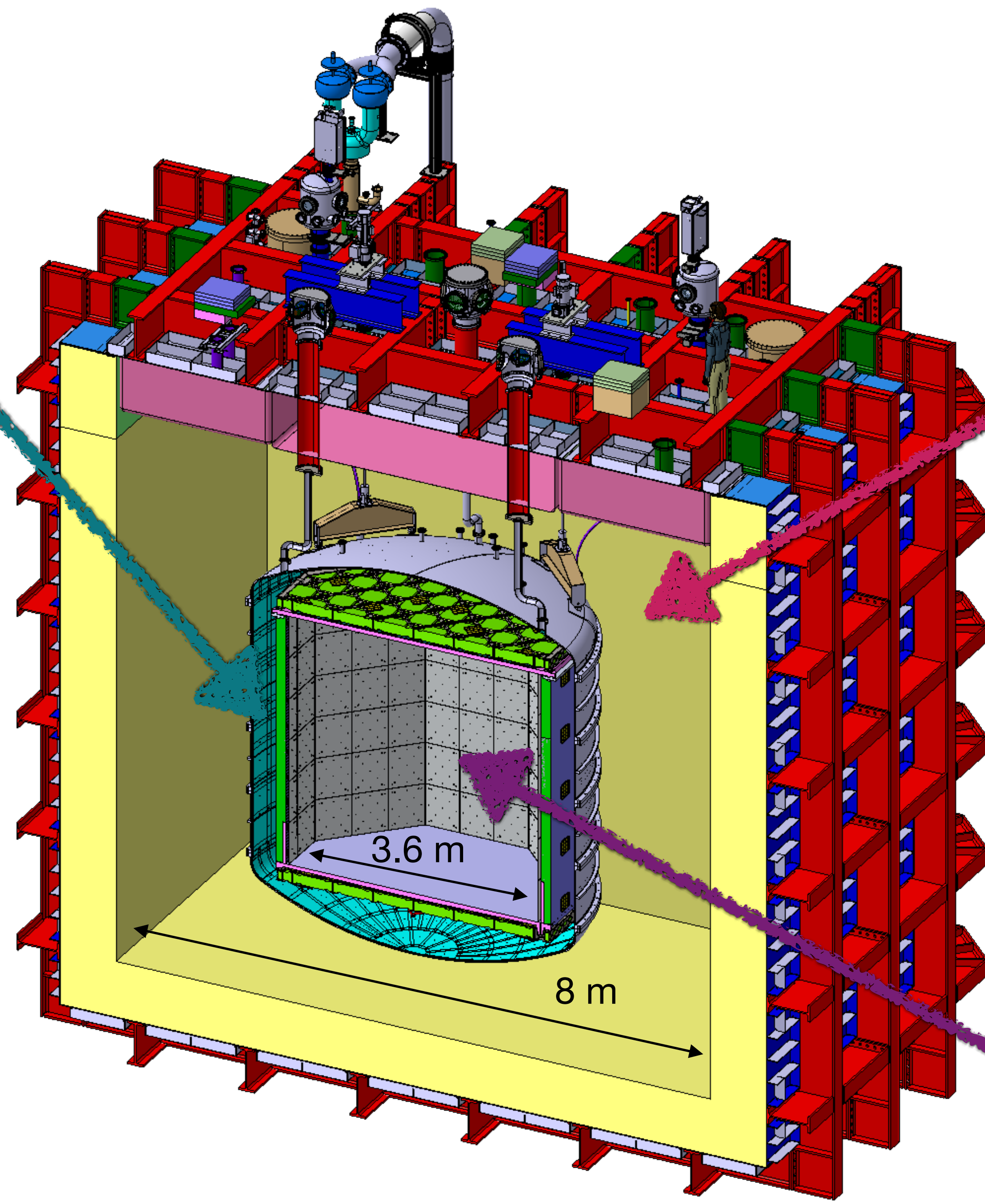
THE DARKSIDE-20K DETECTOR @ LNGS

Inner Veto

Radiogenic n's

32-ton underground LAr

- Membrane (ProtoDUNE-like) cryostat
- Atmospheric argon (AAr) volume (≈700 t)
- Vacuum vessel containing UAr and TPC/Veto
- Underground argon (UAr) volume (≈100 t)
- Inner detectors TPC and Neutron Veto with >25 m² SiPM arrays
- Outer Veto with SiPM arrays near the cryostat walls



Outer Veto

Cosmic μ's and showers

700-ton atmospheric LAr

TPC

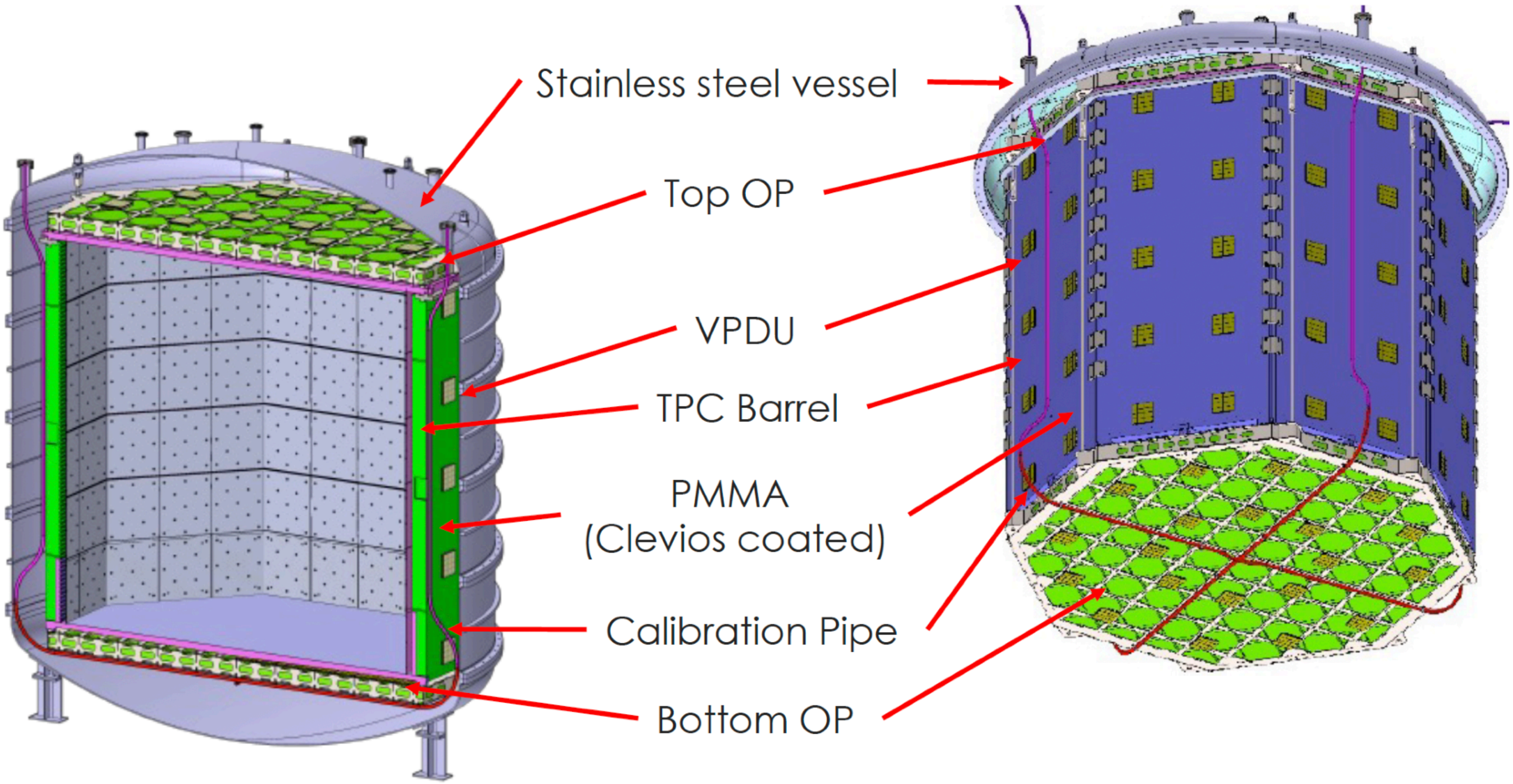
Dark matter detector

50-ton underground LAr/GAr, PMMA walls

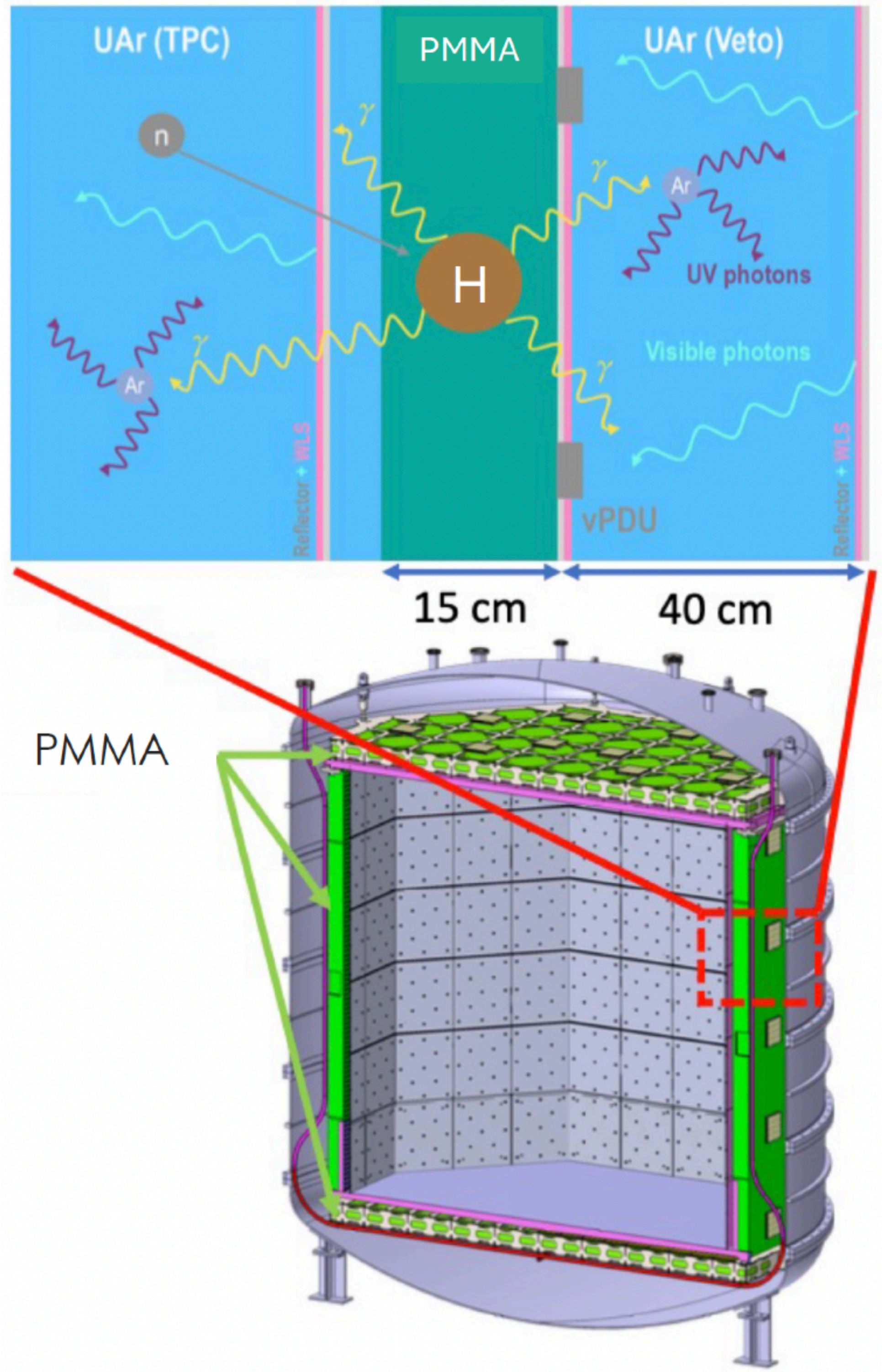
(20-ton fiducial mass)

THE DARKSIDE-20K DETECTOR @ LNGS

- Octagonal shape dual phase argon TPC:
  - Active UAr mass: 49,7 tonnes
  - Fiducial UAr mass: 20,2 tonnes
- Neutron veto:
  - Active UAr mass: 32 tonnes

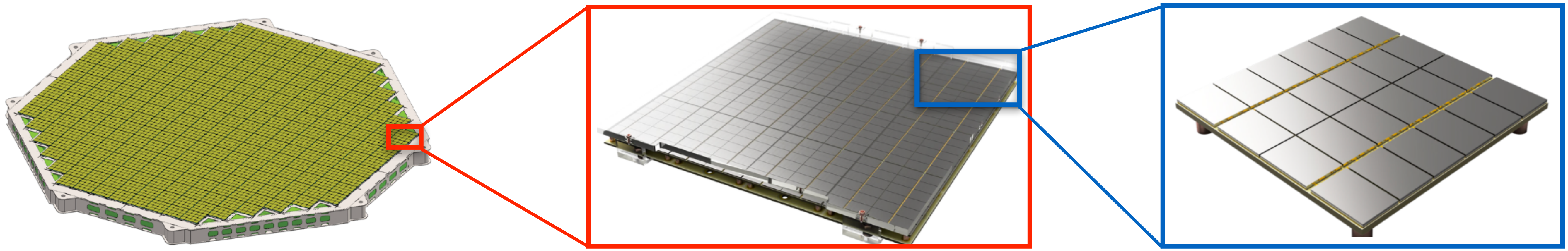


THE DARKSIDE-20K DETECTOR @ LNGS



- Acrylic (Hydrogen) + Argon
- Detection of 2,1 MeV gammas from neutron capture on H (53%) in TPC or Veto
  - 4π coverage: TPC walls, top and bottom endcaps
  - 40 cm thick UAr buffer + UAr in TPC
- Produced γ rays interact in UAr in both buffer and TPC
- 3M ESR used as reflector and PEN as wavelength shifter
- Scintillation light detected by SiPMs in both buffer and TPC

LOW RADIOACTIVITY, HIGH EFFICIENCY SiPM PHOTOSENSORS

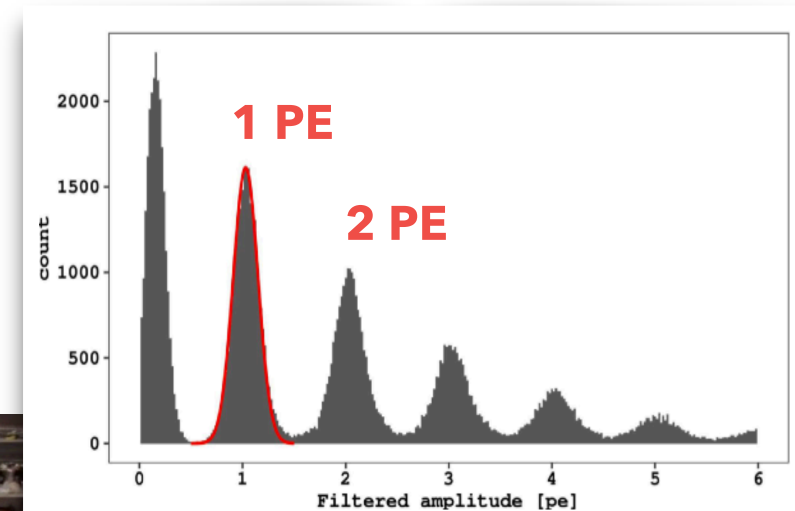


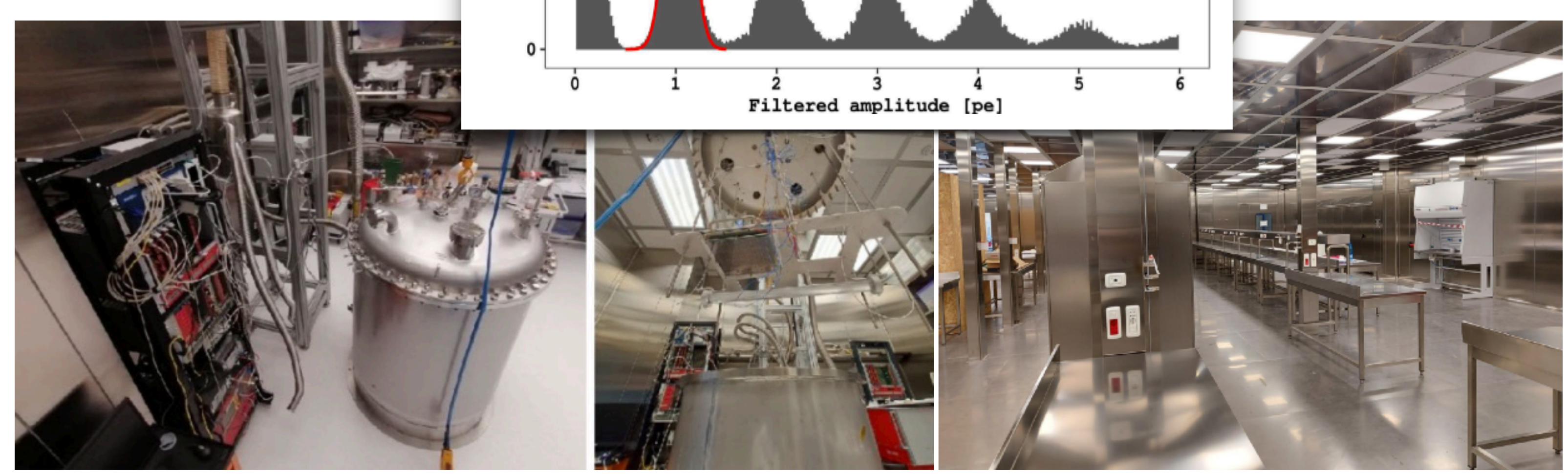
TPC optical plane ($\sim 21\ \mathrm{m}^2$)
525 PDUs

Photo Detection Unit
16 tiles arranged into 4 channels

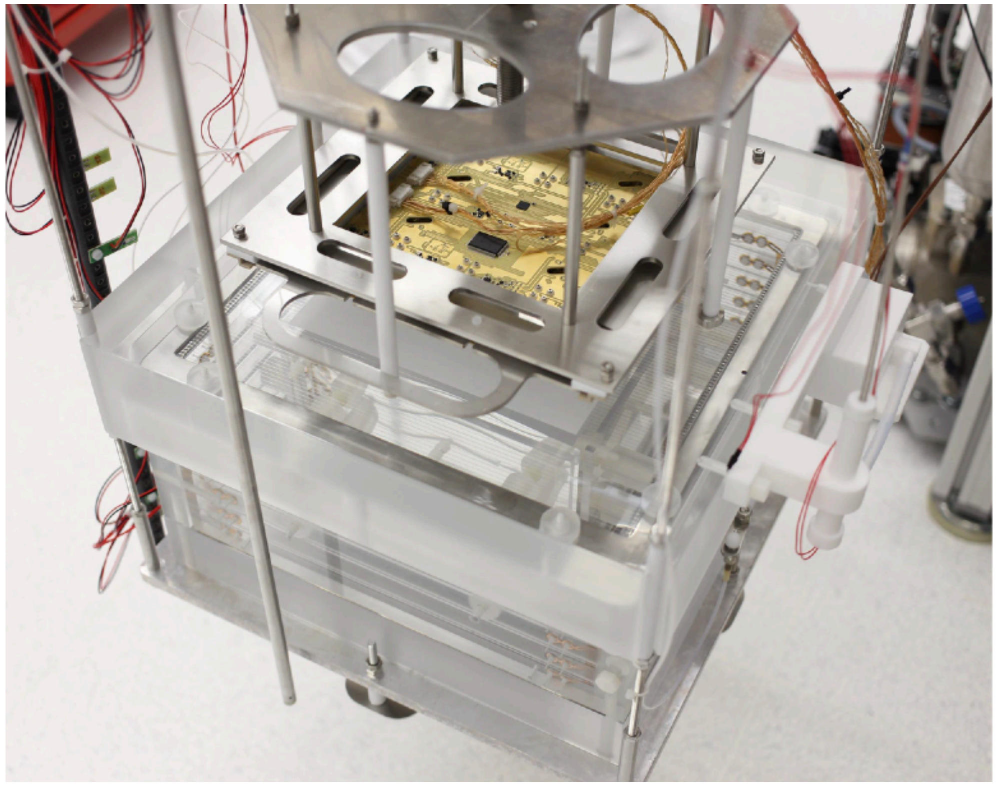
Tile / photo-detector module
24 SiPMs + signal amplifier

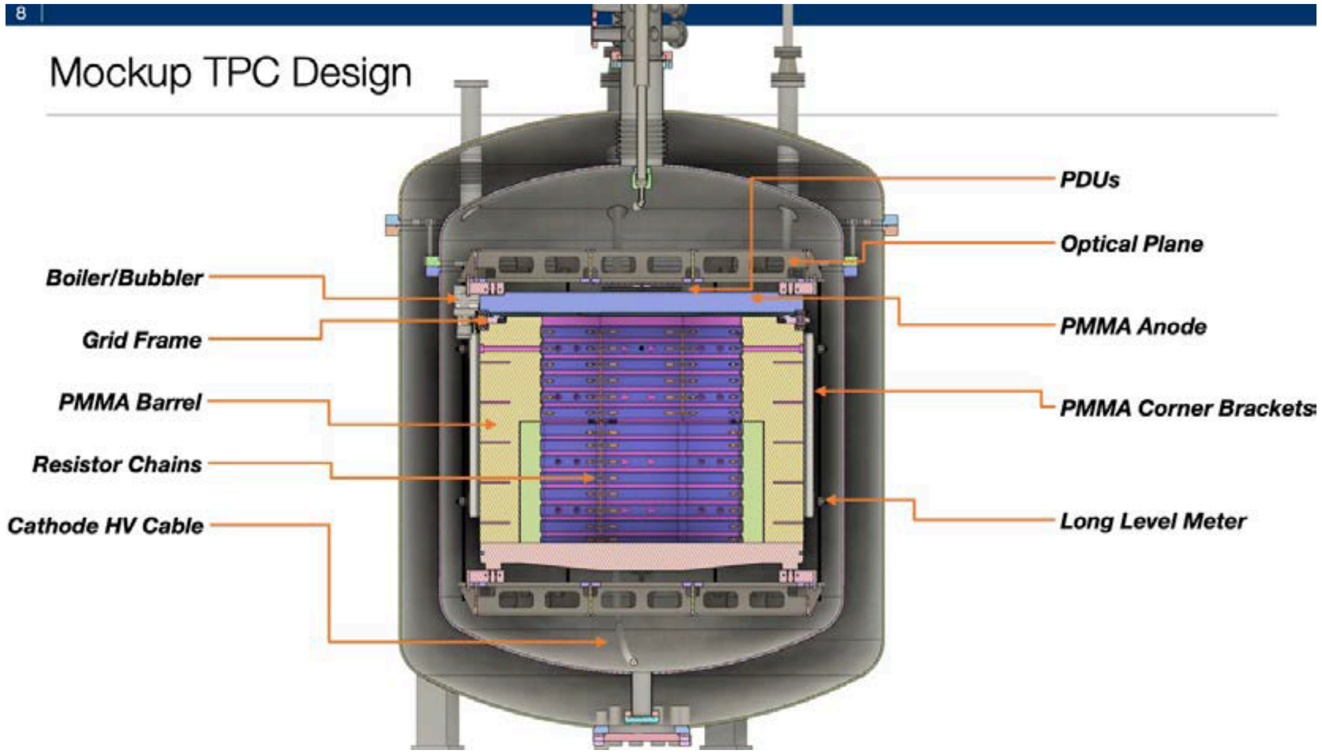
- Wafer delivery from LFoundry started in 2022
- Packaging and assembly for TPC sensors: **Nuova Officina Assergi** (NOA), about to start operations
- Packaging and assembly for Veto sensors: RAL and Liverpool, UK
- Several test facilities to qualify production: Naples, Liverpool, Edinburgh, AstroCent





DARKSIDE-20K: PROTOTYPES





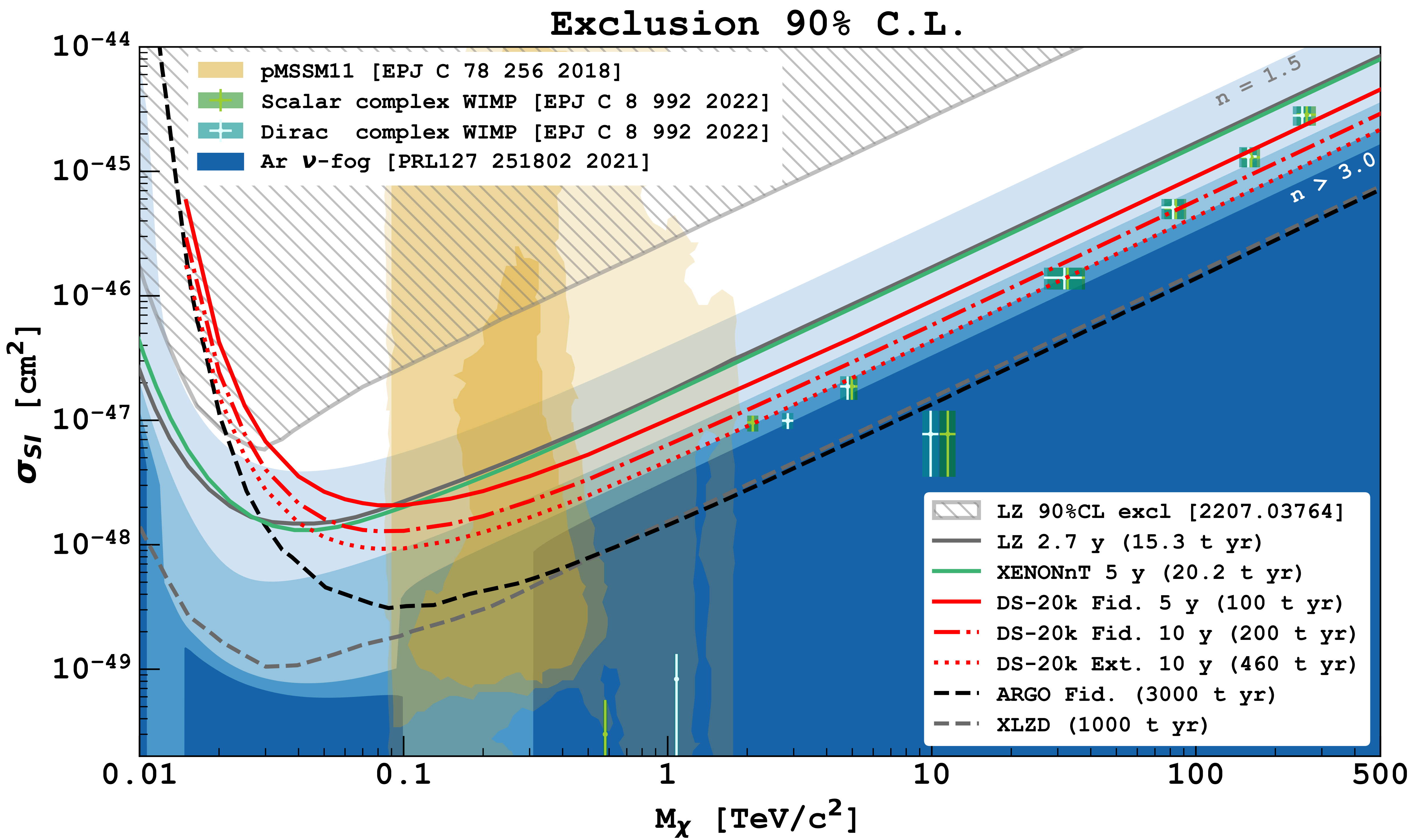
Proto-0 Detector @ Napoli

- Real experiment prototype test (~300 l LAr)
- Performance of the PDUs in LAr with real TPC (measurement of S1, S2)
- Robustness of the TPC design
- Electric field uniformity
- Study of the gas pocket thickness
- Runs foreseen in fall 2024

Mock-up System @ LNGS

- Mock-up test (~1 ton LAr) to validate the technical choices of the detector
- Robustness of the PMMA, Clevios and TPB coating on PMMA
- Electric field values and high voltage feedthroughs
- Resistor chains elements
- Grids and wires
- Cryogenics

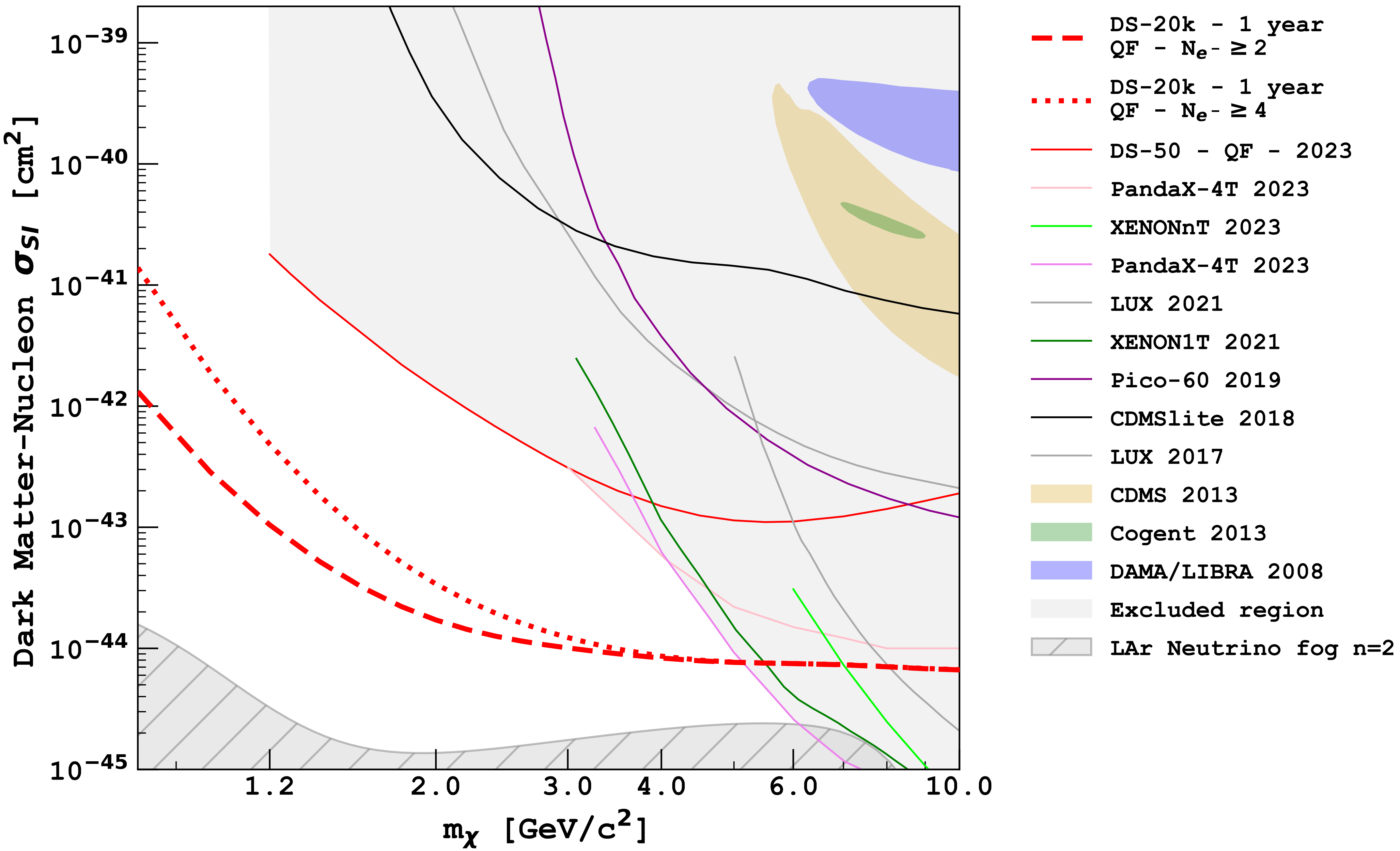
HIGH MASS WIMP SI INTERACTION EXCLUSION LIMITS PROSPECTS



LOW MASS WIMP SI INTERACTION EXCLUSION LIMITS PROSPECTS

Sensitivity projection for a dualphase LAr TPC optimized for light dark matter searches through the ionization channel

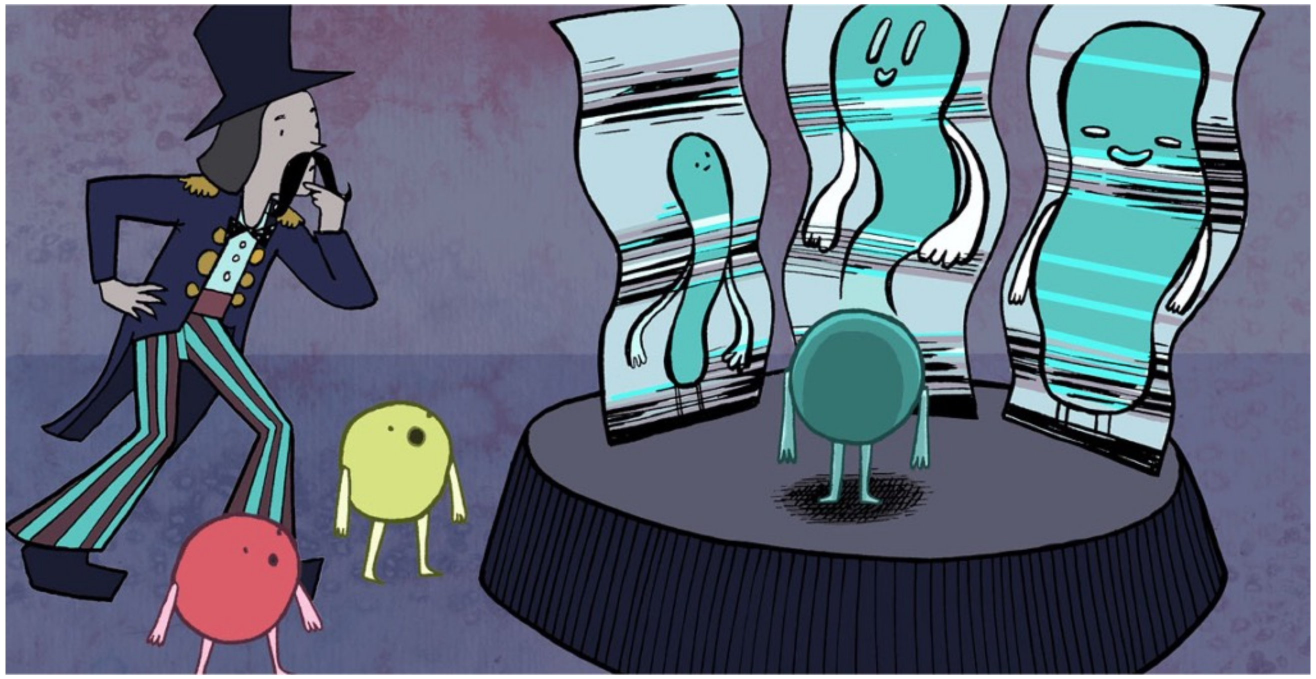
arXiv: 2407.05813



NL DETECTORS

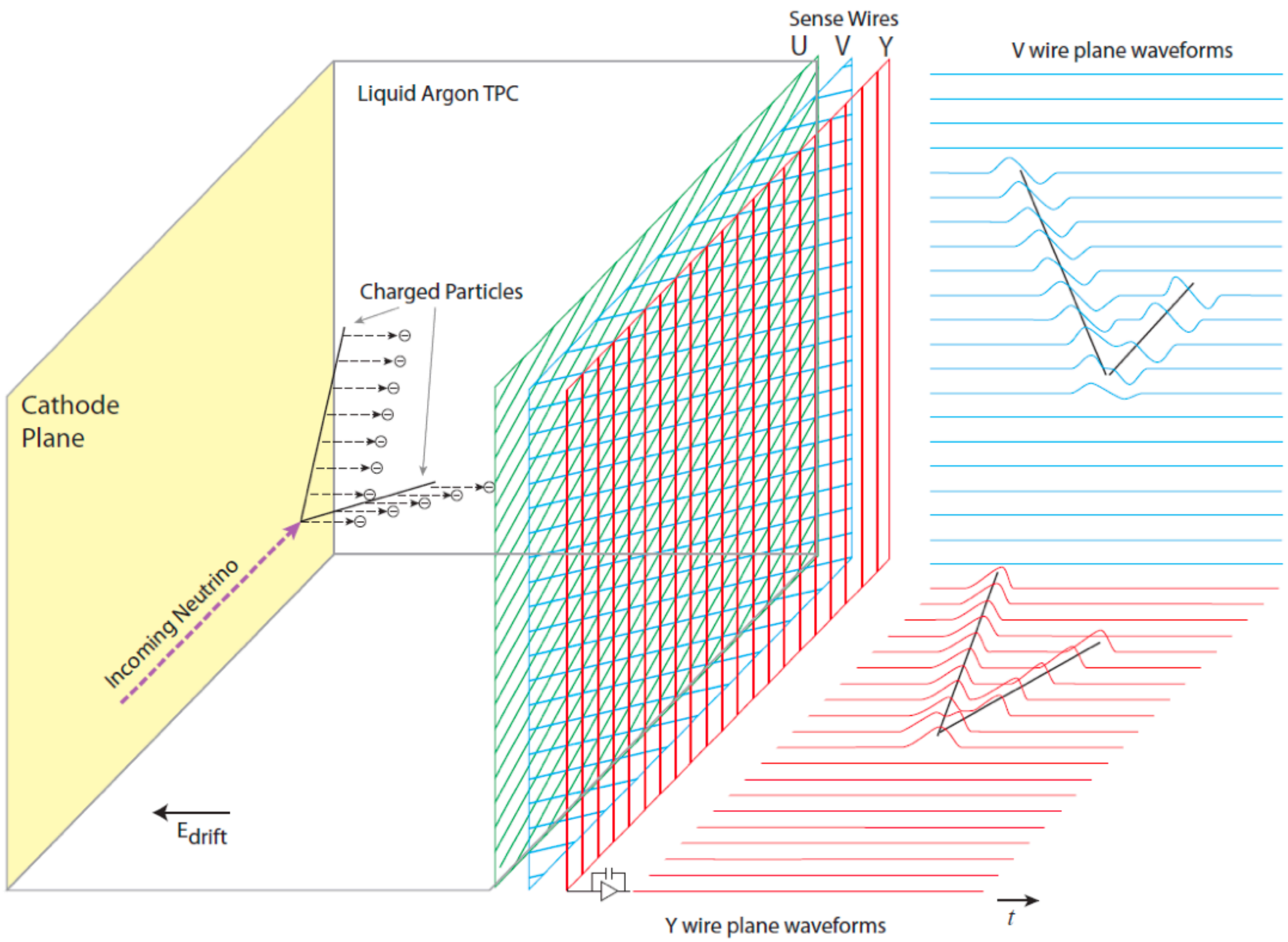
NEUTRINO PHYSICS

OPEN QUESTIONS IN NEUTRINO PHYSICS

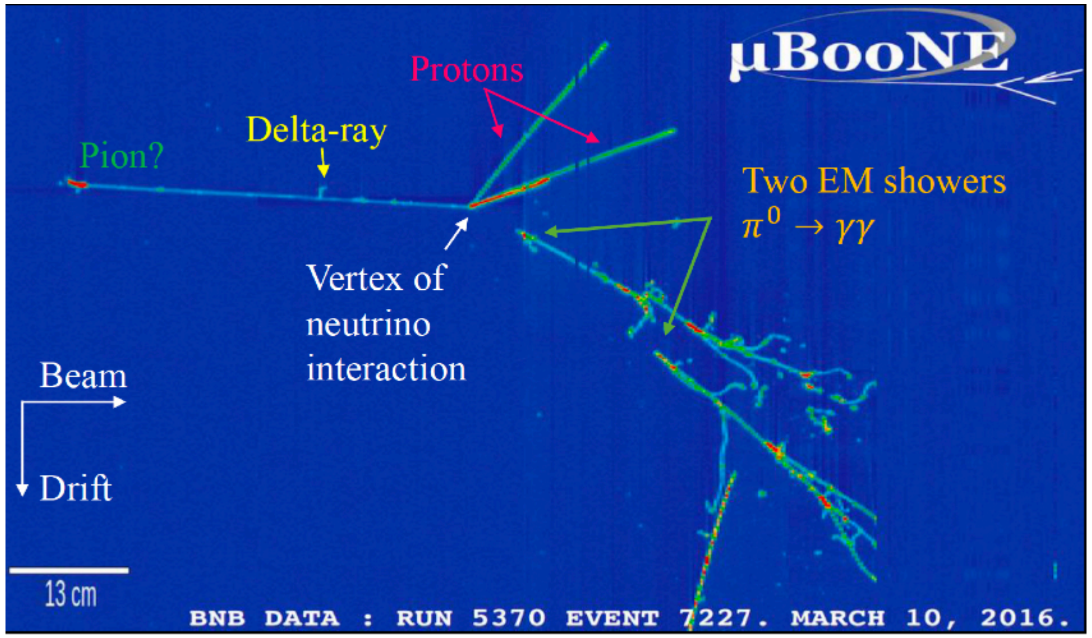


- What are the absolute values of neutrino masses, and the mass ordering?
- What is the nature of neutrinos? Are they Dirac or Majorana particles?
- What is the origin of small neutrino masses?
- What are the precise values of the mixing angles, and the origin of the large ν mixing?
- Is the standard three-neutrino picture correct, or do other, sterile neutrinos exist?
- What is the precise value of the CP violating phase δ?

LIQUID ARGON TPC



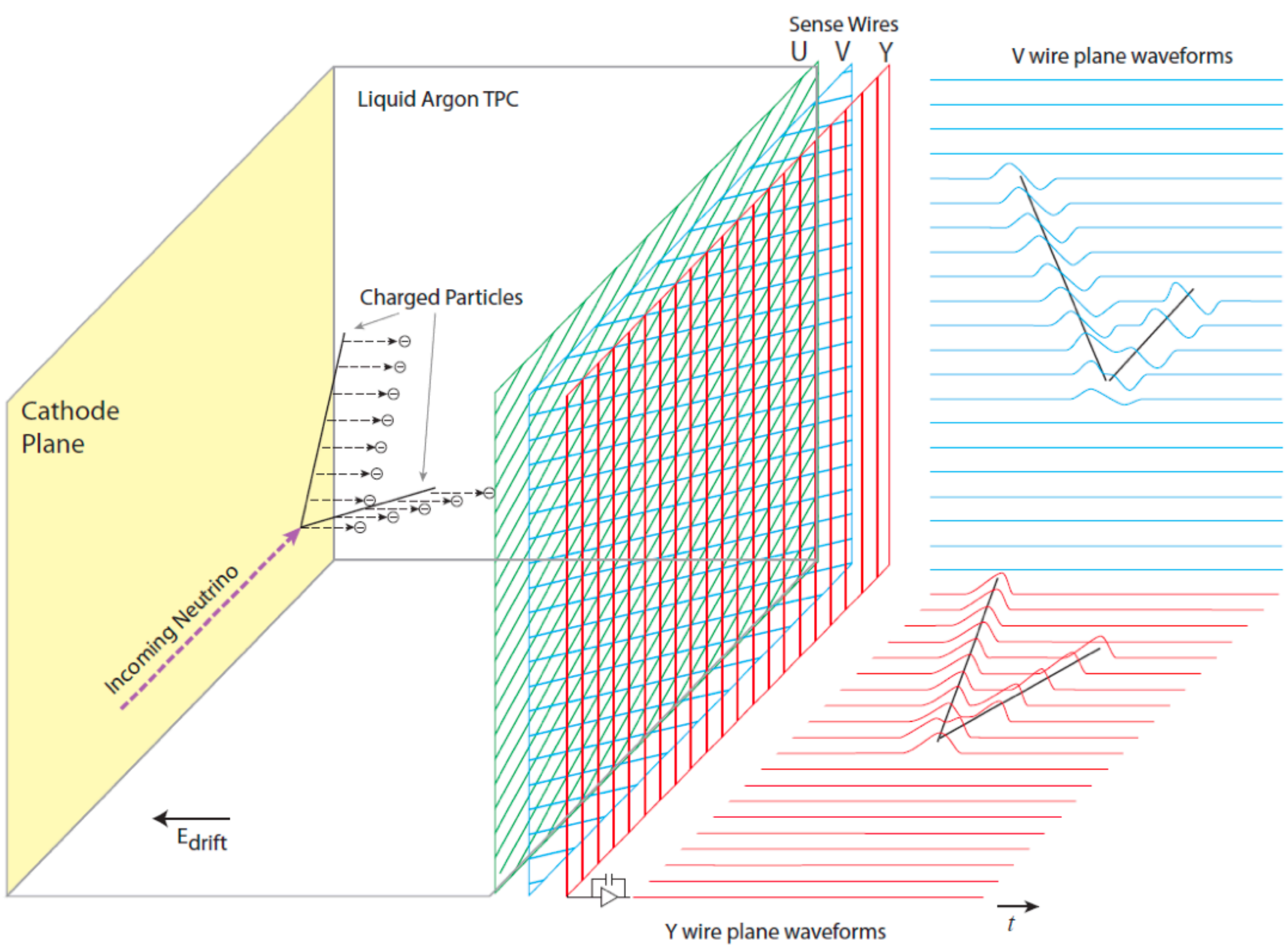
- Originally proposed by Rubbia in 1977 for neutrino physics
- R&D over >3 decades, now detectors @ kton scale
    - **ICARUS, μBooNE, LArIat, ArgonCube, SBND, ProtoDUNE**
- Ionization electrons drifted by uniform electric field towards readout anodic planes (drift ~1 mm/μs @ 500 V/cm)
    - 3D reconstruction + calorimetry
- VUV photons propagated and shifted to VIS photons
    - information on interaction time, triggering + calorimetry



Xiangpan Ji WIN2023

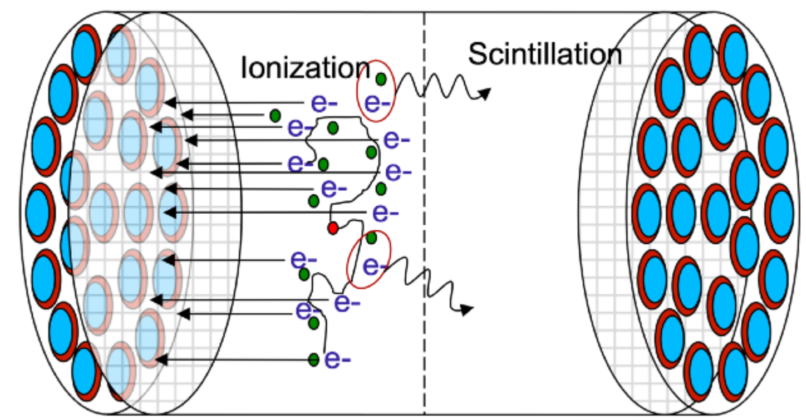
NOBLE LIQUID DETECTORS FOR NEUTRINO PHYSICS

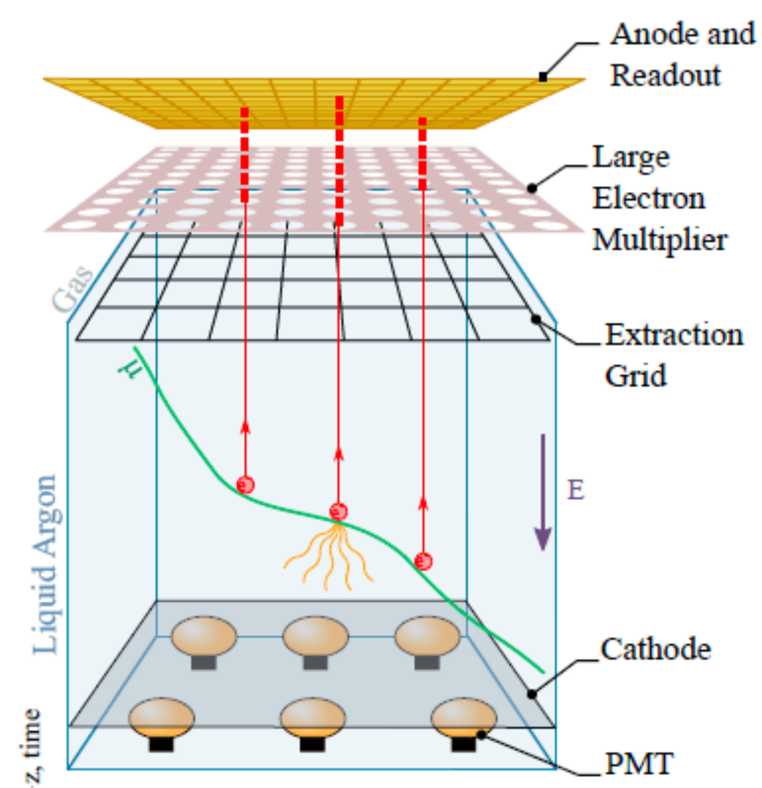
LAr: ICARUS. uBOONE. SBND. DUNE



Single phase LArTPC

LXe: EXO-200, nEXO

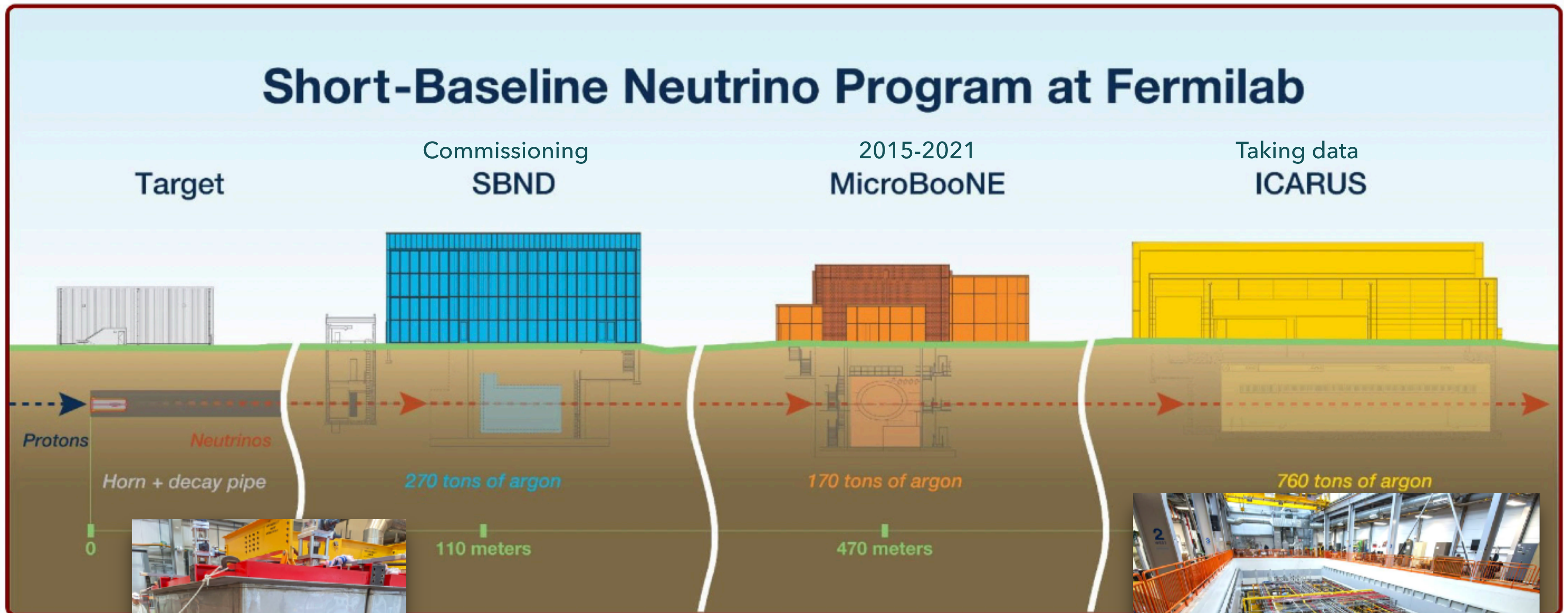




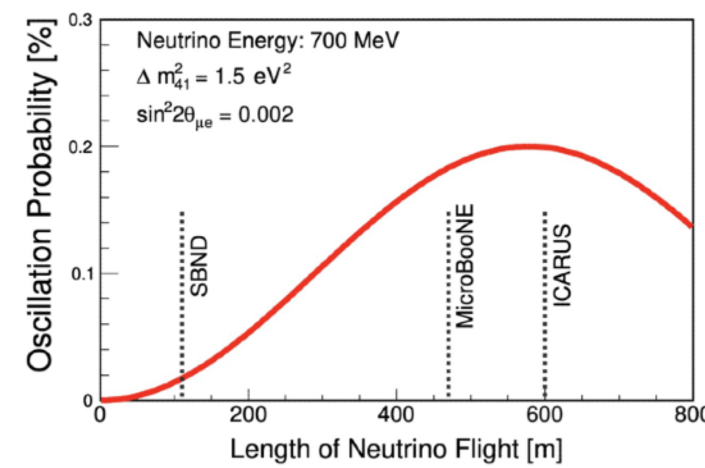
Double phase LArTPC with charge r/o

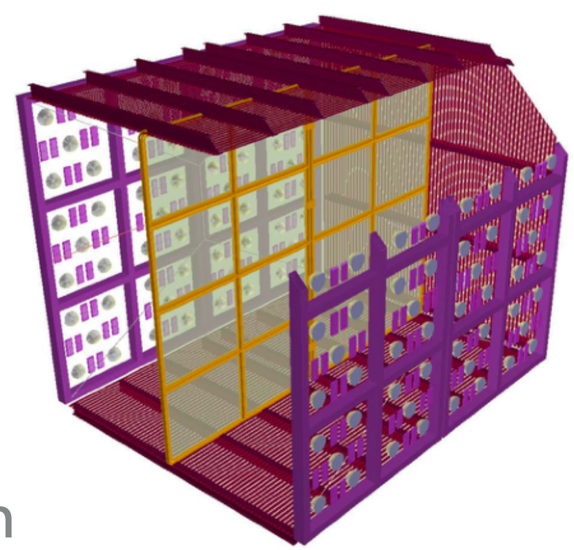
LArTPC NEUTRINO EXPERIMENTS

- Enormous physics potential offered by high granularity imaging, extremely high resolution, low backgrounds:
  - Short-baseline neutrino physics (neutrino anomalies, precision cross-sections, BSM)
  - Long-baseline neutrino physics (precision 3-flavor oscillation physics)
  - Underground physics (proton decay, solar, supernova, …)



- Booster Neutrino Beam $\nu_\mu(93.6\%), \nu_\mu(5.9\%), \nu_e + \bar{\nu}_e(0.5\%)$
- Sterile neutrino searches, BSM searches, cross-section measurements





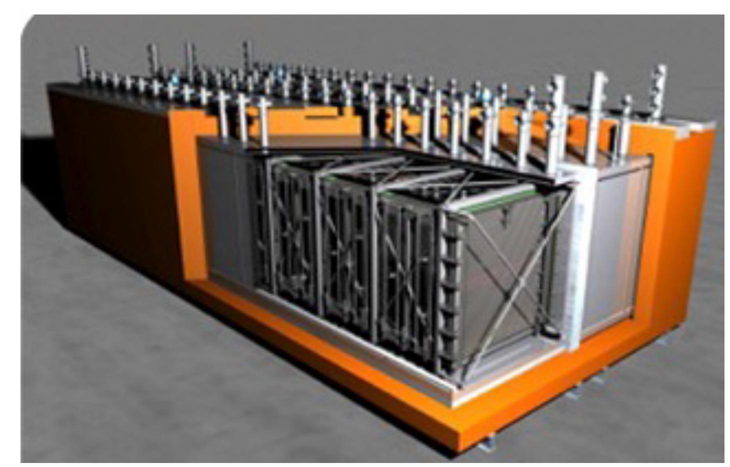
SBND

270 ton - 5 x 4 x 4 m

2 TPC 2 m drift

Wire readout

PDS: 120 PMTs, 192 X-ARAPUCA



ICARUS

760 ton - 2 x (19.6 x 3.6 x 3.9 m)

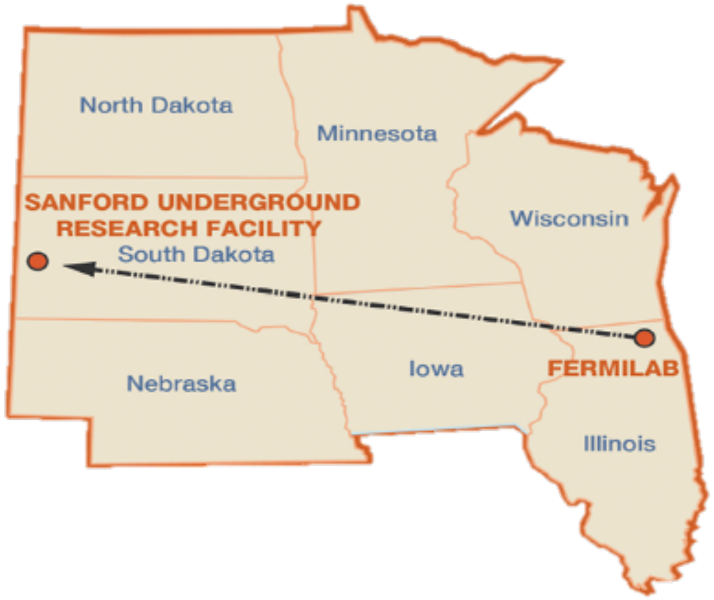
4 TPC 1.5 m drift

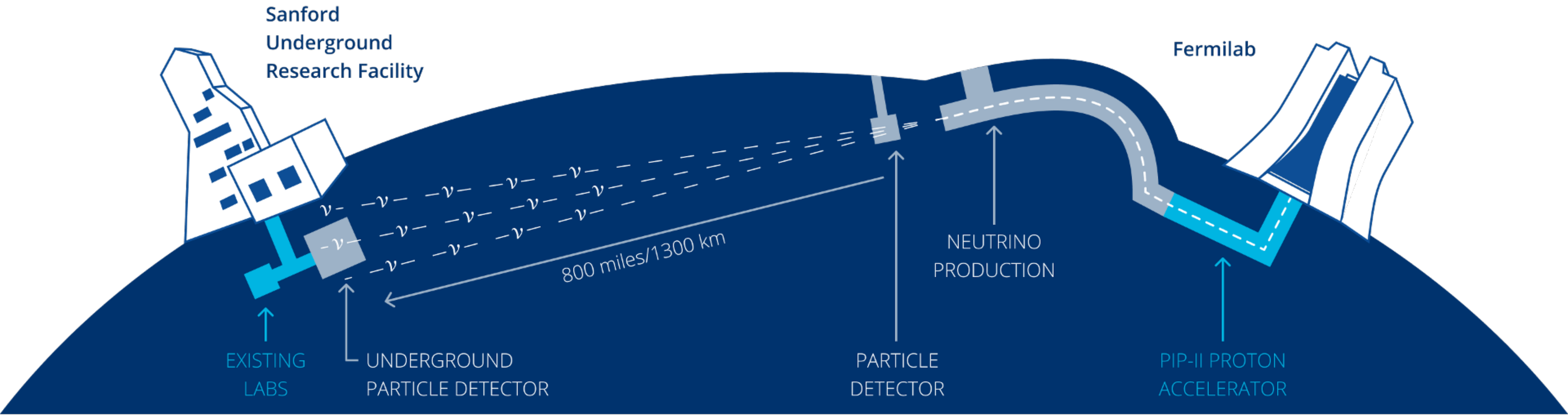
Wire readout

PDS: 360 PMTs

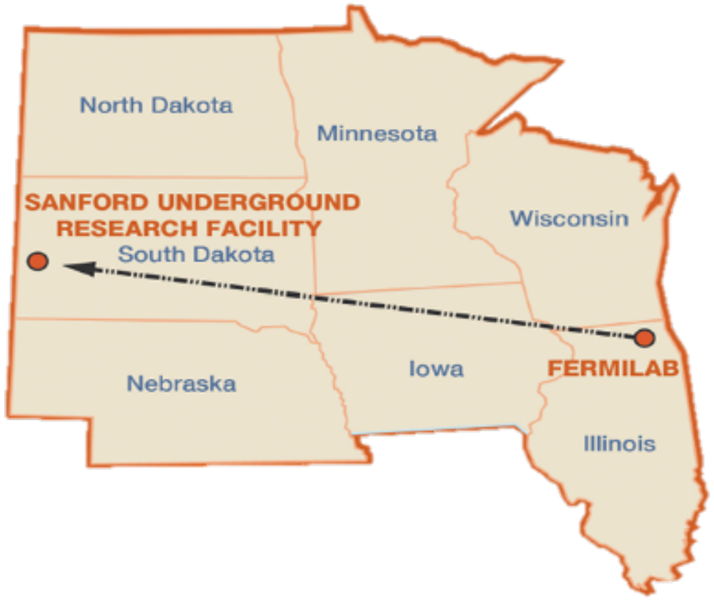
DUNE EXPERIMENT

- High-power proton beam – 1.2 MW upgradeable to 2.4 MW
- A high power, wide-band neutrino beam (~ GeV energy range)
- **Near detector** (**575 m** from the ν source - 100 s millions of ν interaction)
- Far detector in South Dakota (~1300 km) and 1,5 km deep underground
- Phase I: 2×17 kton LArTPC; 2 additional modules in Phase II

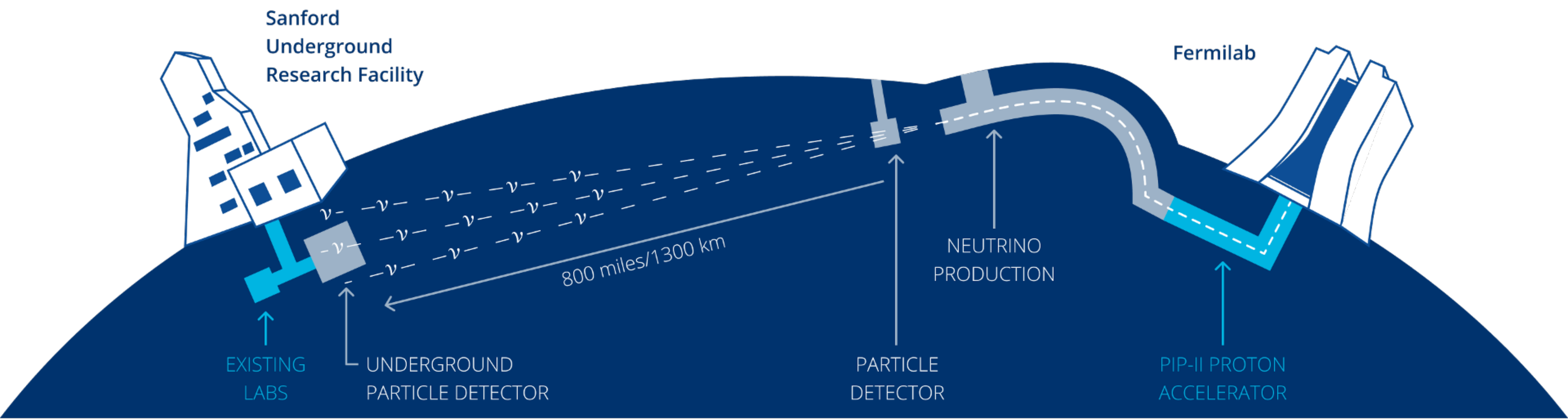




DUNE EXPERIMENT

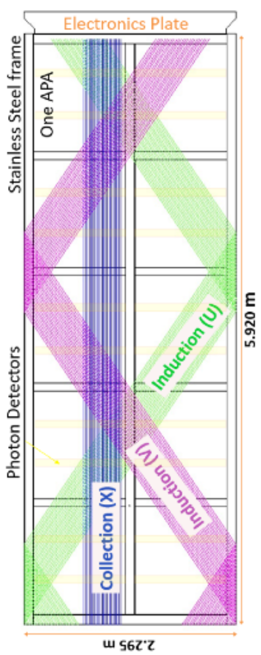


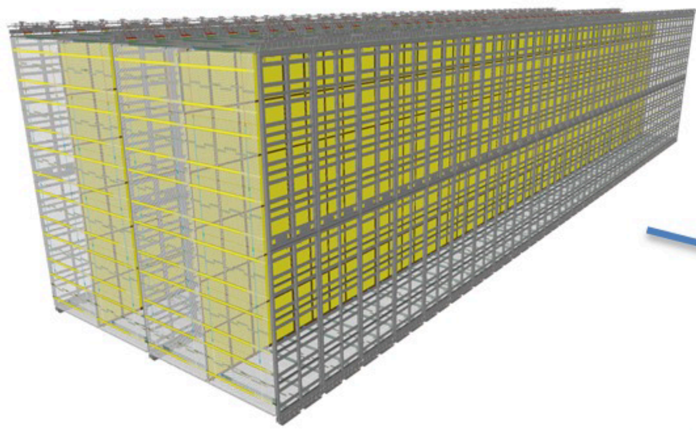
- **Near Detector :** measurements of ν_μ unoscillated beam.
- **Far Detector**: measurements of oscillated ν_μ and ν_e spectra
- **THEN** repeat for antineutrinos – and compare oscillations of neutrinos and antineutrinos



DUNE FAR DETECTOR (PHASE I)

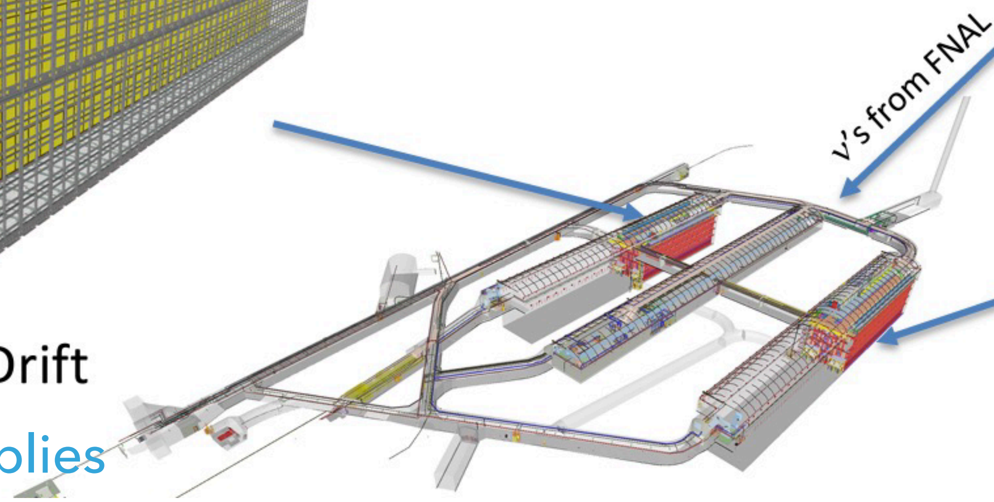
2 ×17 kton single phase LArTPCs

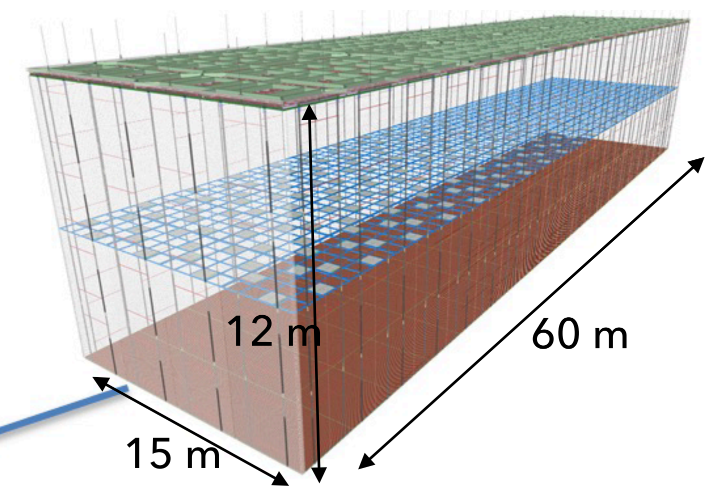




APA* Horizontal Drift

* Anode Plane Assemblies



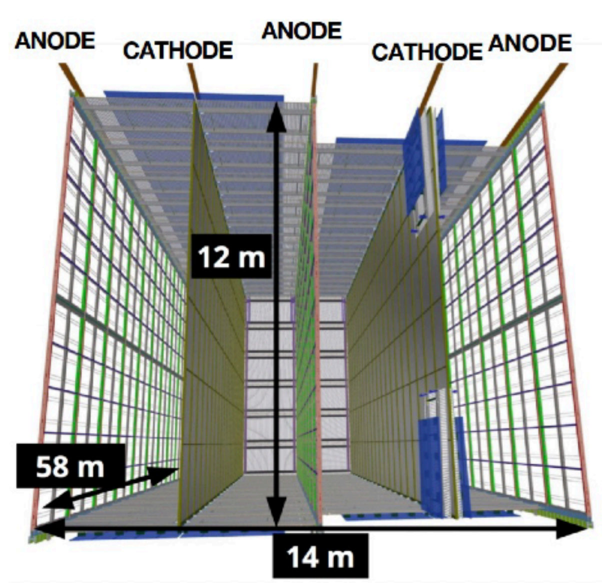


CRP** Vertical Drift

** Charge Readout Planes

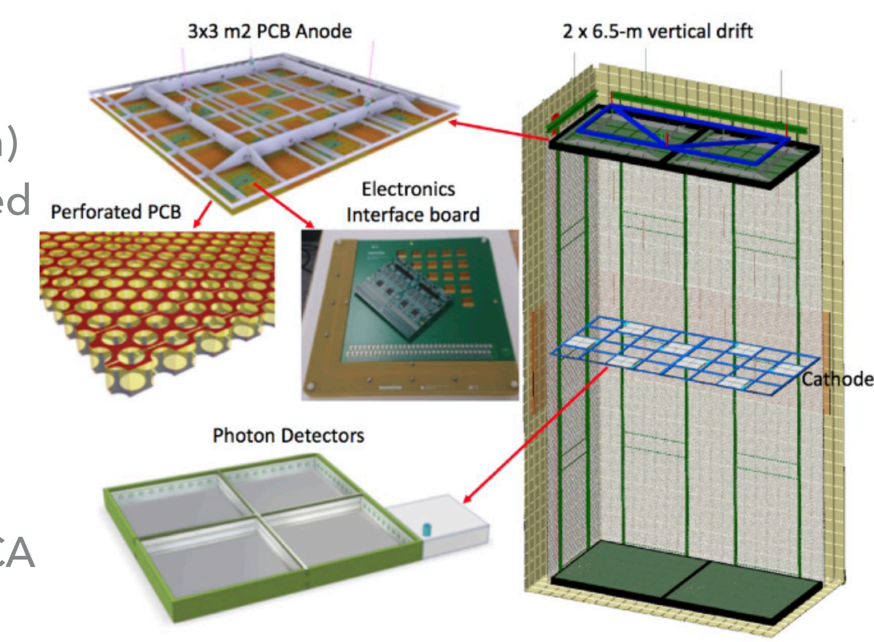
FD1-HD

- 4 TPC 3.6 m horizontal drift
- HV = -180 kV
- High-resistivity CPA for fast discharge prevention
- Anode: 150 APAs, each with 4 wire planes (Grid, 2x Induction, Collection)
- Photon Detectors: X-ARAPUCA modules embedded in APA

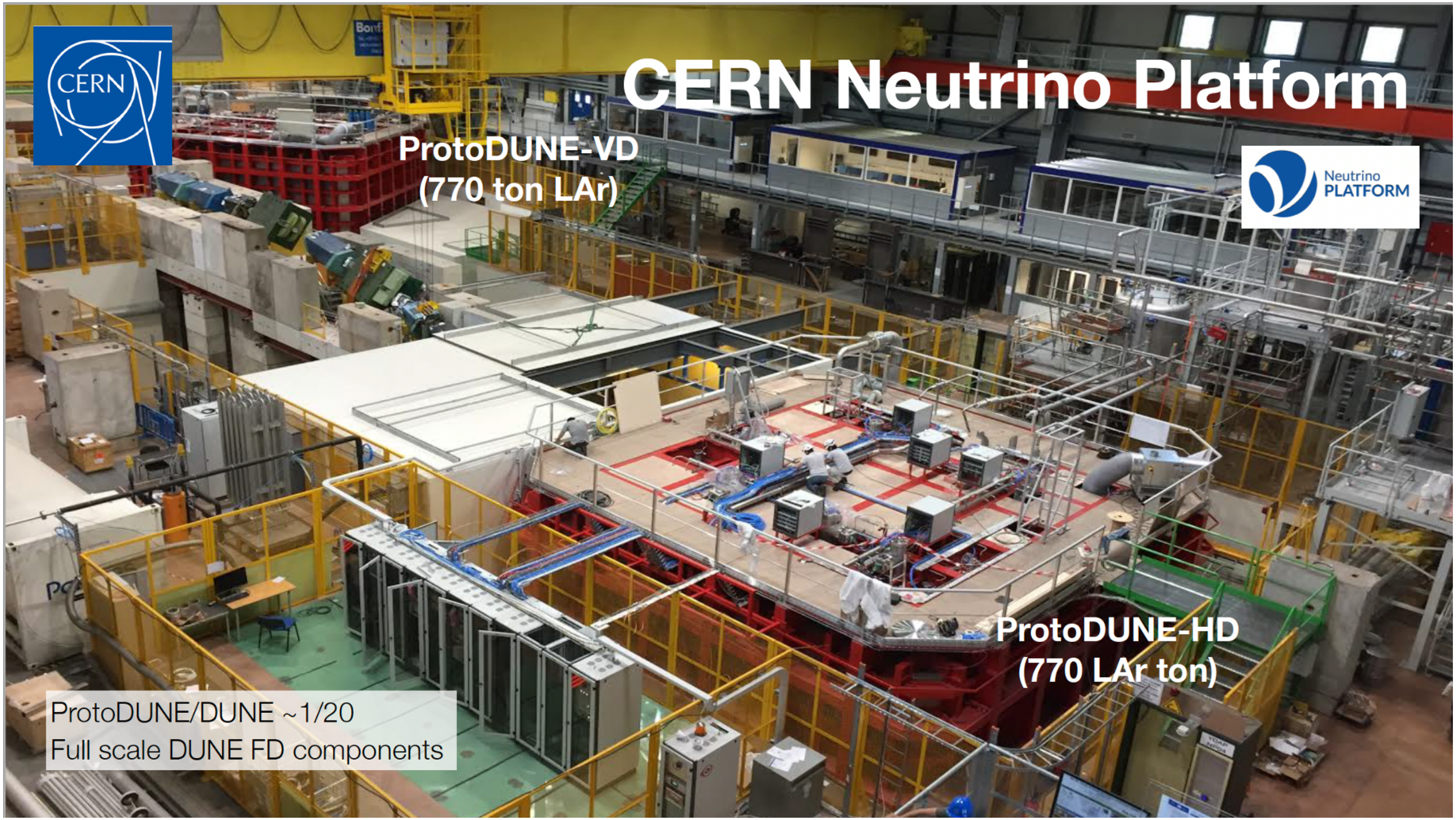


FD2-VD

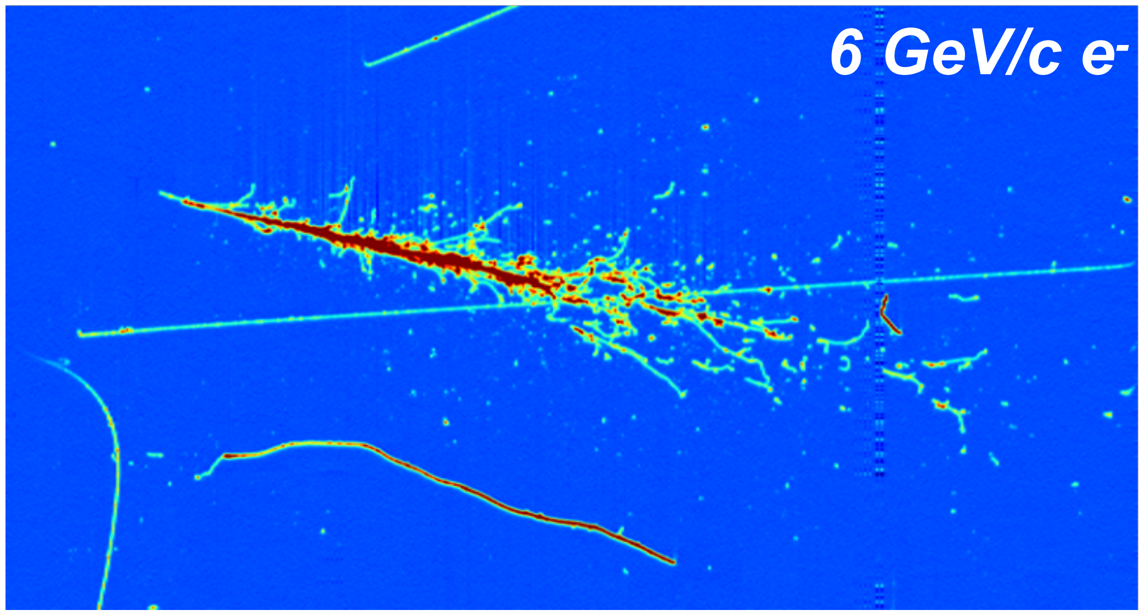
- 2 TPC 6.5 m vertical drift
- HV = -300 kV
- Anode: 2 CRPs (top & bottom)
- Charge Readout via perforated PCB anode, fully immersed in LAr
- Doping w/ O(10 ppm) xenon for greater light collection uniformity
- Photon Detectors: X-ARAPUCA megacell modules integrated on cathode and on cryostat walls

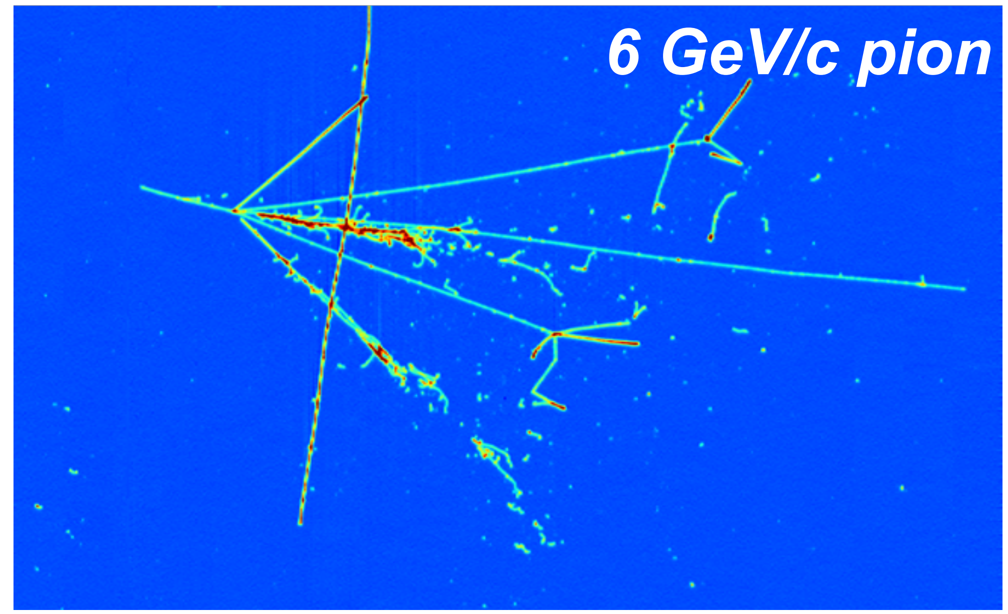


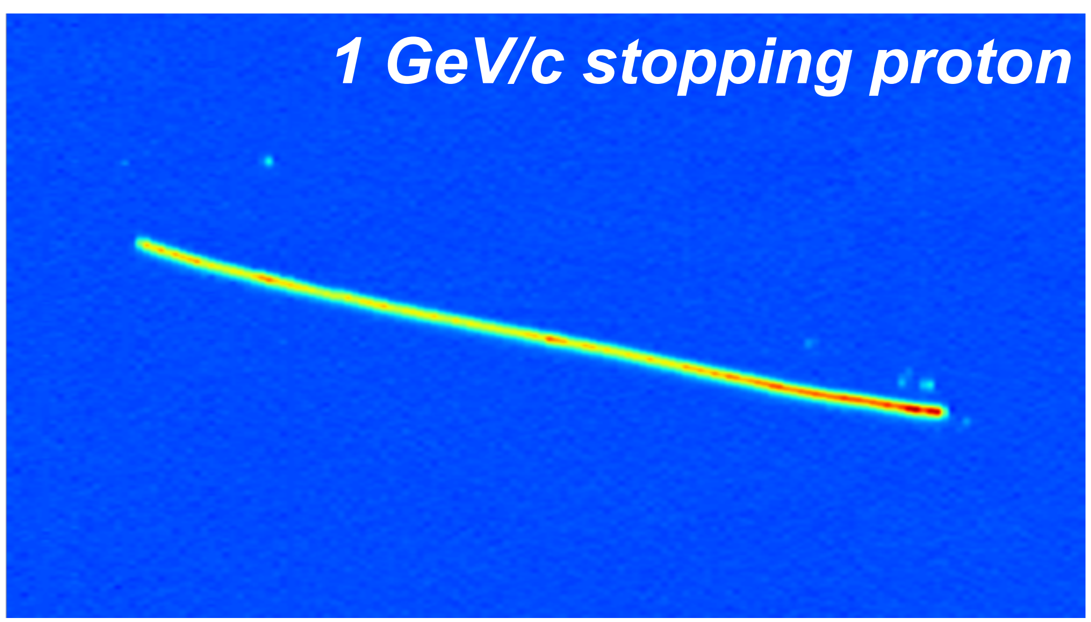
PROTODUNE

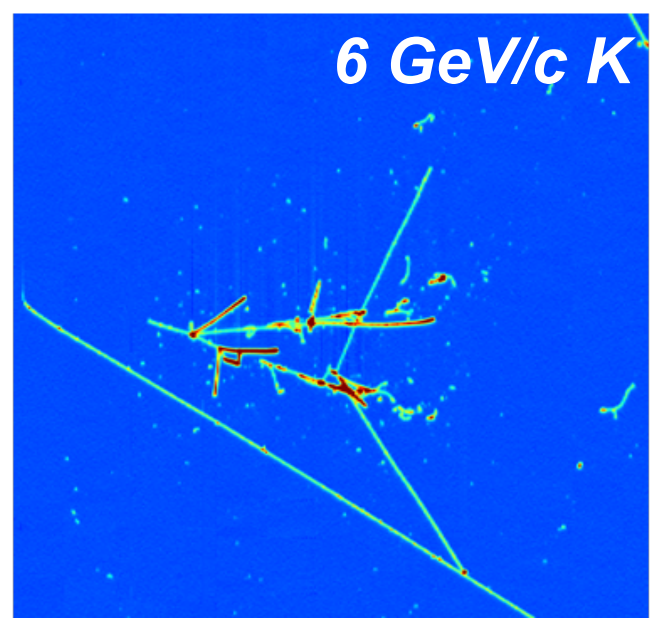

CERN Neutrino Platform
CERN
Neutrino PLATFORM
ProtoDUNE-VD
(770 ton LAr)
ProtoDUNE-HD
(770 LAr ton)
ProtoDUNE/DUNE ~1/20
Full scale DUNE FD components

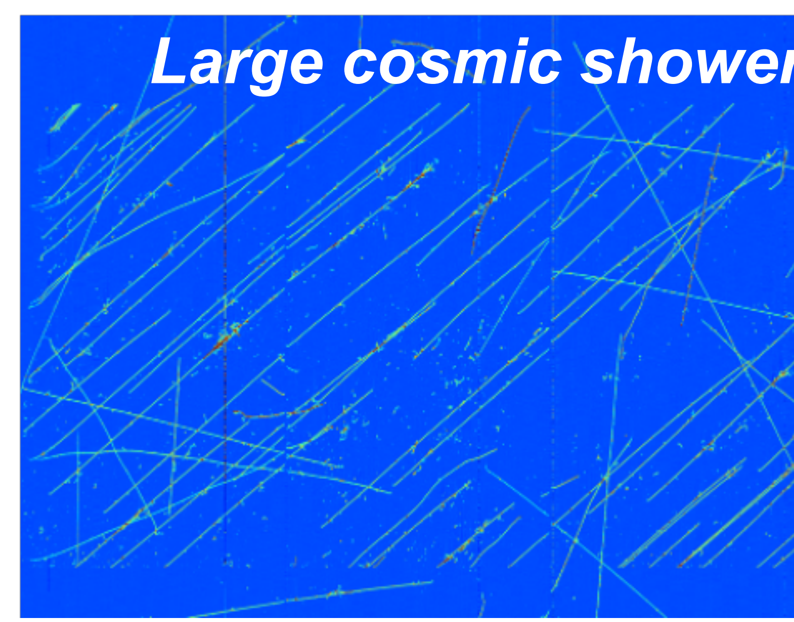
PROTODUNE


6 GeV/c e-


6 GeV/c pion

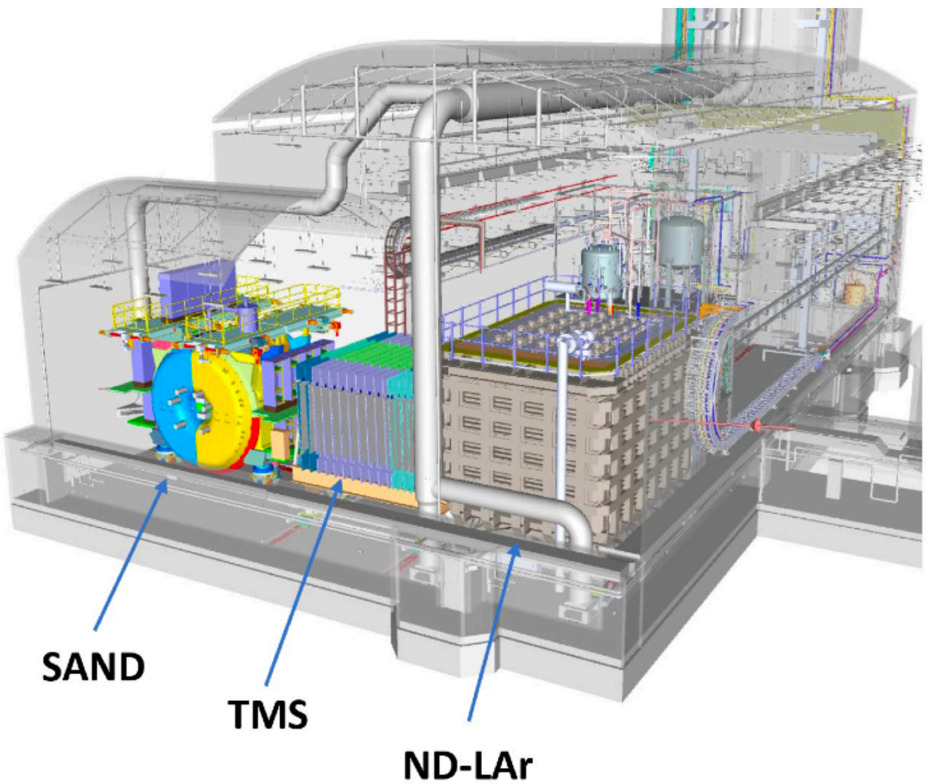

1 GeV/c stopping proton


6 GeV/c K


Large cosmic shower

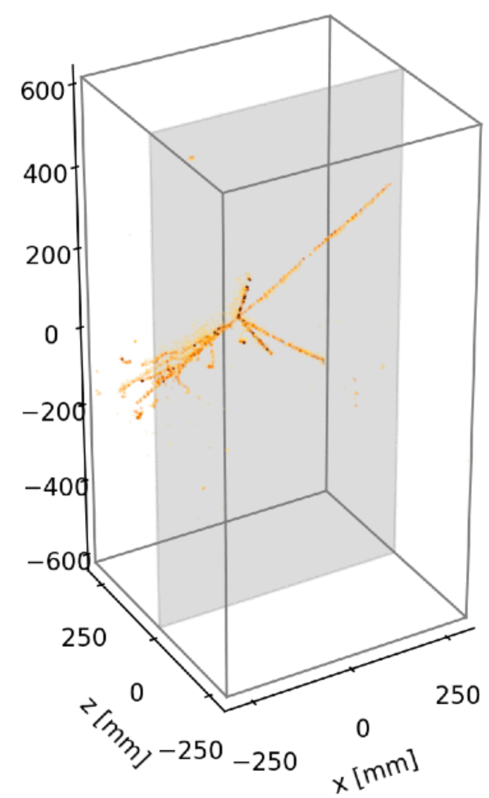
DUNE NEAR DETECTOR COMPLEX (PHASE I)

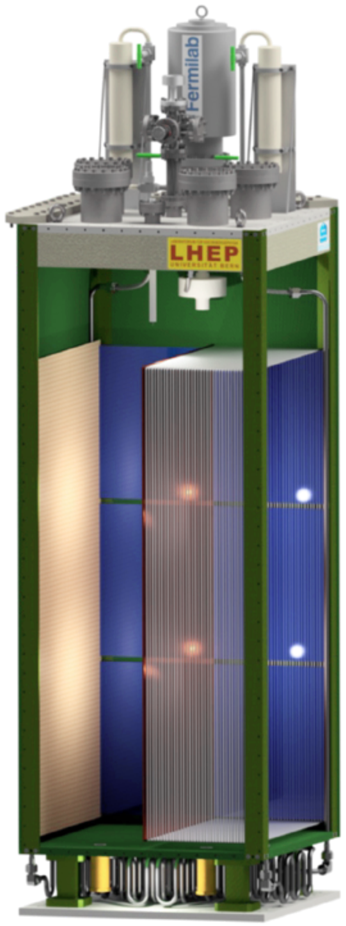
- Measures the neutrino beam rate and spectrum to predict unoscillated event rates in the far detector
- Constrains systematic uncertainties (flux, cross sections, detector response) for oscillation measurements
- Additional physics program



- ND-LAr: 67 ton 7×5 array of modular 1×1×3 m LArTPCs with 50 cm drift, pixel readout and high coverage light readout
- TMS: magnetized steel range stack for measuring muon momentum/sign from ν_μ CC interactions in ND-LAr
    - DUNE-PRISM: ND-LAr + TMS move up to 28.5m off-axis
- SAND: on-axis magnetized neutrino detector with 1 ton LAr target (GRAIN), tracking (STT), and calorimeter (ECAL)

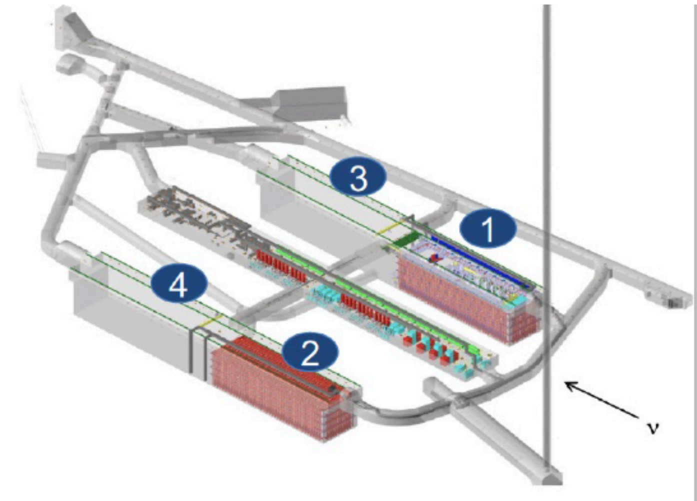
Raw 3D images of cosmic rays in ton-scale prototype



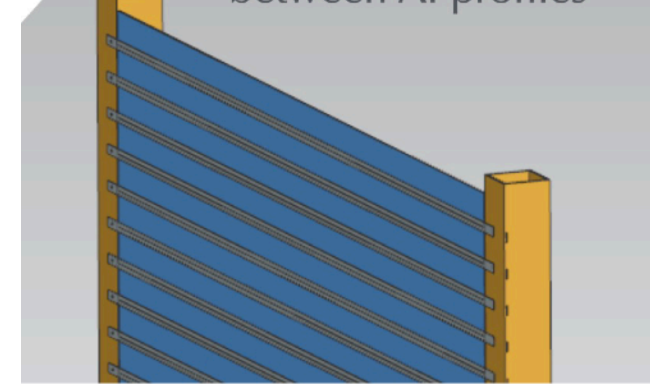


DUNE PHASE II

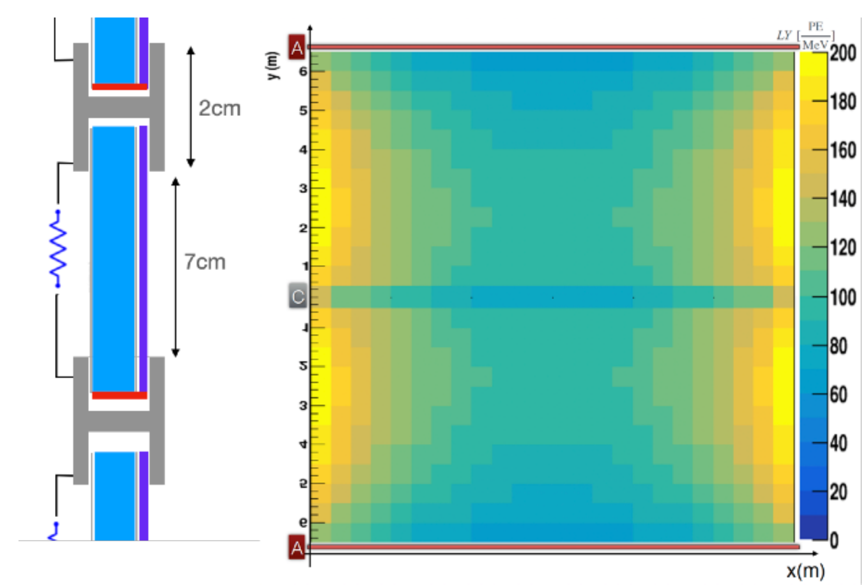
- **Far Detector with 4 modules**
  - FD-3 SP LArTPC enhanced VD 4π concept TBD (by 2027)
  - FD-4 : «module of opportunity»: decision by 2028
- **Beam power upgrade to 2.4 MW**
- **Near Detector: TMS replaced by ND-GAr**
  - ND-LAr
  - ND-GAr important for higher precison ν-Ar measurements and when the statistics reach ~200 kt-MW-yrs
  - SAND



FD3-4 FC panels with long, thin xARAPUCA detectors between Al profiles



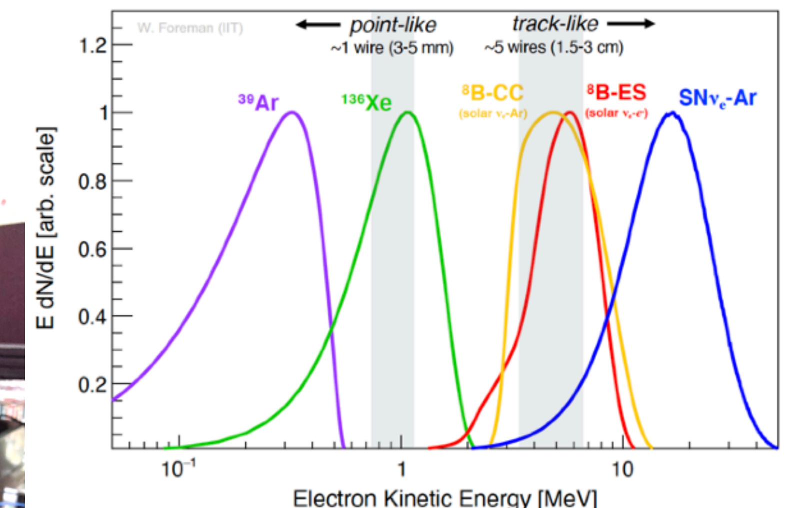
convert TPC Field Cage structure into a fully active PDS → LY ×2

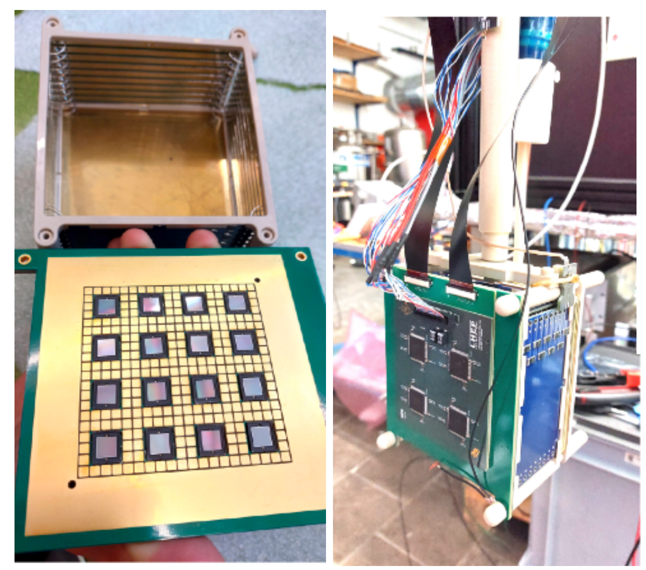


DUNE PHASE II: EXPLORE NEW TECHNOLOGIES

- **General LAr TPC Requirements for Low-Energy Physics**
  - low E threshold (down to 100-10 keV)
  - good angular resolution (<1°)
  - high position and vertex resolution (<1 mm)
- **Key improvements of the detector**
  - Charge readout: from combination of 2D views to genuine 3D pixelated readout
    - LArPix, QPix
  - Light detection:
    - Xe doping, 4π readout, metalenses, metasurfaces
  - Light-charge integrated highly granular readout:
    - all-silicon unit based on VUV SiPMs with charge collection pads (SOLAR)
    - QPix + thin-film photoconductor (ASe) coating
  - Fully optical readout:
    - double phase LArTPC (ARIADNE)
  - Reconstruction algorithms with AI methods
  - Low radiological background

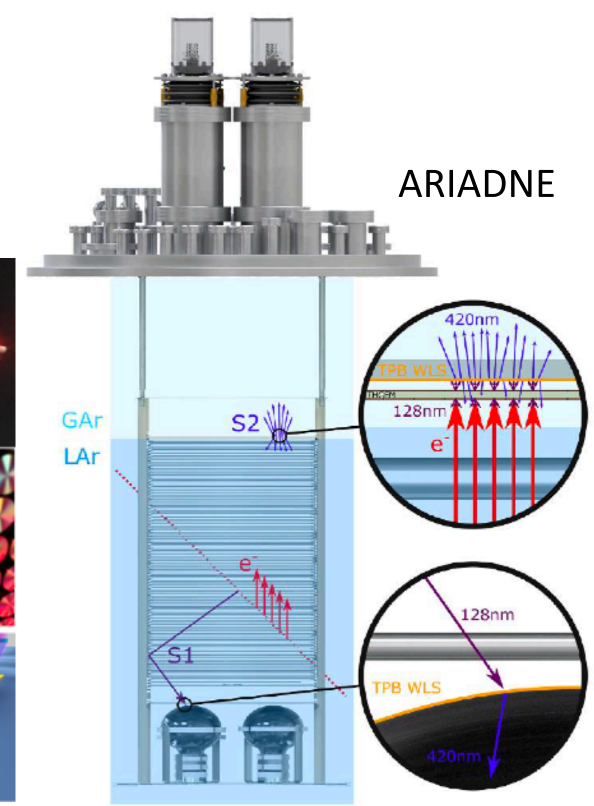
J. Phys. G: Nucl. Part. Phys. 50 033001





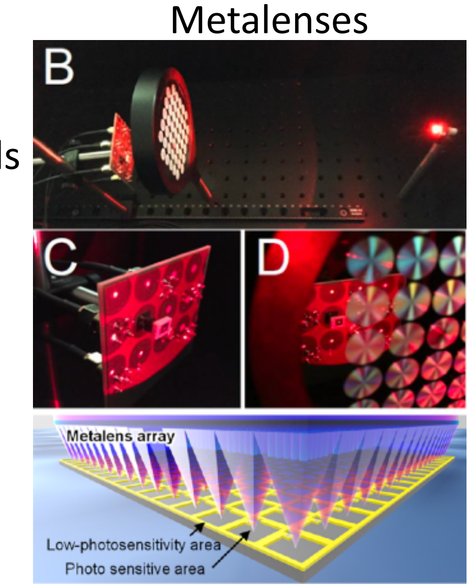
SOLAR prototype

Timepix3 cameras

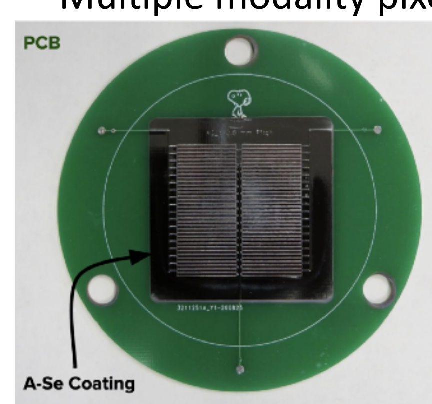


ARIADNE

Metalenses

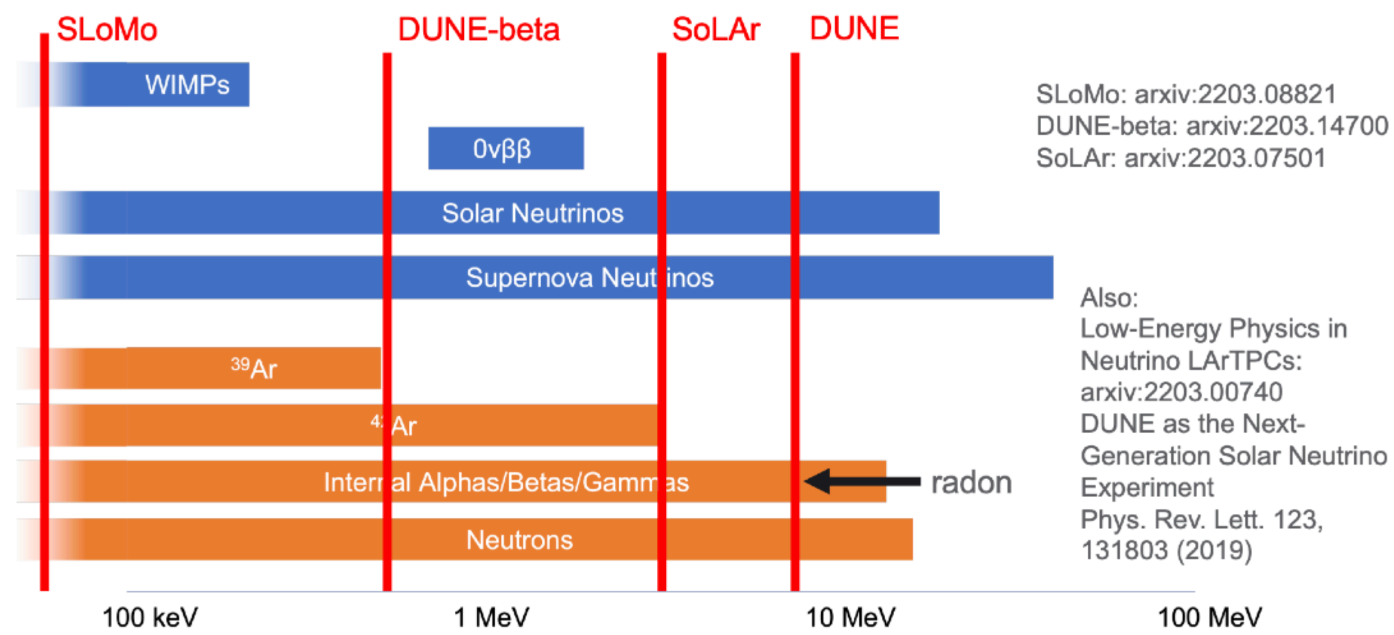


Multiple modality pixels

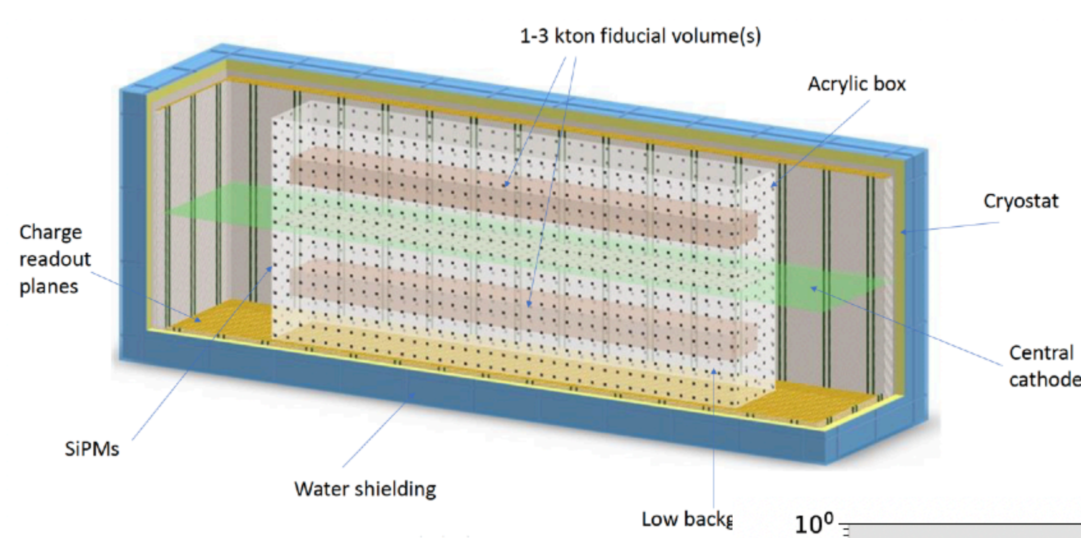


DUNE PHASE II: BLUE SKY

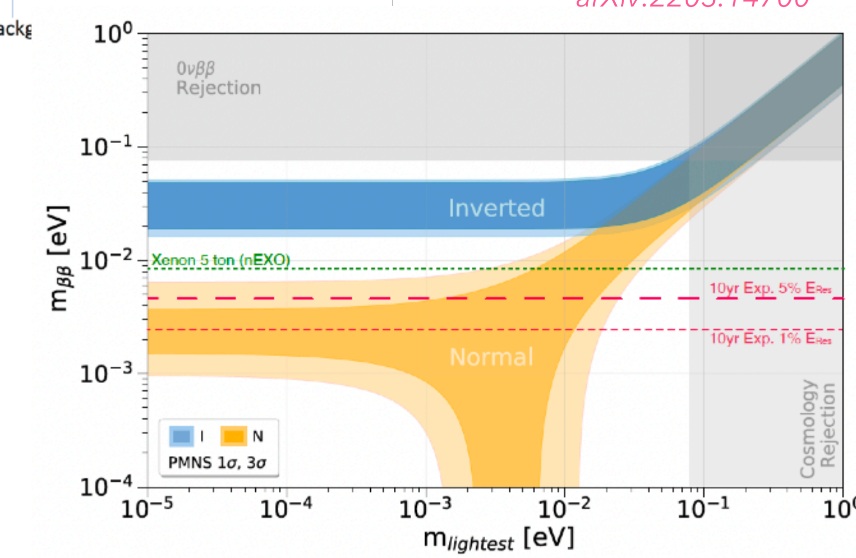
- Further Low-Energy Physics goals:
  - Measurement of lower-energy neutrinos in real time with high statistics
  - $0\nu\beta\beta$
  - WIMP dark matter
  - CEvNS…
- Higher detector challenges:
  - External shielding
  - Materials selection QA/QC
  - Radon reduction
  - Low-radioactivity underground argon
  - % level energy resolution
  - % level Xe-doping
  - Photosensitive dopants
  - …



Chris Jackson, Seattle Snowmass Summer Meeting 2022



arXiv:2203.14700



NL DETECTORS

$0\nu\beta\beta$

THE NATURE OF NEUTRINOS

- Can be probed with a rare nuclear decay, the double beta decay mode without emission of neutrinos (ΔL =2)

$$2n \rightarrow 2p + 2e^-$$

$$2p \rightarrow 2n + 2e^+$$

- Expected signature: sharp peak at the Q-value of the decay

$$Q = E_{1e} + E_{2e} - 2m_e$$

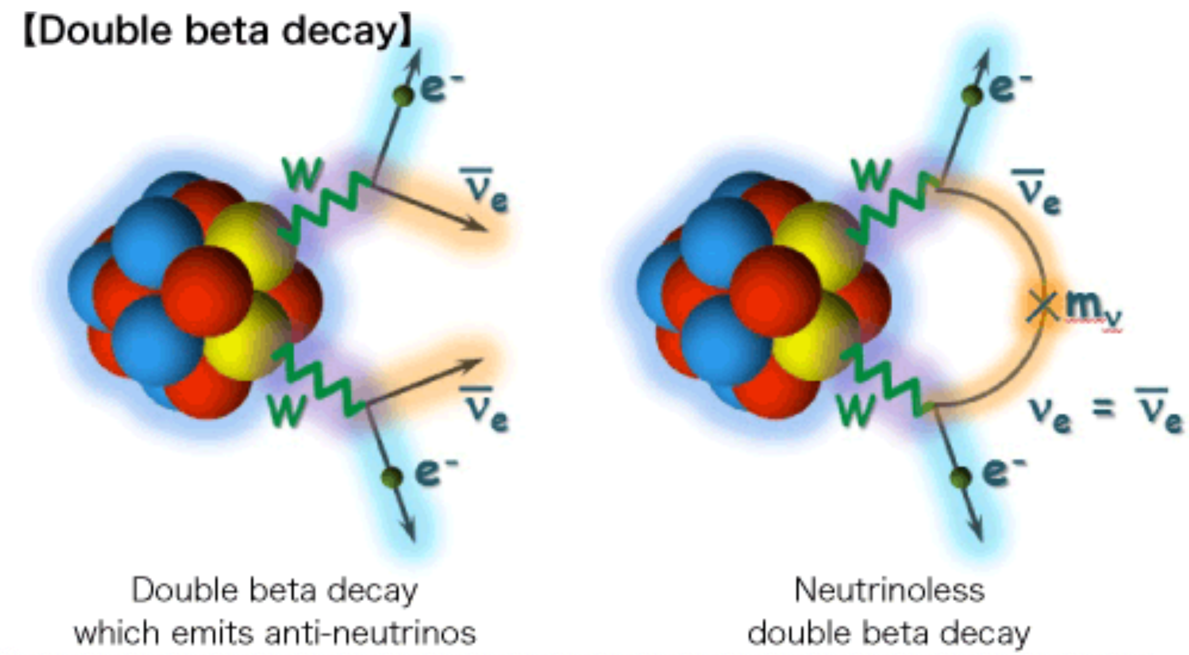
Minimal detector requirements:

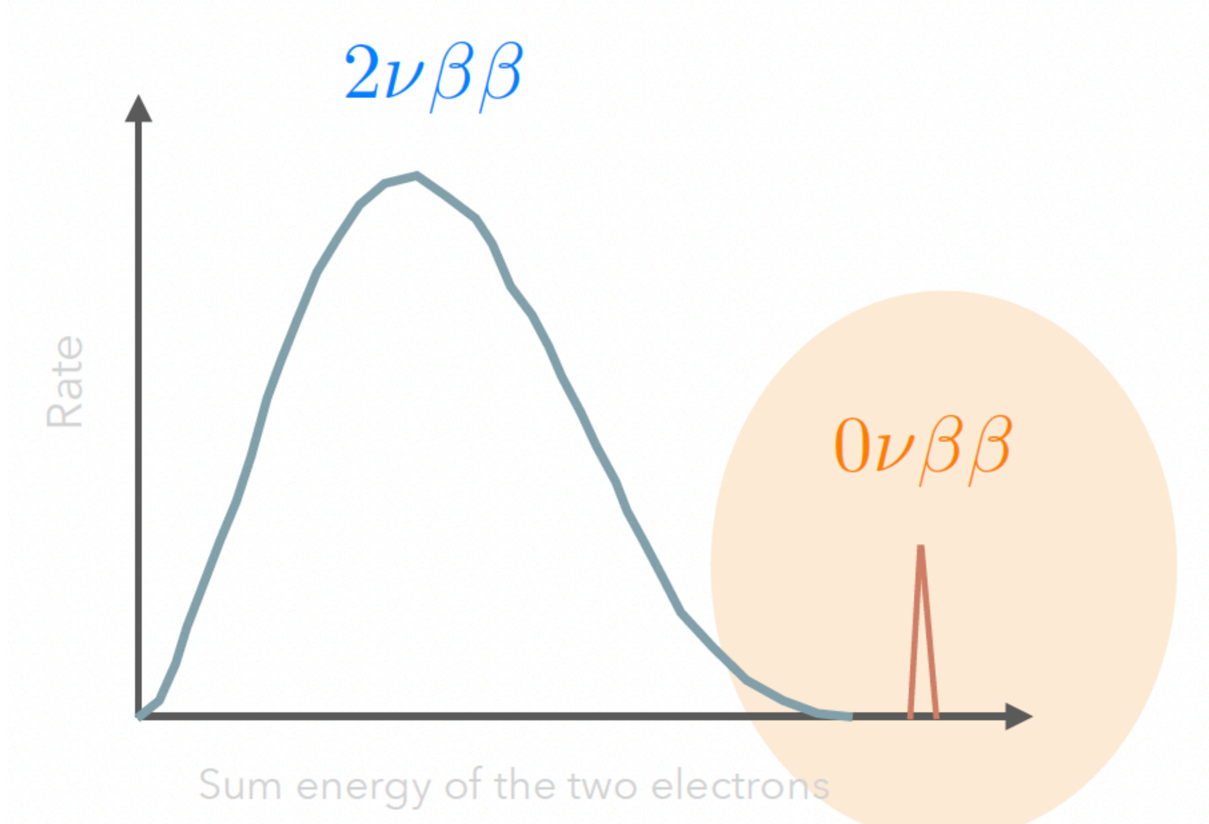
Large masses

High isotopic abundance

Ultra-low background noise

Good energy resolution





EXPERIMENTAL TECHNIQUES

TPCs:
LXe: EXO-200, nEXO
DARWIN/XLZD, NEXT

Ionisation

Tracking: SuperNEMO

Crystals: GERDA, Majorana, LEGEND, COBRA

Scintillation

Isotope in LS: KamLAND-Zen, SNO+

Crystals: CANDLES

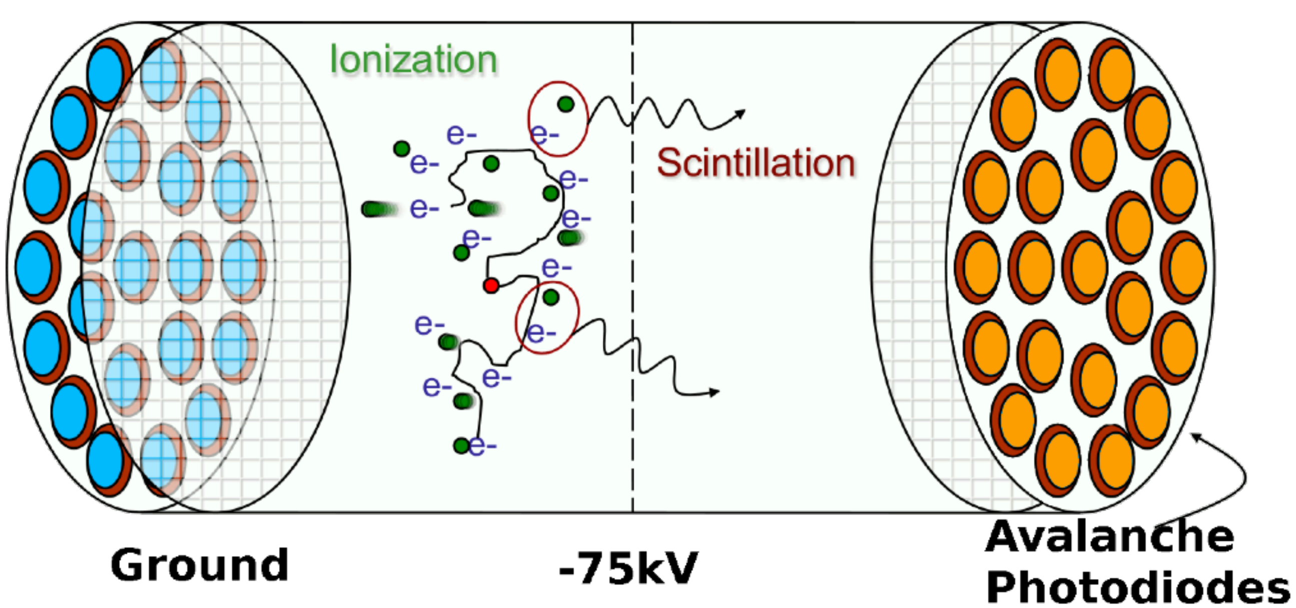
Scintillating bolometers:
AMoRe
CUPID

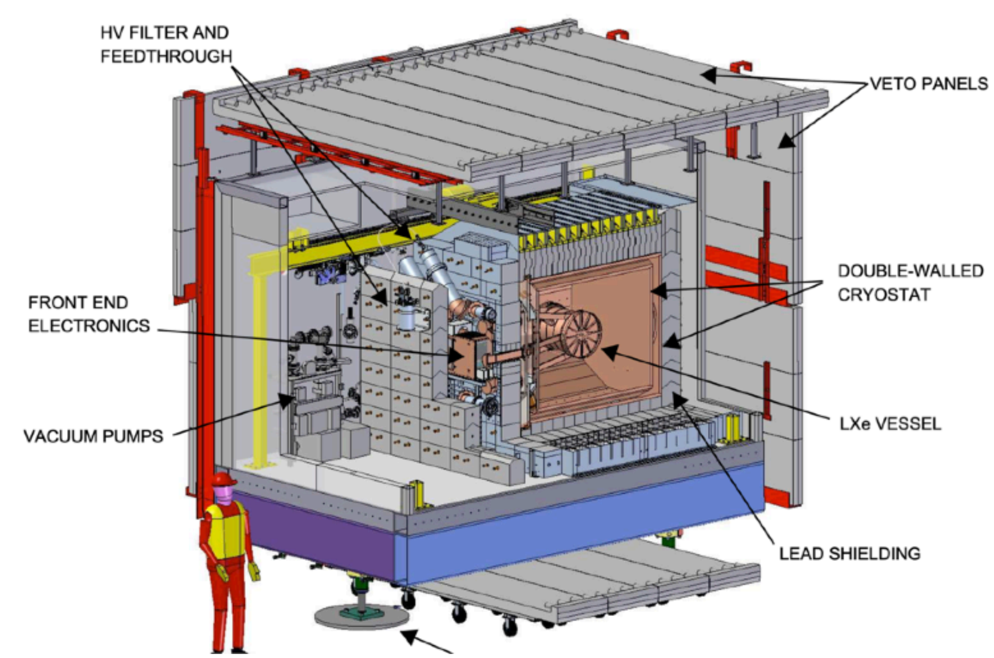
Phonons

Bolometer: CUORE

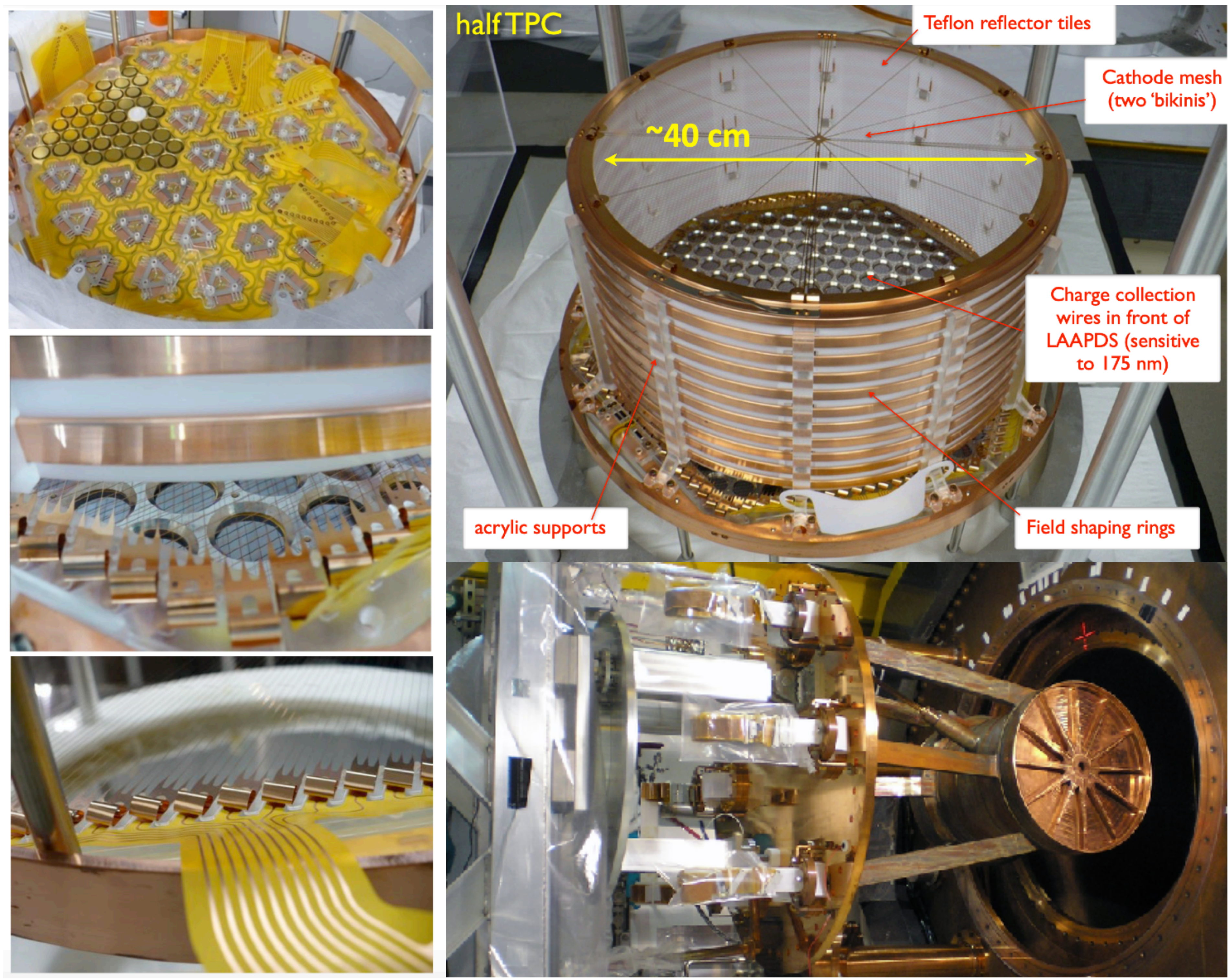
LIQUID XENON TPC: EXO-200

- At Waste Isolation Pilot Plant (WIPP, ~1600 m w.e.), took data fro, Sept 2011 - Dec 2018, in two phases
- 175 kg LXe in total, 80.6% enriched in ^{136}Xe ($Q_{\beta\beta}$ ~2.46 MeV)
- TPC with two drift regions, each with a radius of 18 cm and drift length of 20 cm; drift field: 380 V/cm (phase I) and 567 V/cm (phase II)
- Two measurements of energy deposited in event
  - Scintillation light (178 nm), by large avalanche photo-diodes (APDs)
  - Ionization charge, by 2 wire grids (induction and collection)
- TPC enclosed by a radio-pure, thin-walled Cu vessel in cryofluid, surrounded by passive shielding and an active muon veto system



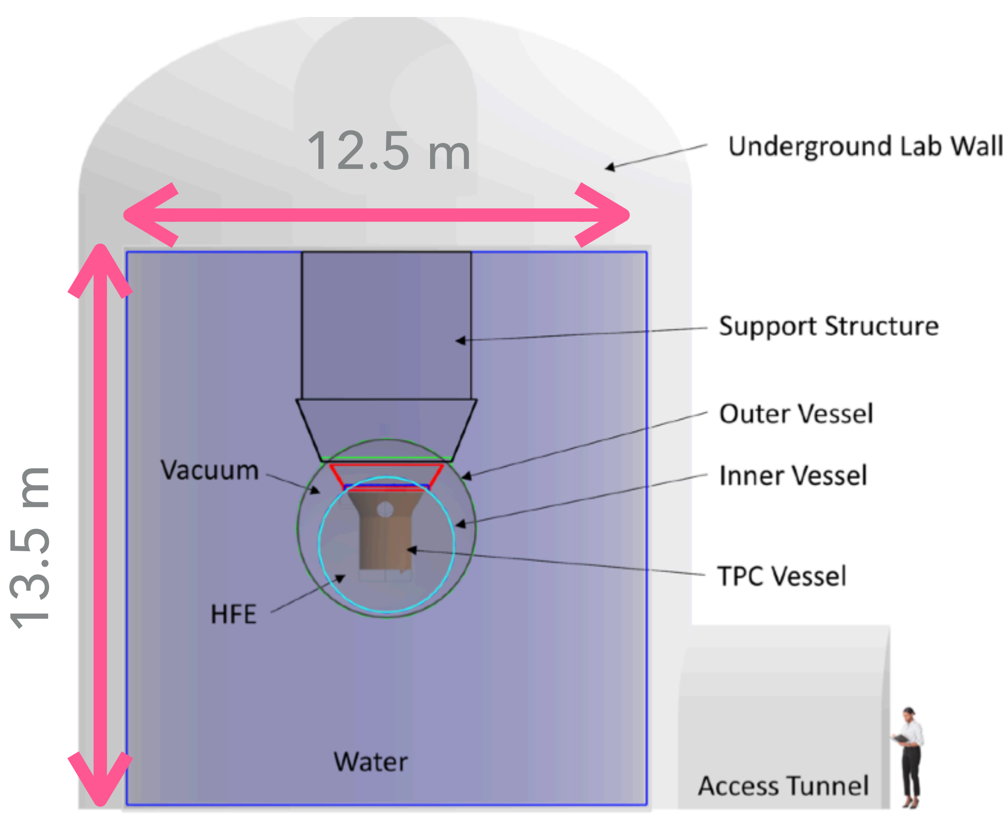


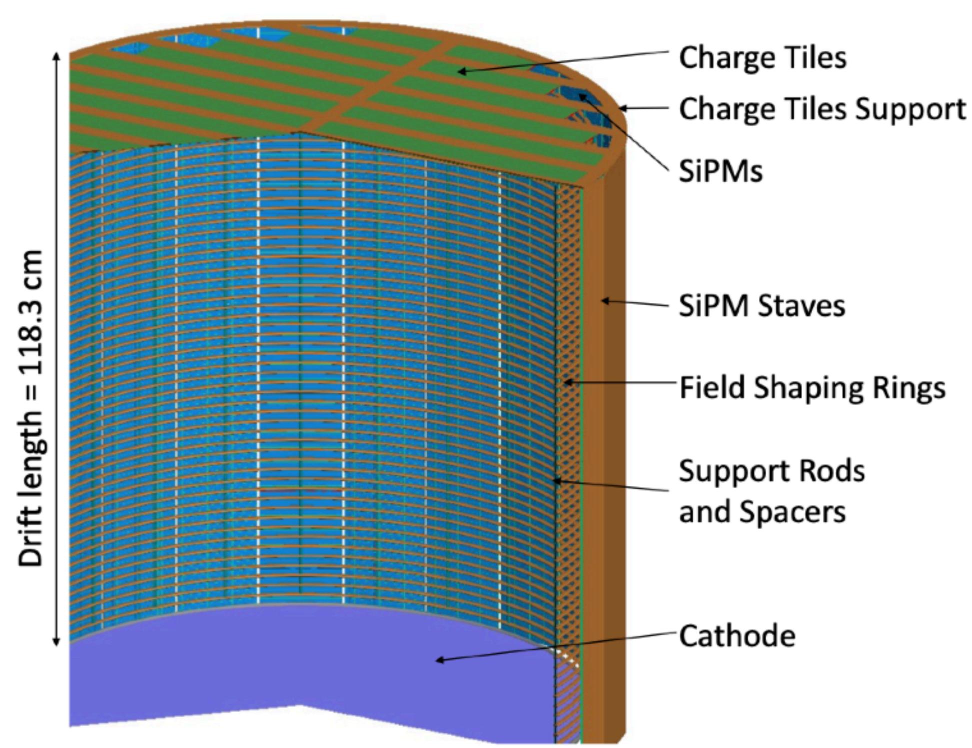
LIQUID XENON TPC: EXO-200

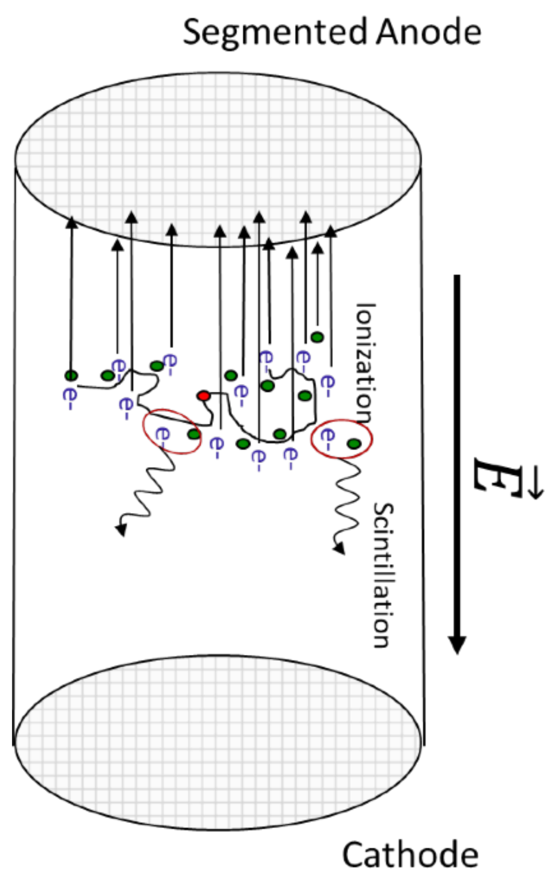


LIQUID XENON TPC: THE nEXO EXPERIMENT

- TPC filled with enriched xenon, surrounded by 33 t of hydro-fluoro ether (HFE) as thermal bath and radiation shield; thin-walled, electro-formed Cu cryostat, water Cherenkov muon veto
- TPC vessel: Cu cylinder with 127.7 cm height & ø with 4.8 t (3.65 t) contained (active) Xe
- Charge: collected at the anode by ~3800 Channels in 120x10cm tiles
- Scintillation light: collected by SiPM arrays arranged in a barrel configuration ~7700 channels over 4.6m²
- Combine both for <1% energy resolution at $Q_{\beta\beta}$







SUMMARY

- Neutrino and DM experiments exploring New Frontiers with Noble Liquids
- Technological challenges boost synergies in noble liquid experiments:
  - Time projection chambers (TPCs) for particle tracking and interaction visualization
  - Light and charge signal detection for particle identification and energy measurement
  - Cryogenic systems for noble liquid handling and purification
  - Data analysis, calibration and background reduction techniques
- Ever-growing community fostering innovation:
  - Many more developments for CEvNS, $0\nu\beta\beta$, low-mass DM, …
  - R&D to bring the full potential of these great detectors!

➠ *several topics not covered here*