TIPP2023

NOBLE LIQUID EXPERIMENTS

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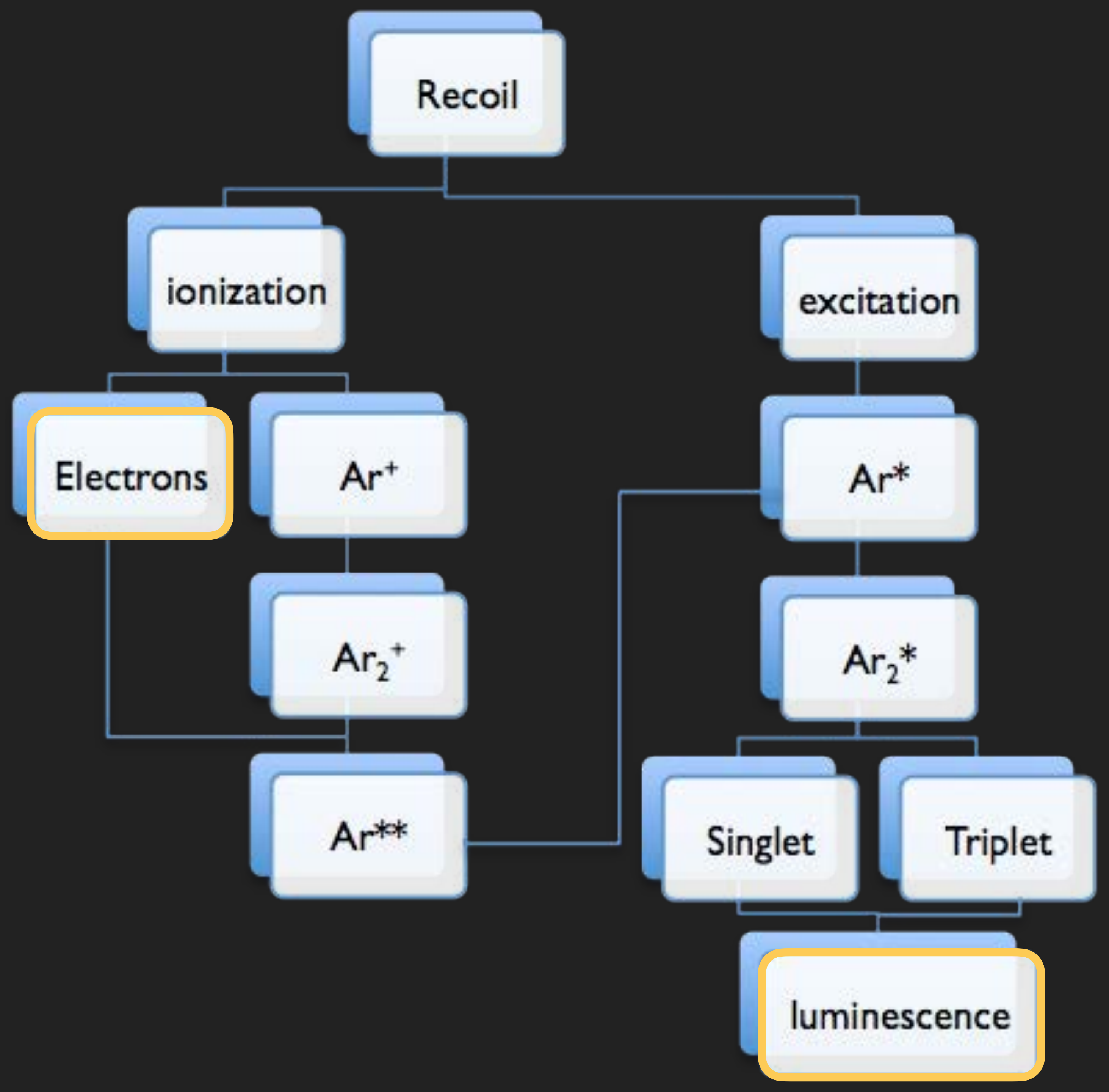
OUTLINE

- Noble Liquid Detectors
- Neutrino Experiments
- Dark Matter Experiments
  - Focus on
    - Key Technologies
    - Future Prospects

LIQUID ARGON AND XENON AS PARTICLE DETECTORS

- high density and large stopping power
  - Massive and self-shielding detectors
- both scintillation/ionization with high yields
  - Calorimetry, excellent energy resolution
  - Particle identification
  - Precise timing
- do not attach electrons, can be purified in-situ
  - Tracking, 3D reconstruction, low-background
- inert, non flammable, very good dielectrics
- can be obtained commercially

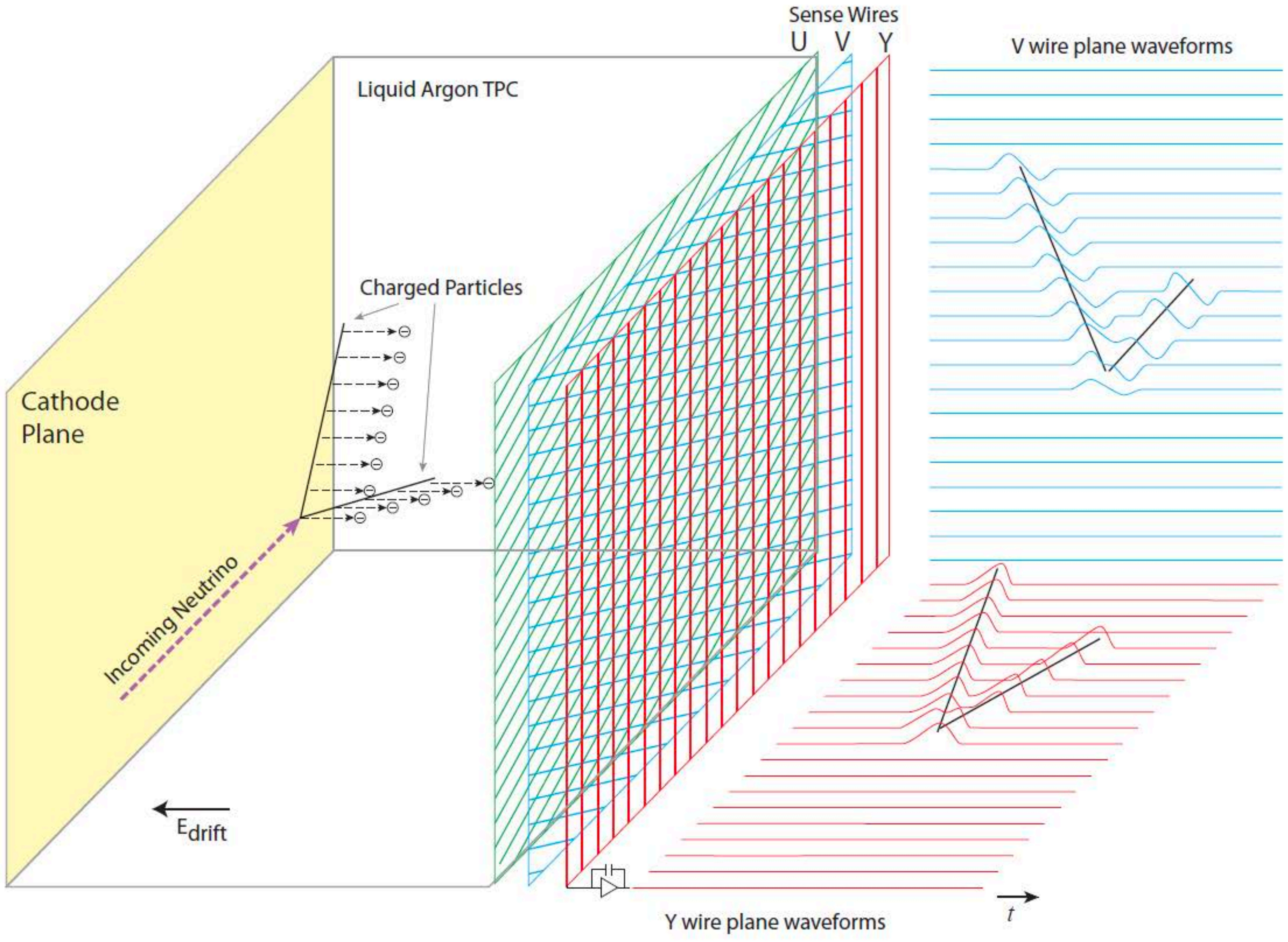


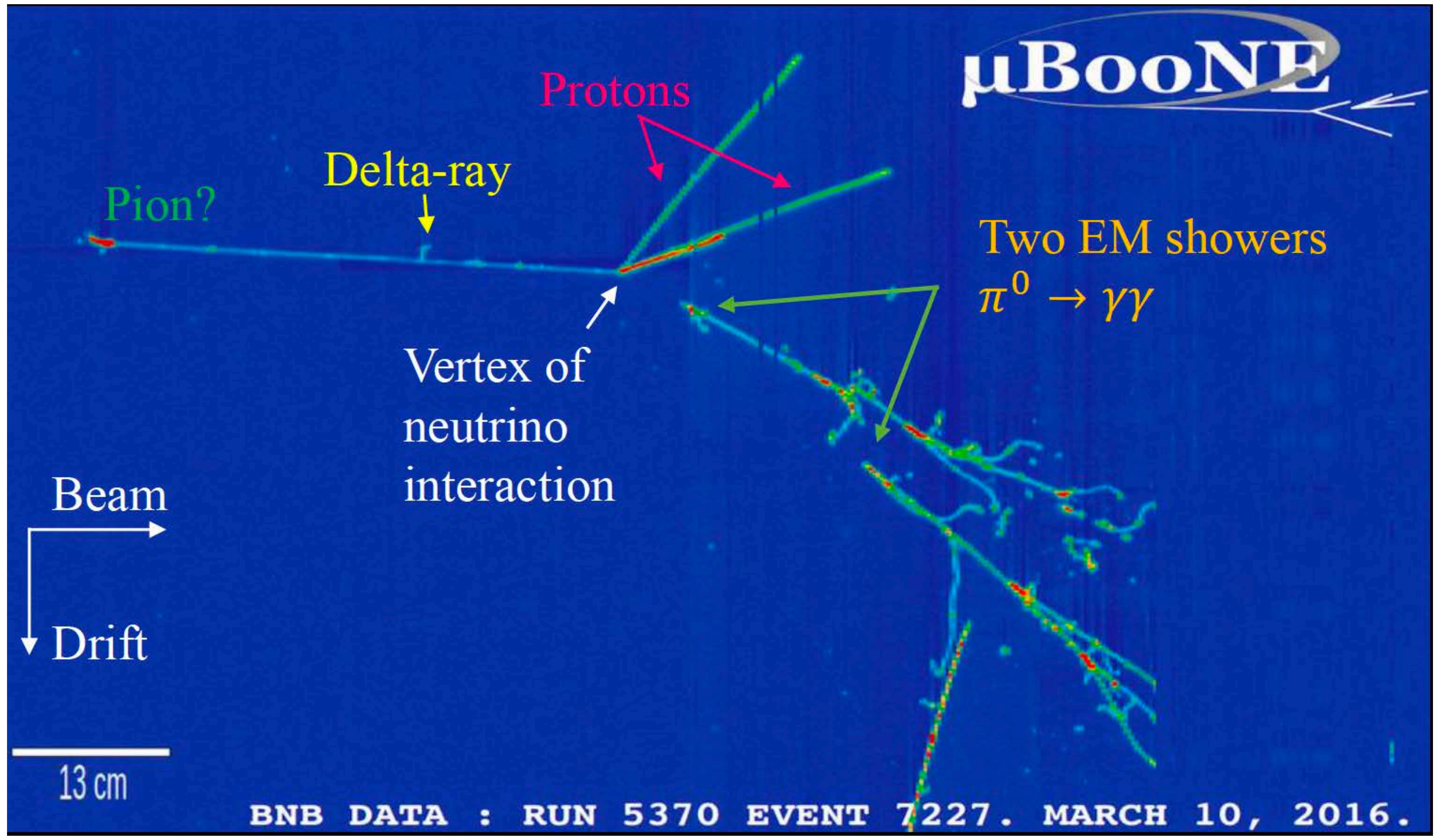
Properties	Argon	Xenon
Boiling Point T_b at 1 atm [K]	87.3	165.0
Liquid density at T_b [g/cm³]	1.40	2.94
Dielectric constant of liquid	1.51	1.95
Scintillation wavelength	128 nm	178 nm
Time constant	6 ns, 1.5 μs	3 ns, 27ns
Scintillation yield [γ/MeV]	40000	46000
Ionization yield [e/MeV]	42000	64000
Volume fraction in Earth's atmosphere [ppm]	9340	0.09

Large homogenous detectors for rare events

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



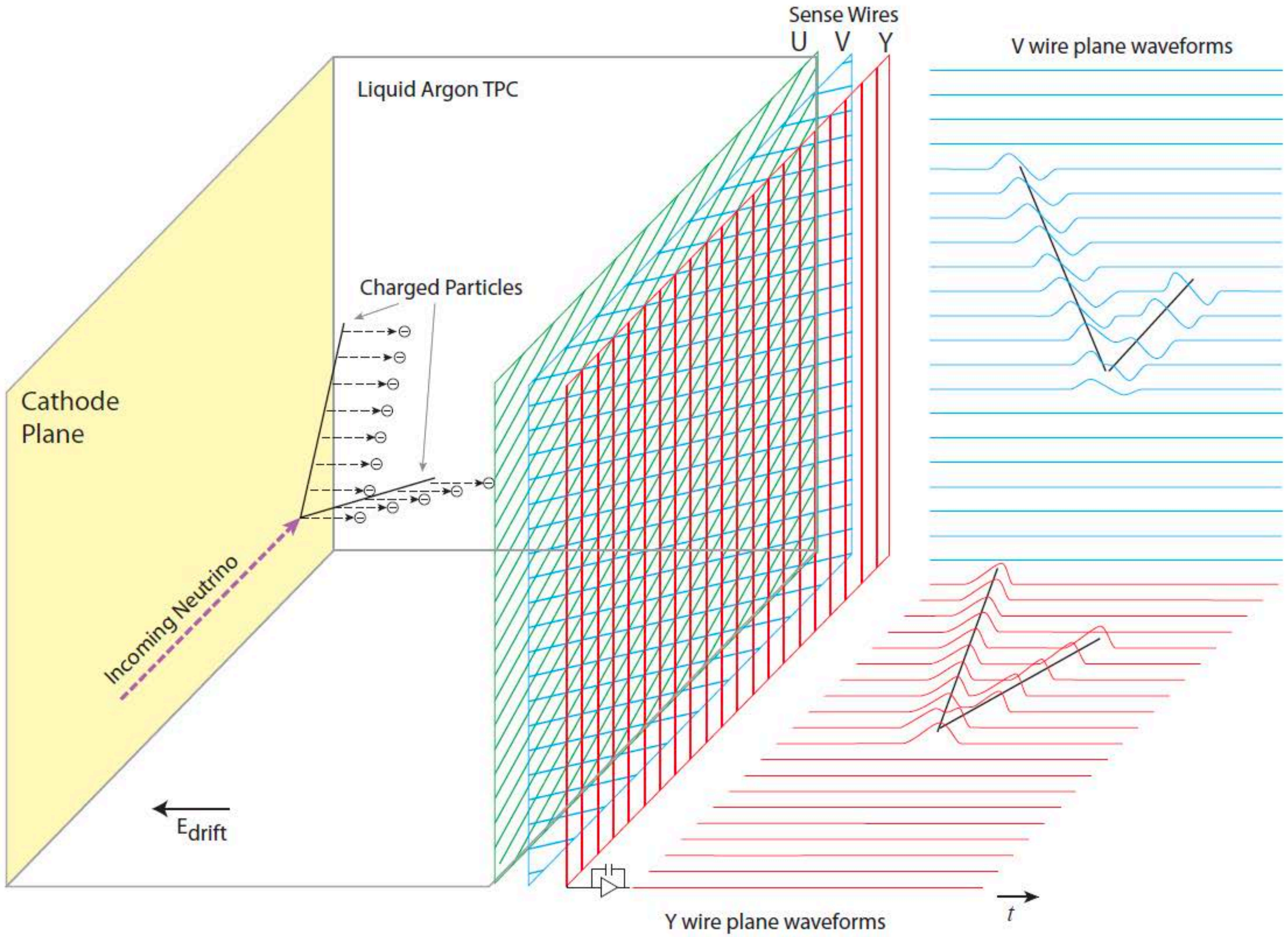


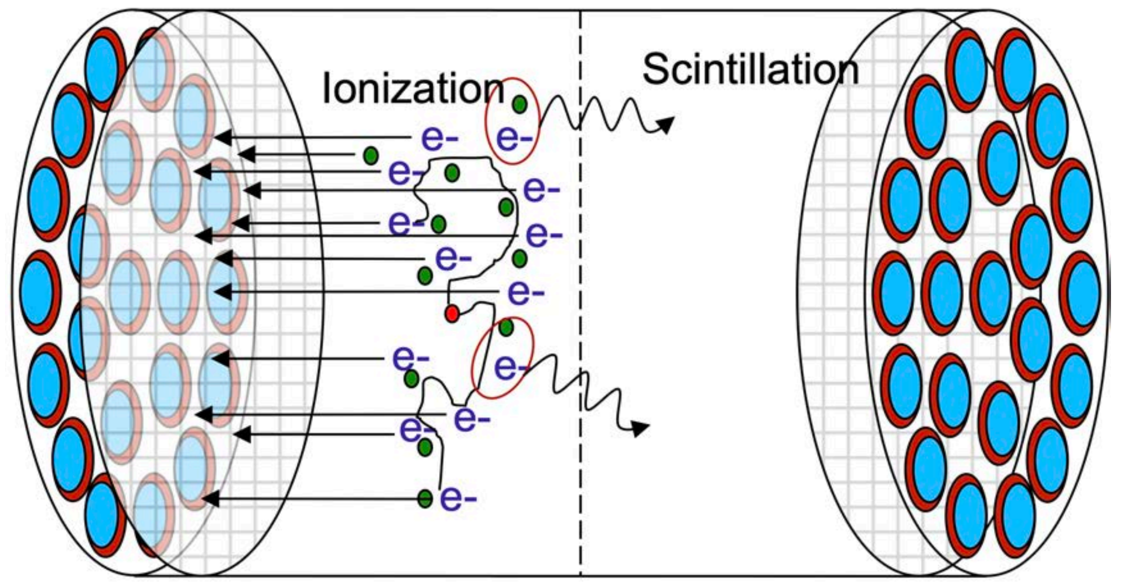
Xiangpan Ji WIN2023

See also Andrea Tesi in B4

NOBLE LIQUID DETECTORS FOR NEUTRINO AND DM

LAr: ICARUS, μBOONE, SBND, DUNE **Single phase LArTPC**

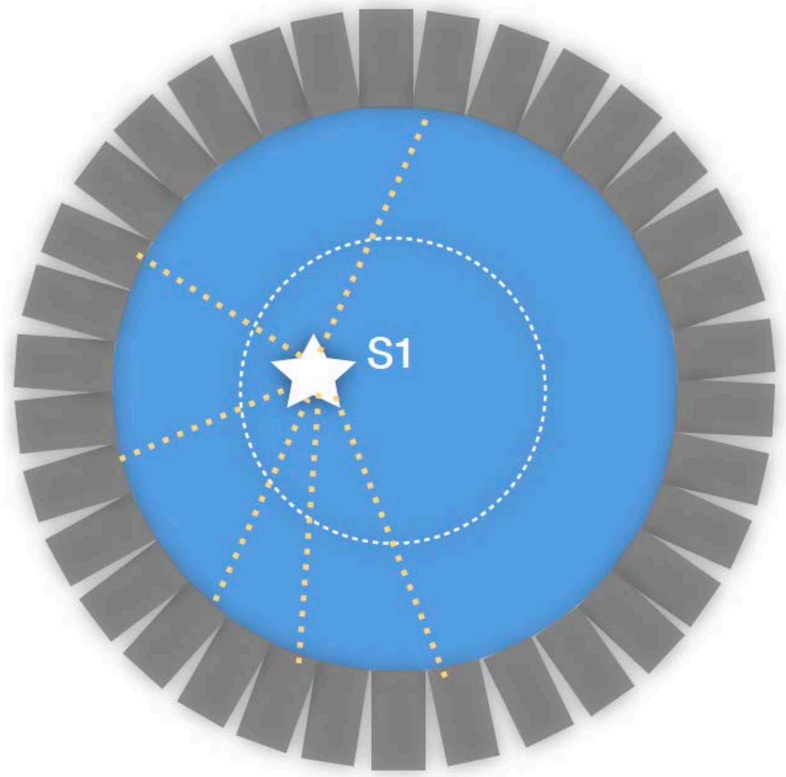


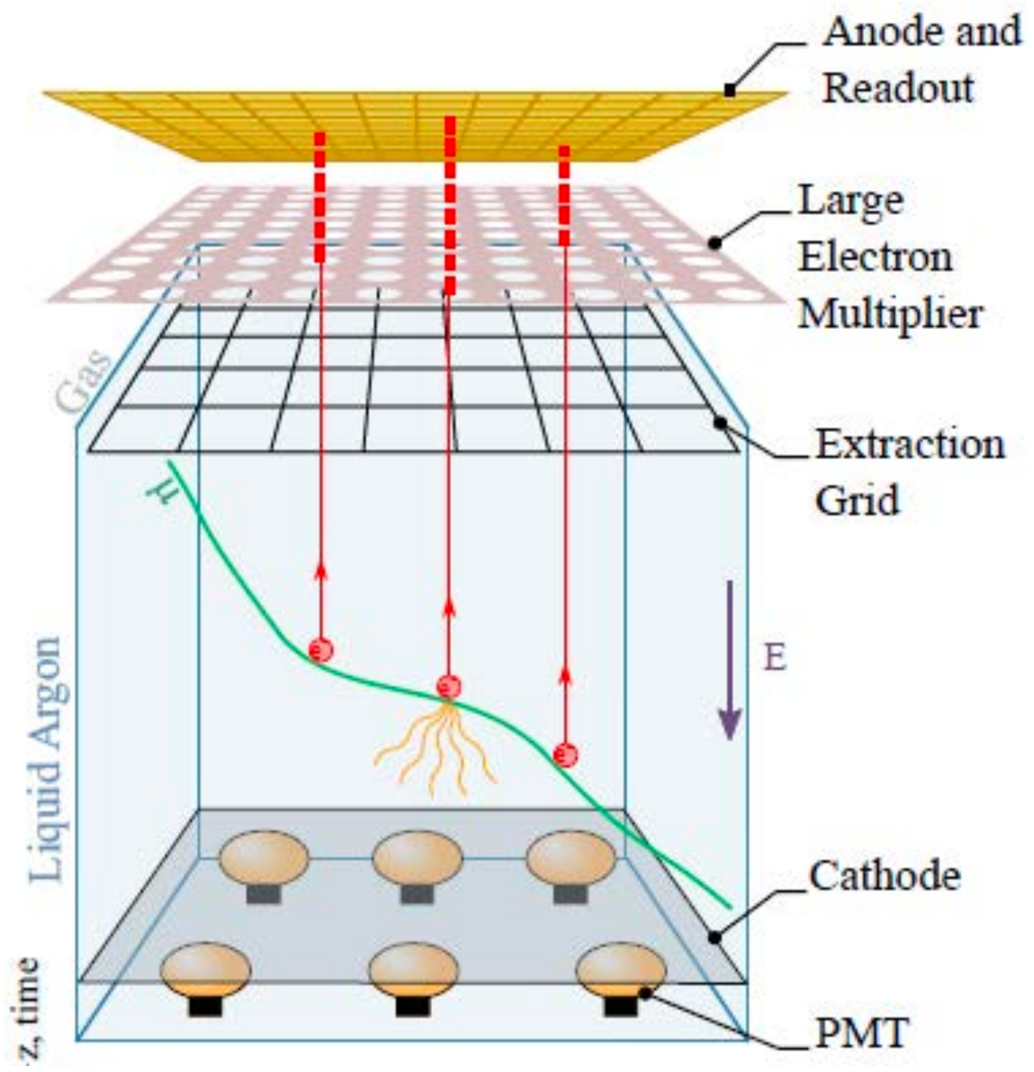


LXe: EXO-200, nEXO

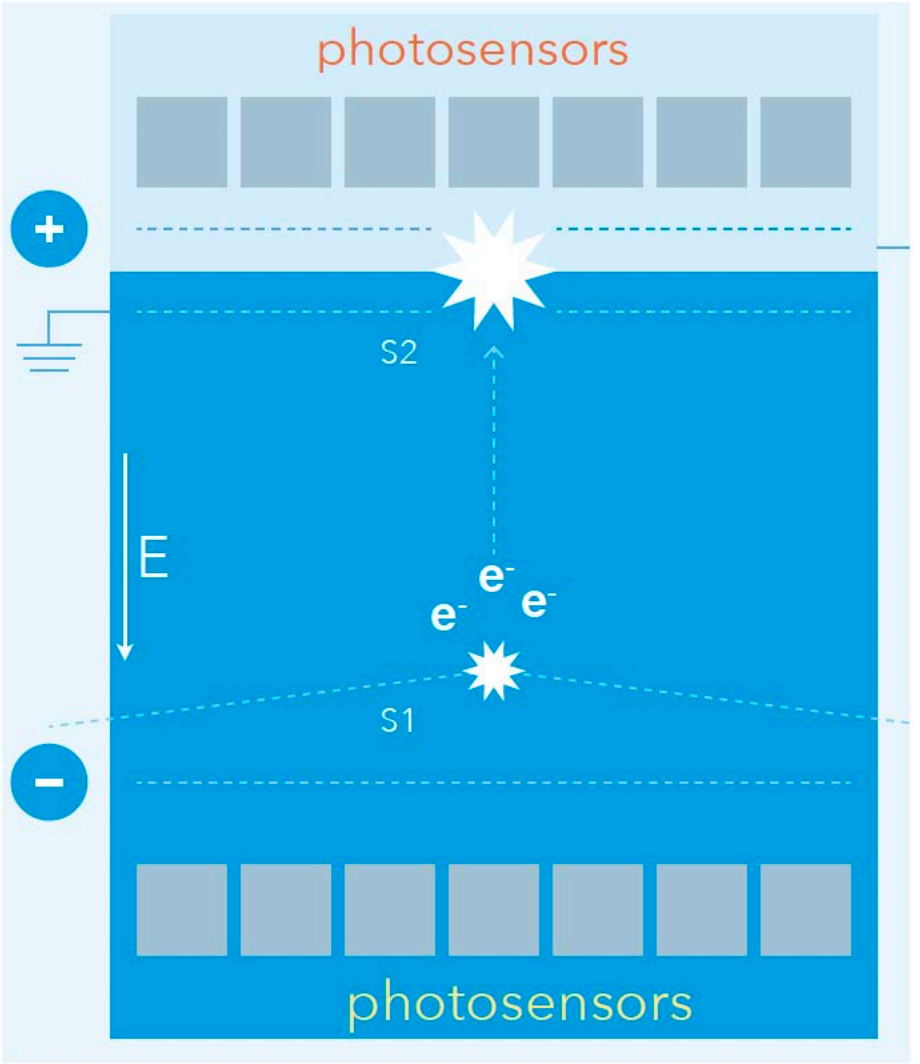
LAr: DEAP-3600
LXe: XMASS

Single phase with light r/o





Double phase LArTPC with charge r/o

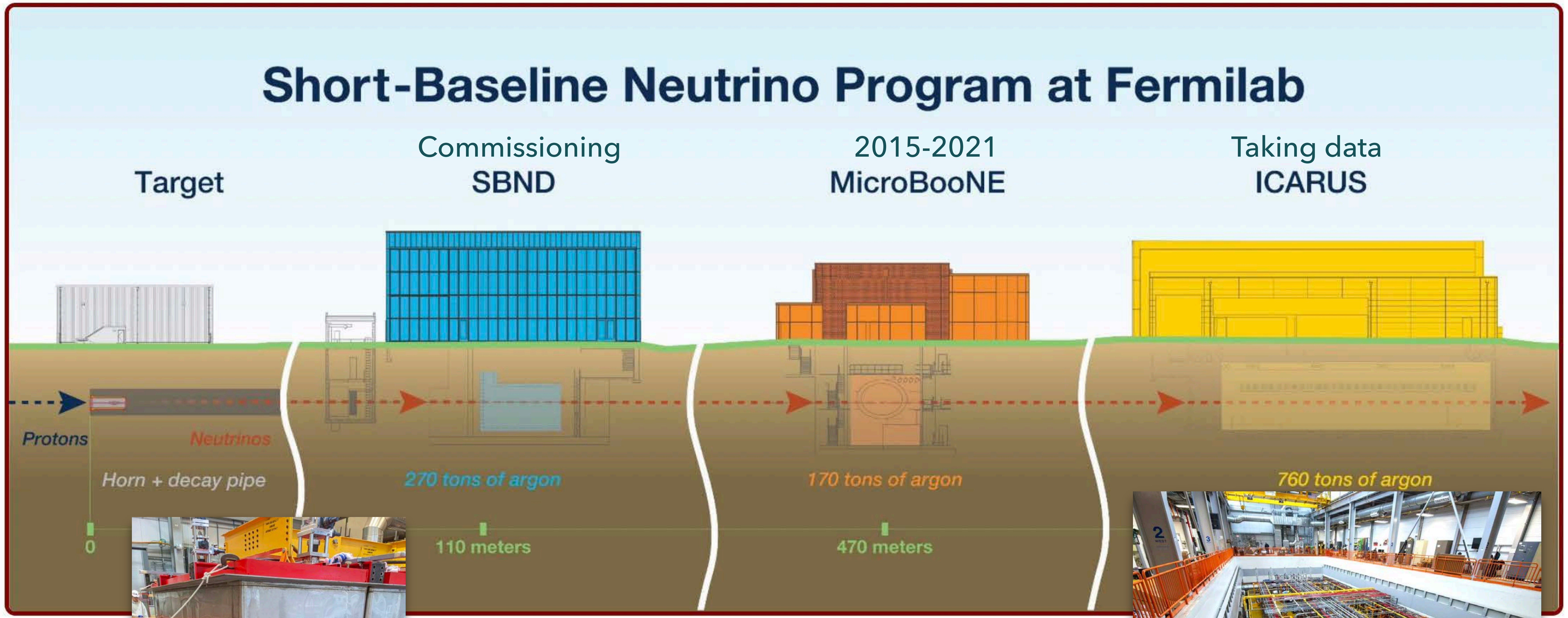


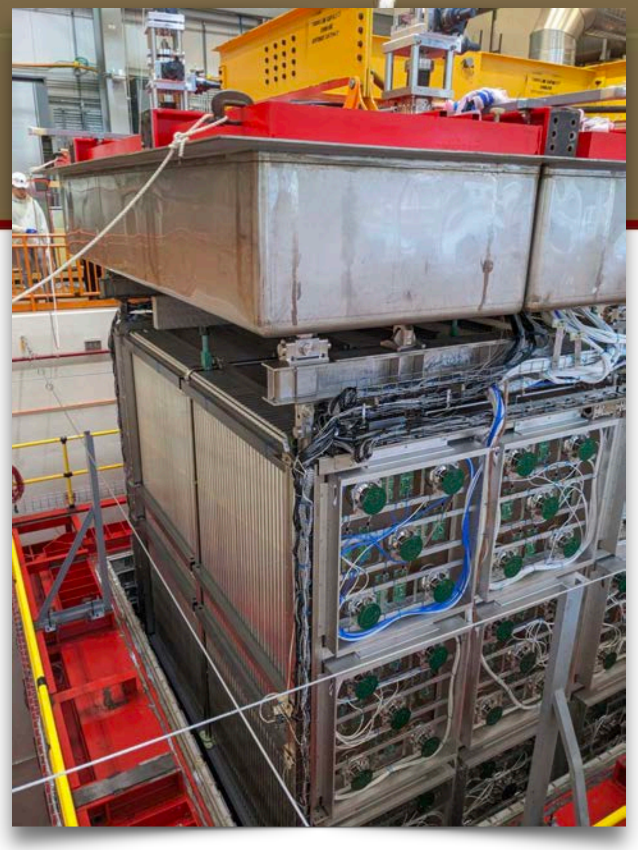
LAr: DarkSide
LXe: LUX/LZ, PandaX, XENON

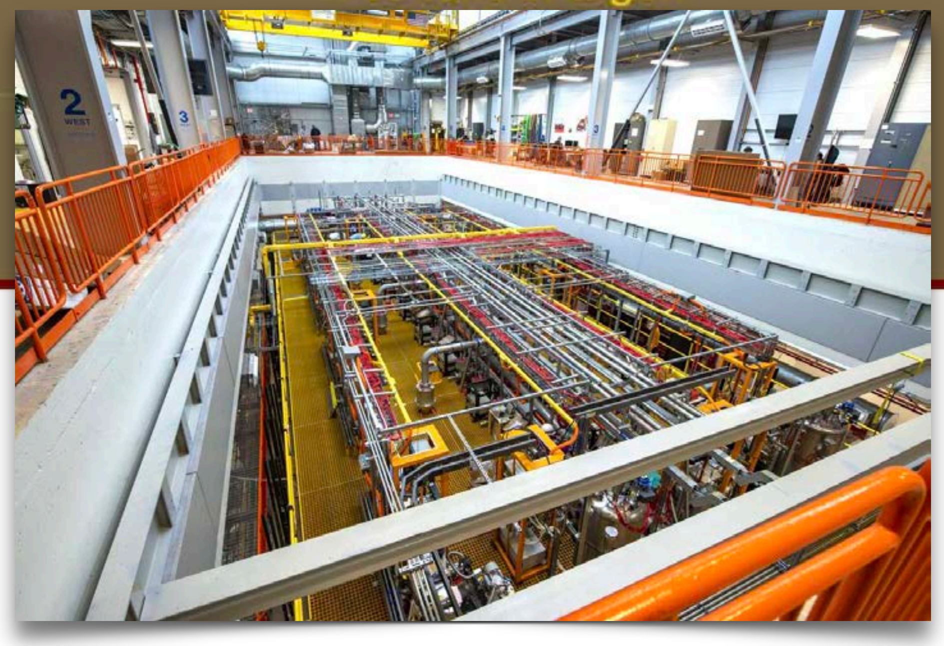
Double phase LArTPC with light r/o

LArTPC NEUTRINO EXPERIMENTS

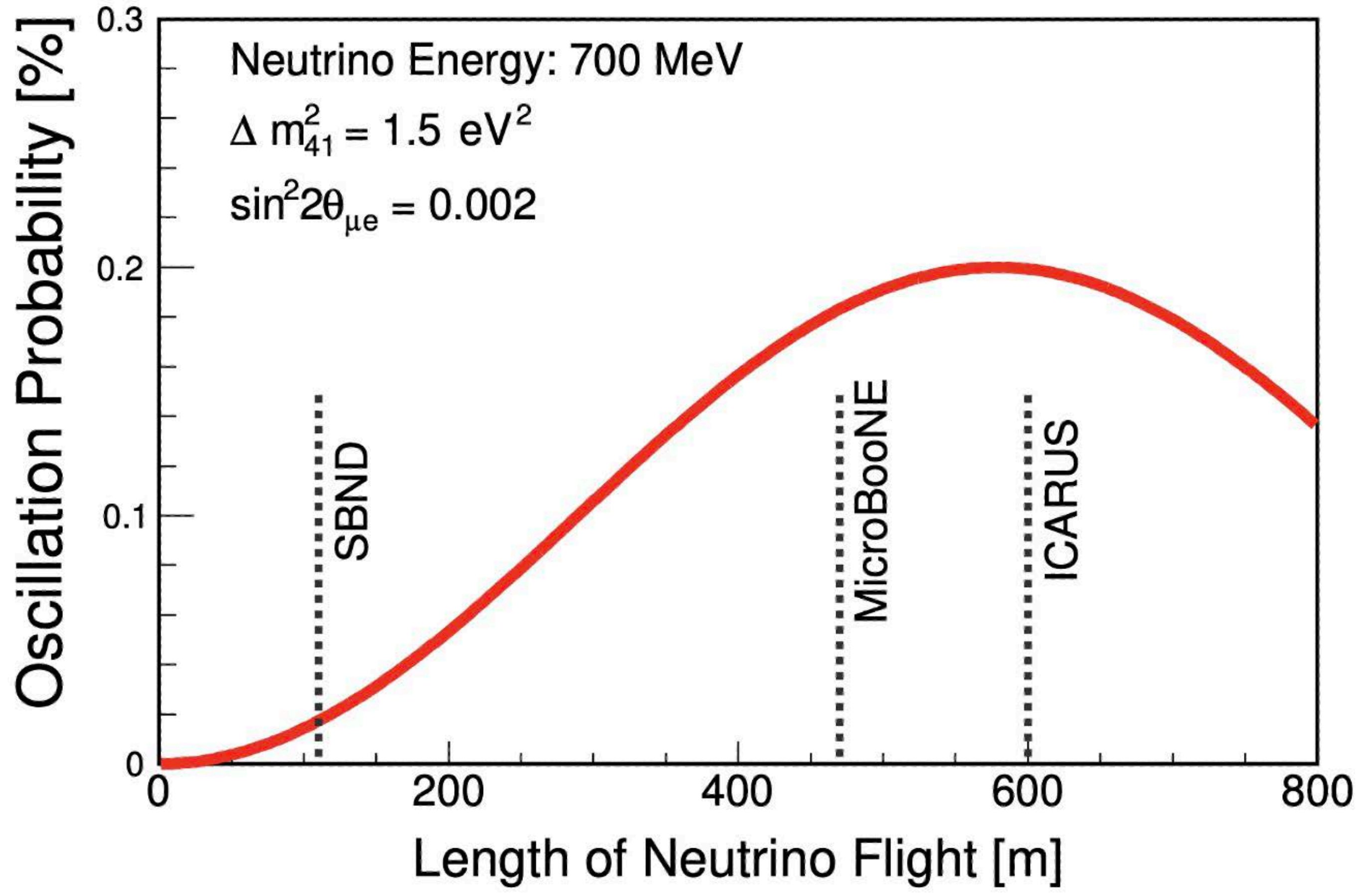
- Enormous physics potential offered by high granularity imaging, extremely high resolution, low backgrounds:
  - Short-baseline neutrino physics (neutrino anomalies, precision cross-sections, BSM)
  - Long-baseline neutrino physics (precision 3-flavor oscillation physics)
  - Underground physics (proton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

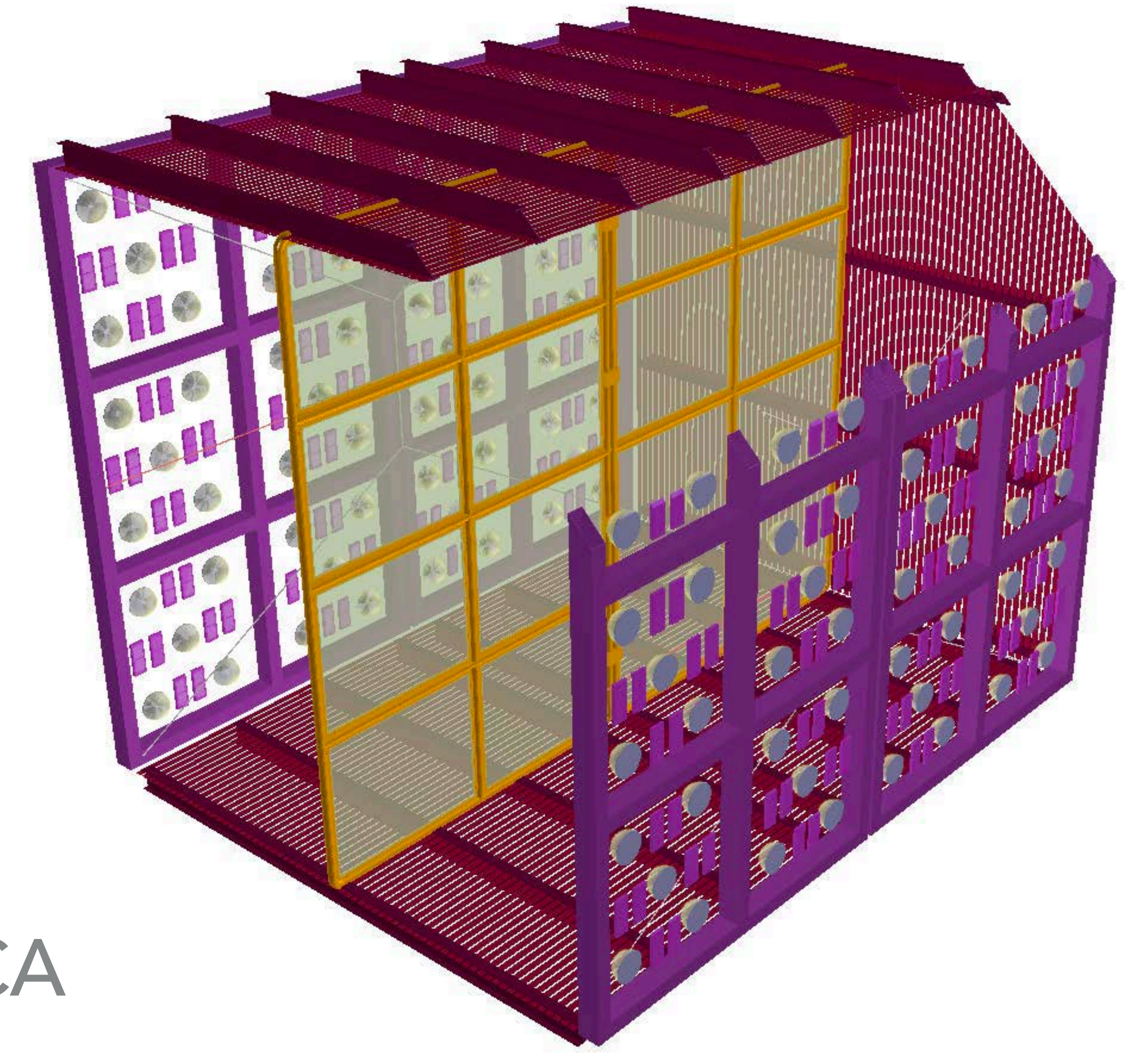






- Booster Neutrino Beam $\nu_\mu(93.6\%), \nu_\mu(5.9\%), \nu_e + \bar{\nu}_e(0.5\%)$
- Sterile neutrino searches, BSM searches, cross-section measurements





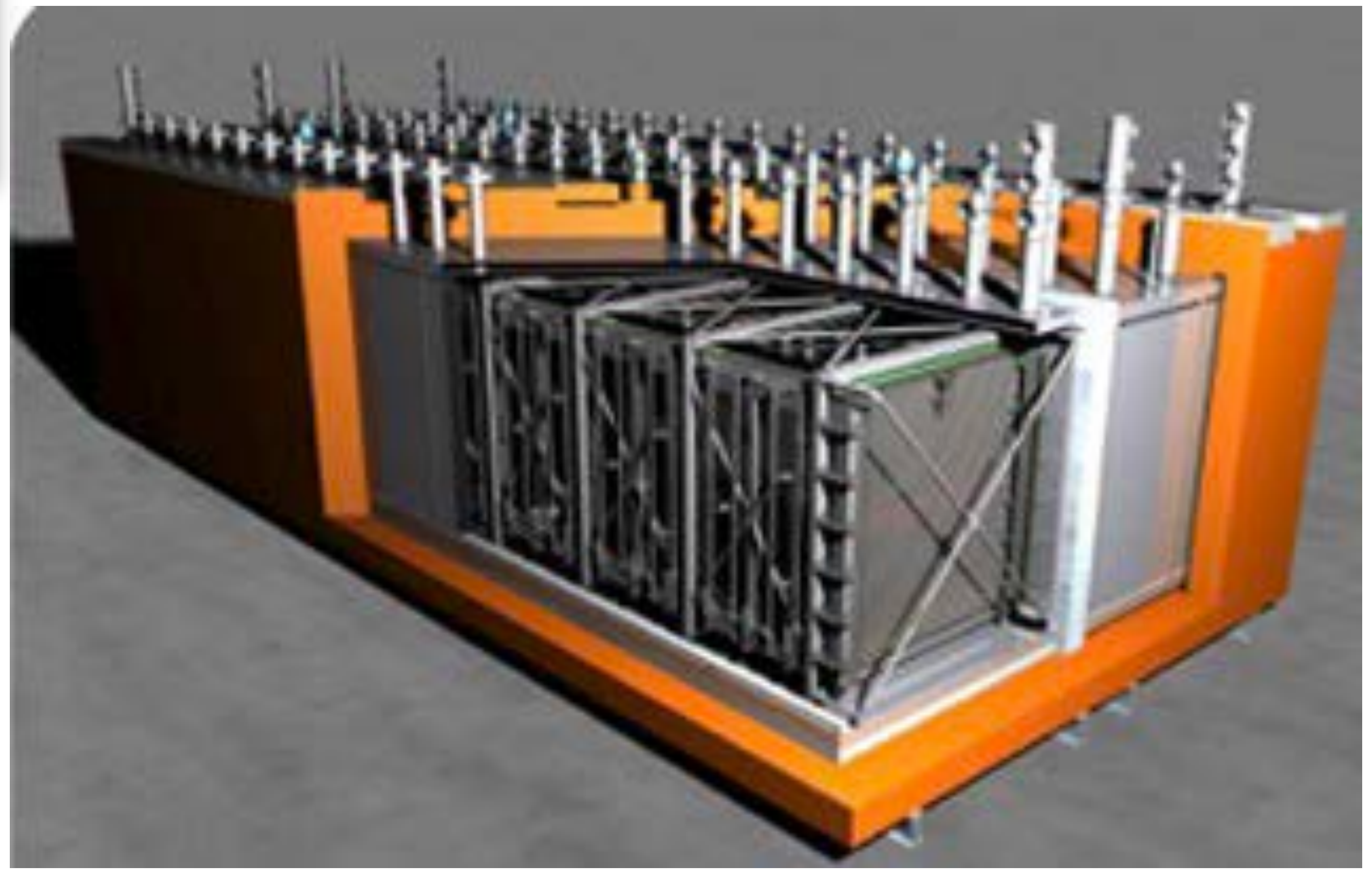
SBND

270 ton - 5 x 4 x 4 m

2 TPC 2 m drift

Wire readout

PDS: 120 PMTs, 192 X-ARAPUCA



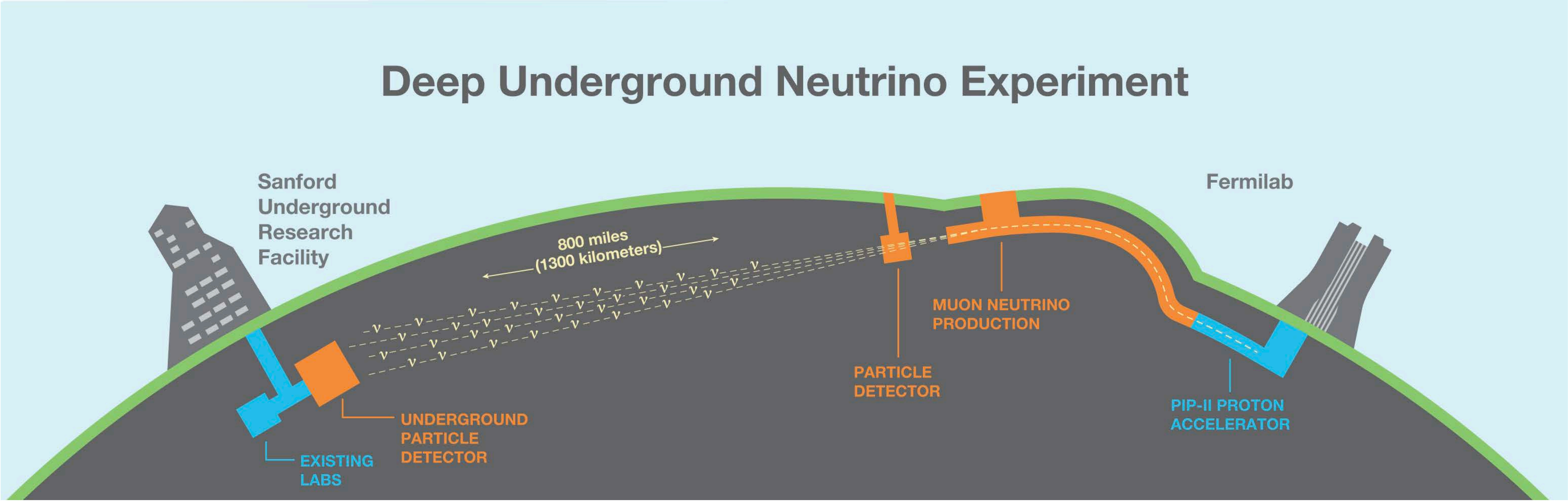
ICARUS

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

4 TPC 1.5 m drift

Wire readout

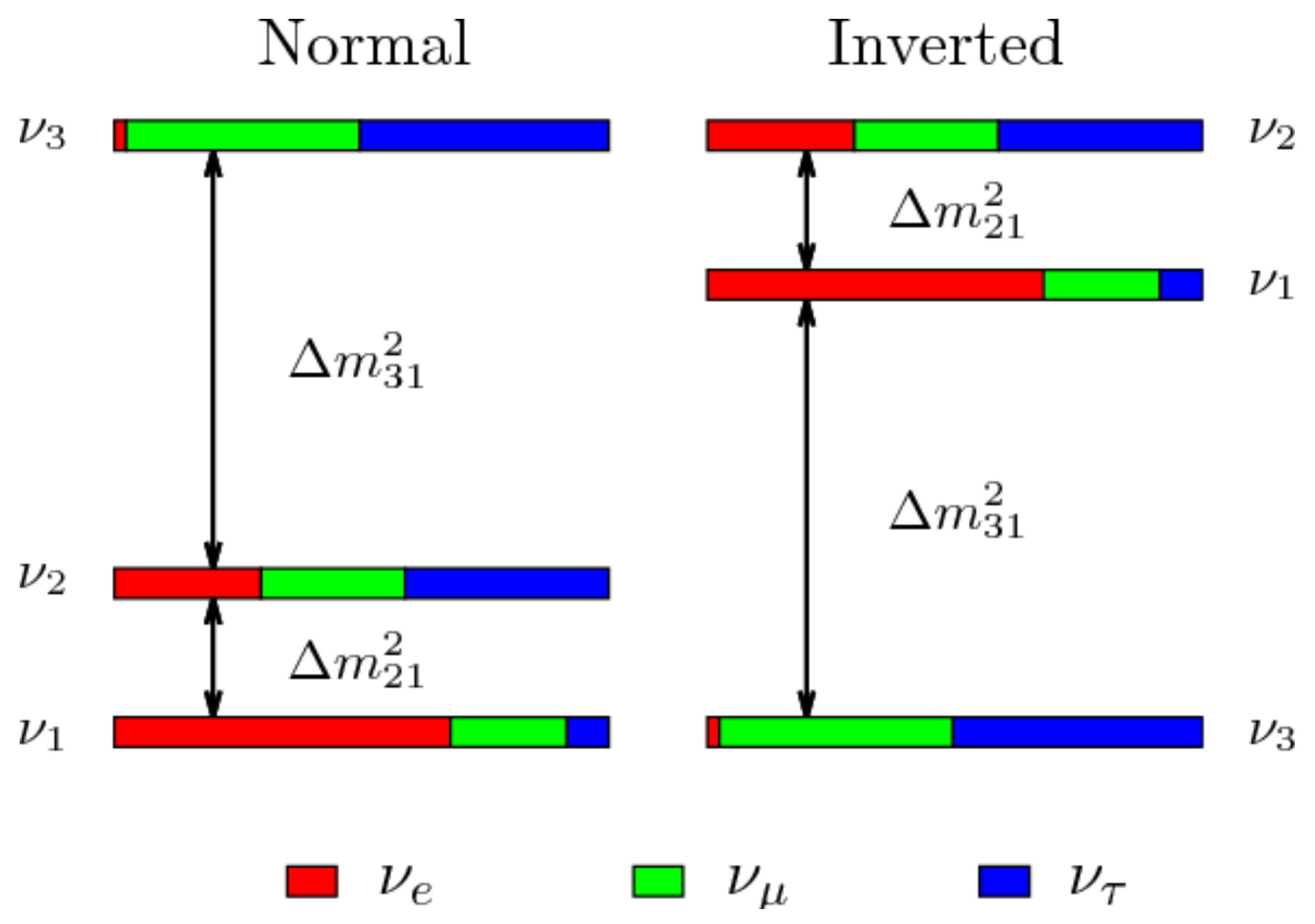
PDS: 360 PMTs



- New broad-band (mostly in 0.5-5 GeV) neutrino beam at **Fermilab** (1.2 MW, upgradeable to 2.4 MW), 1300 km baseline
- Phase I: 2×17 kton LArTPC Far Detector (FD) modules at **Sanford Underground Research Facility**, South Dakota, 1.5 km underground; 2 additional modules in Phase II
- Multiple technologies for the Near Detector (ND) at **Fermilab**, LAr target to control systematic uncertainties

PRECISION 3ν OSCILLATIONS: KNOWNS & UNKNOWNS

- The 3 known flavor states ν_e, ν_μ, ν_τ are linear combinations of 3 states ν_1, ν_2, ν_3 with definite masses m_i through a unitary matrix $U_{\alpha i}$, also called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- We know the two mass squared differences and three mixing angles from neutrino oscillations
- We don't know the sign of Δm^2_{31} (hierarchy) and the size of the Dirac phase δ_{CP}
- We also don't know the absolute neutrino mass or if neutrino is its own anti-particle
- Finally we don't know if our 3-flavor picture of oscillations is complete



PMNS Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P_{\nu_\mu\to\nu_e,(\bar\nu_\mu\to\bar\nu_e)} \approx 4\sin^2\theta_{13}\sin^2\theta_{23}\frac{\sin^2\Delta}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\, J_{CP}^{max}\cos(\Delta\pm\delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{1-A}$$

$$J_{CP}^{max} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu} \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}} \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \qquad V_C = \sqrt{2}G_F n_e\,.$$

3ν knowns: Δm^2_{21}, $|\Delta m^2_{31}|$, $\theta_{23}, \theta_{13}, \theta_{12}$

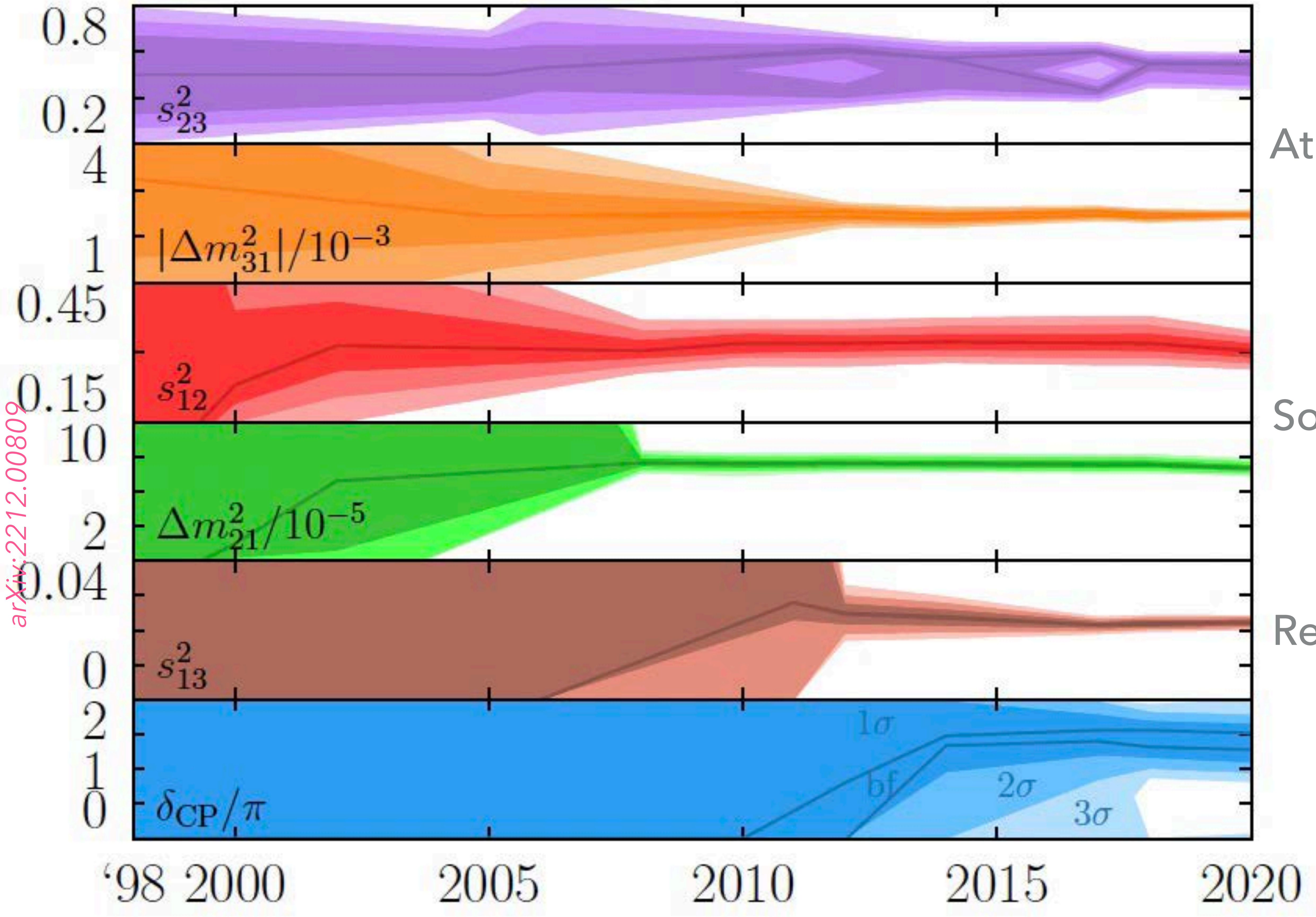
3ν unknowns: δ, sign(Δm^2_{31}), sign($\theta_{23} - \pi/4$), min(m_i), Dirac/Majorana nature

CP is conserved for $\delta = 0$ or π

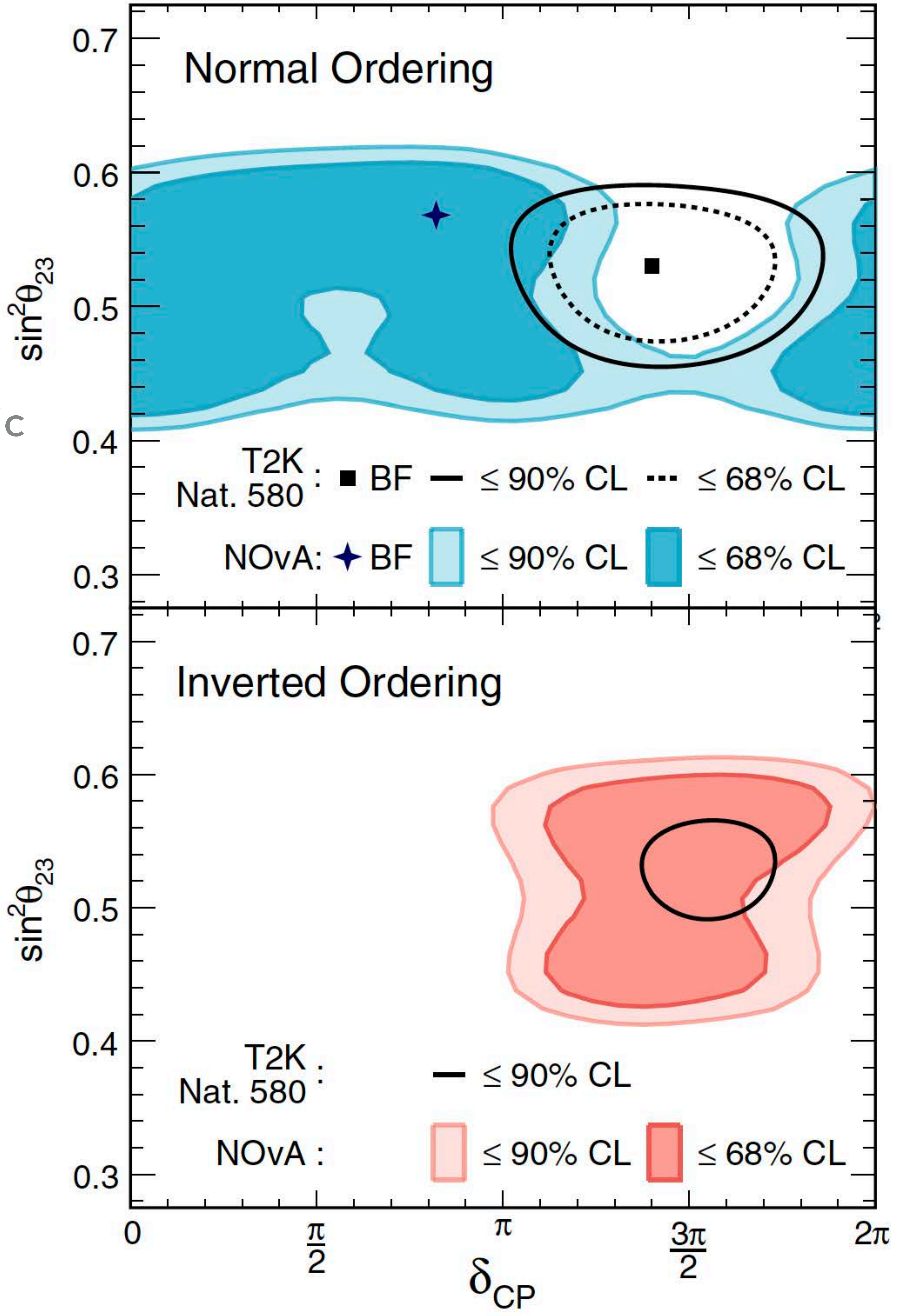
CP violation is max for $\delta = \pi/2$ or $3\pi/2$

3ν OSCILLATIONS CURRENT STATUS

$\theta_{23} \sim 45°$
$\theta_{12} \sim 34°$
$\theta_{13} \sim 8.5°$



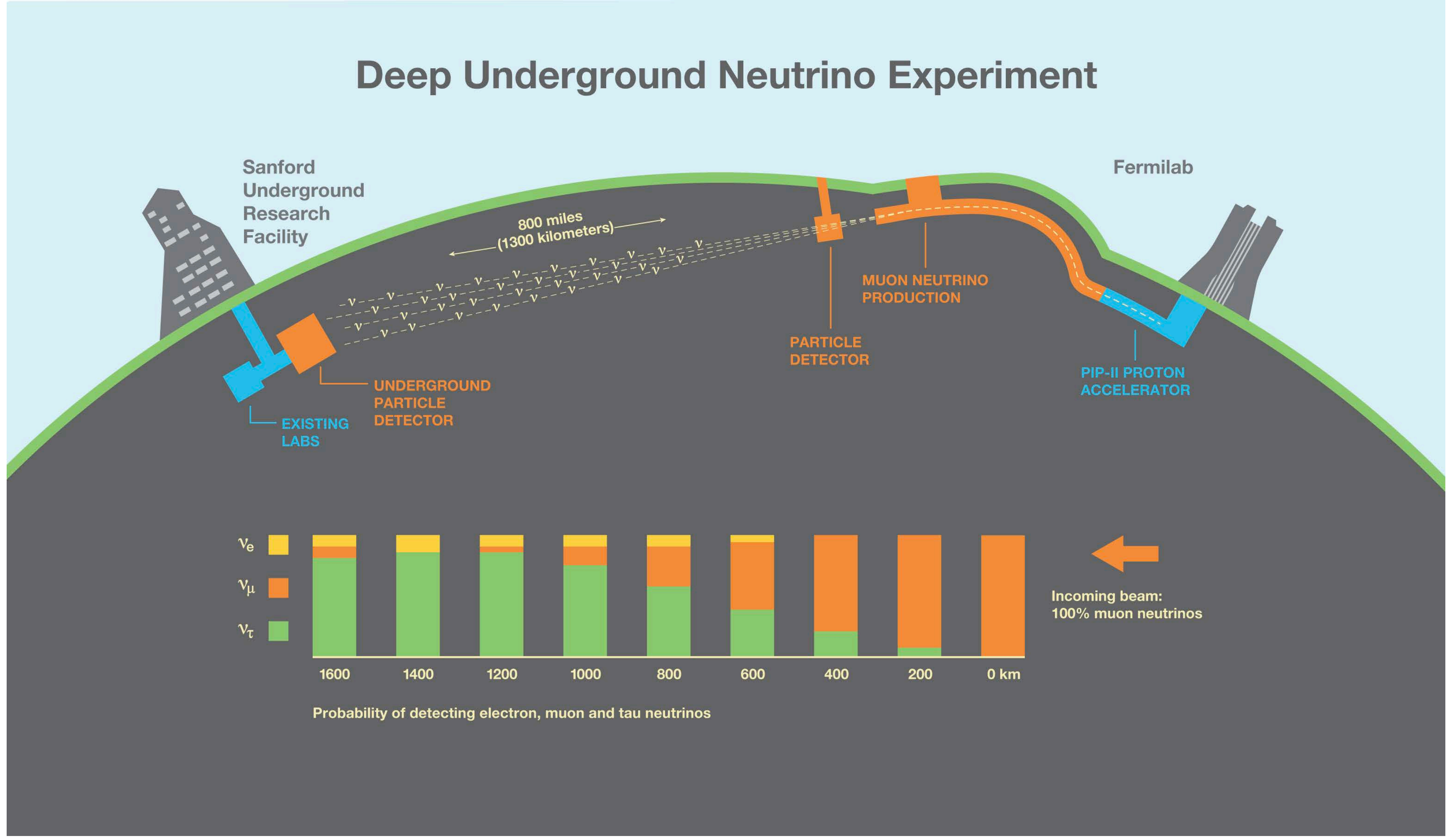
Snowmass NF01 Topical Group Report arXiv:2212.00809

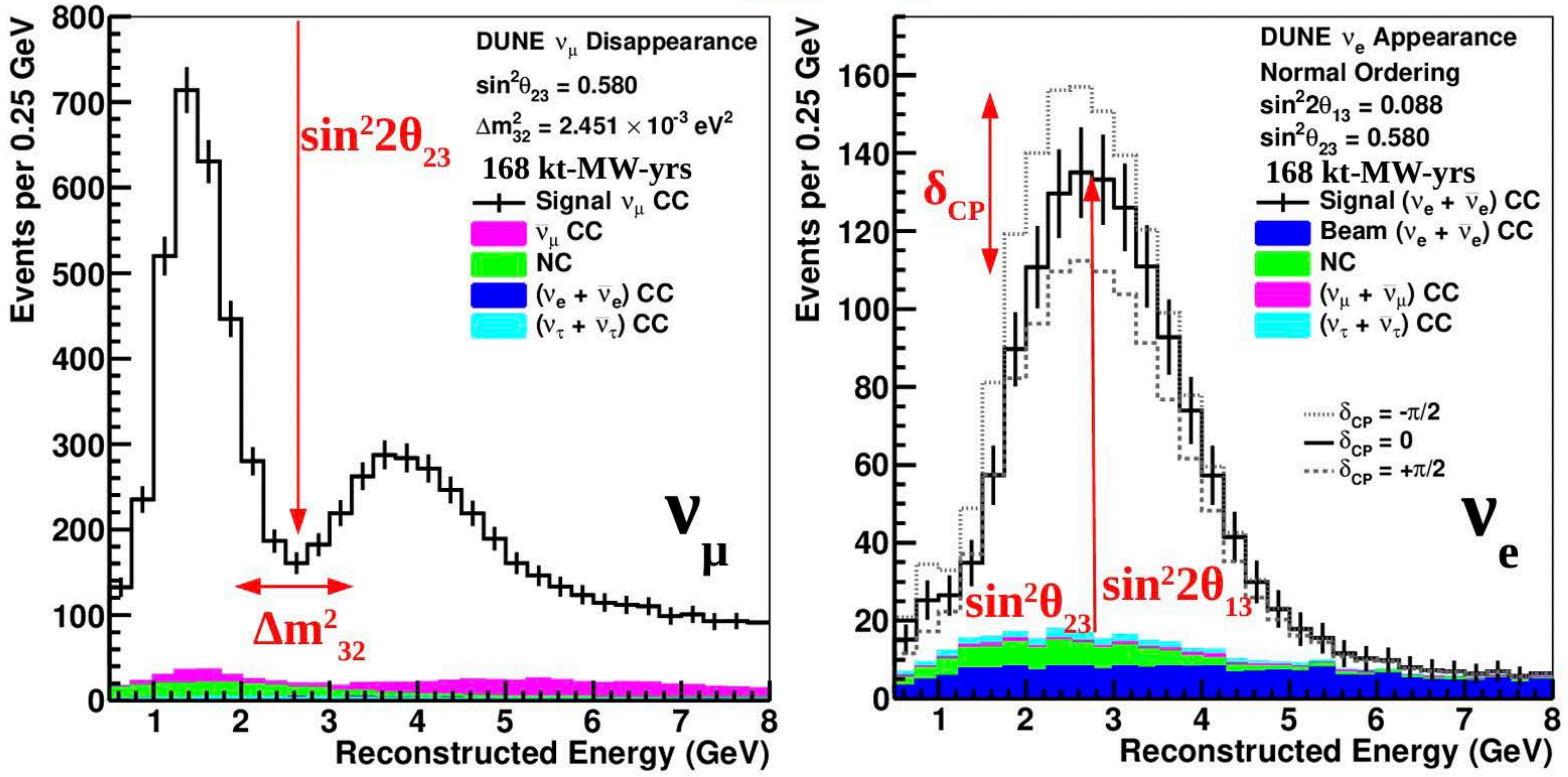


PRD 106, 032004 (2022)

NEUTRINO OSCILLATIONS IN DUNE

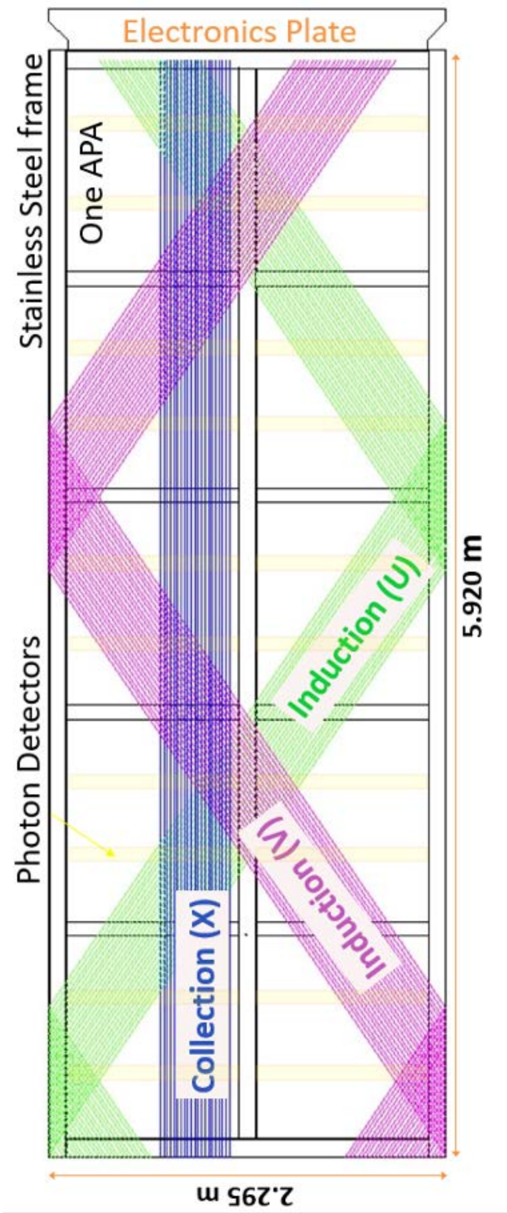
- **Near Detector** : measurements of ν_μ unoscillated beam
- **Far Detector**: measurements of oscillated ν_μ & ν_e spectra
- **THEN** repeat for antineutrinos – and compare oscillations of neutrinos and antineutrinos
    - ν_μ disappearance: $|\Delta m^2_{32}|$, θ_{23}
    - ν_e appearance: octant of θ_{23}, δ_{CP} , mass ordering

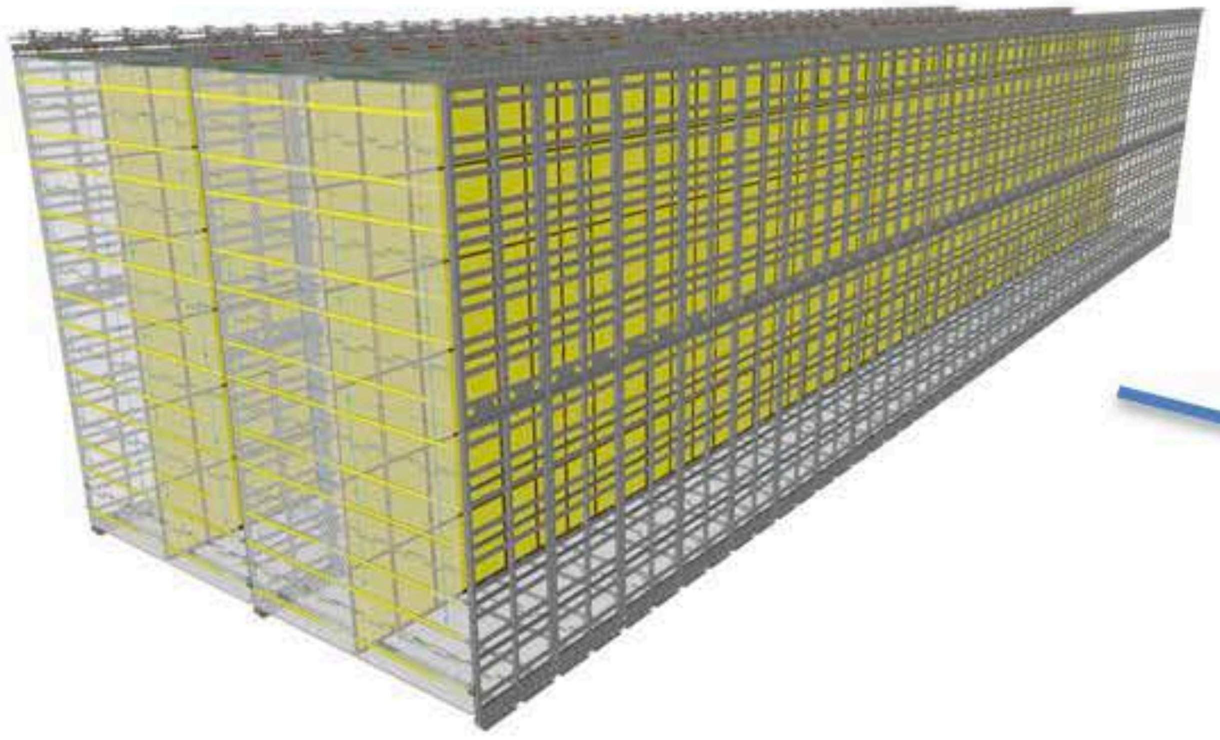




DUNE FAR DETECTORS (PHASE I)

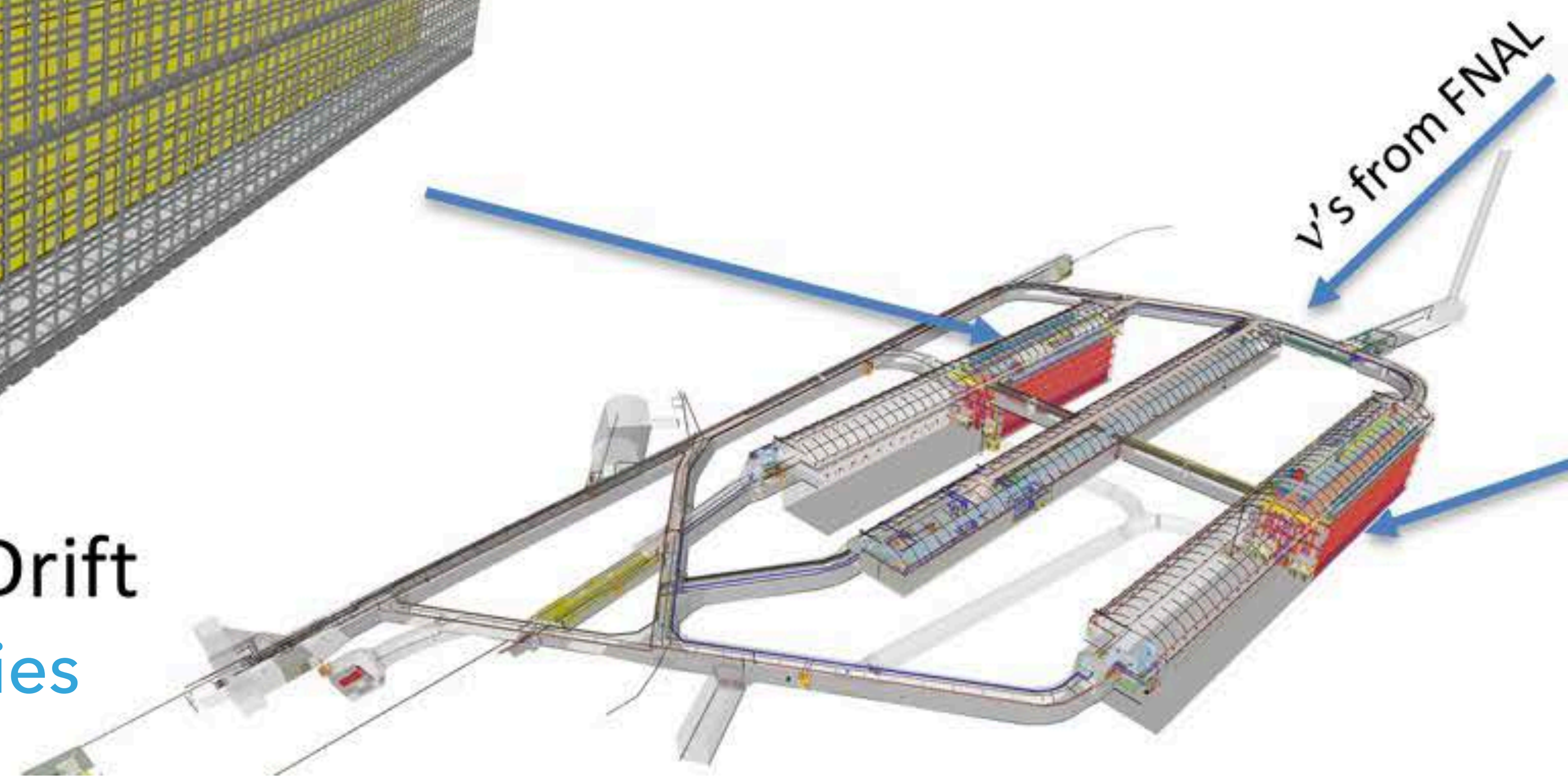
2 ×17 kton single phase LArTPCs

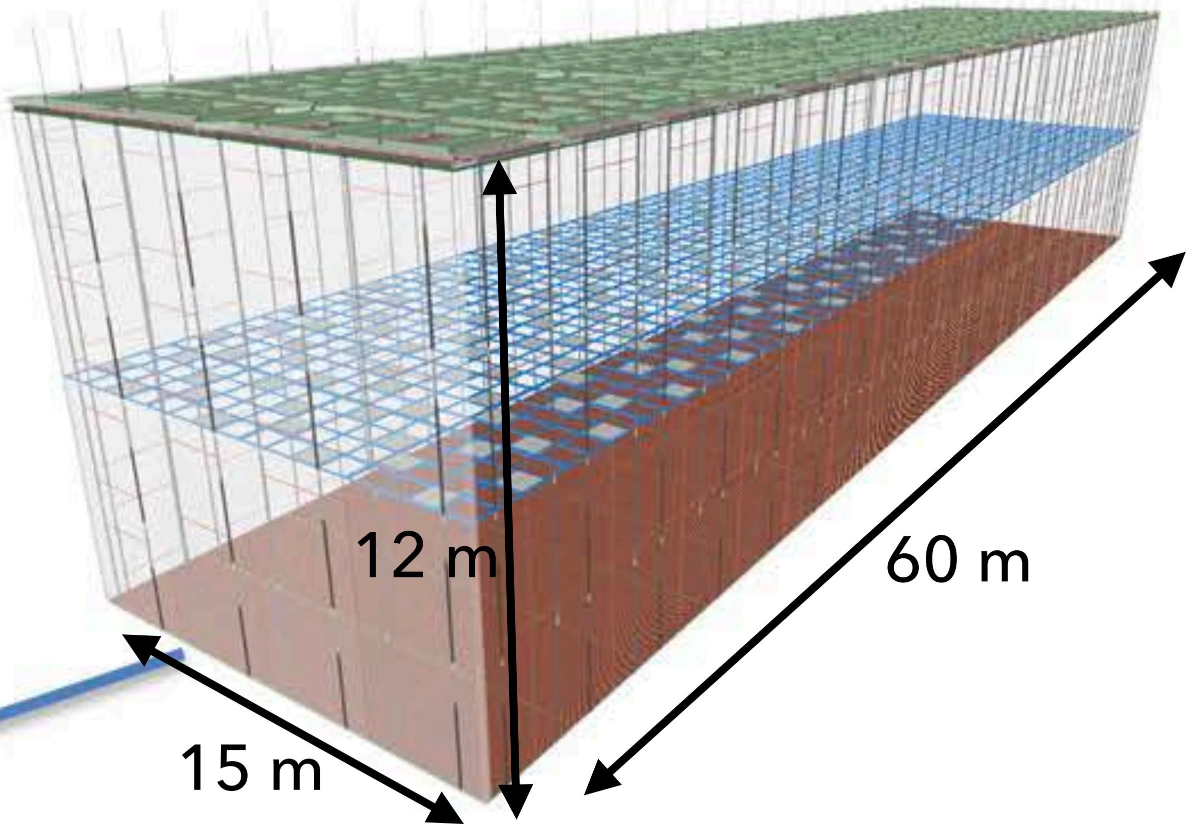




APA* Horizontal Drift

* Anode Plane Assemblies



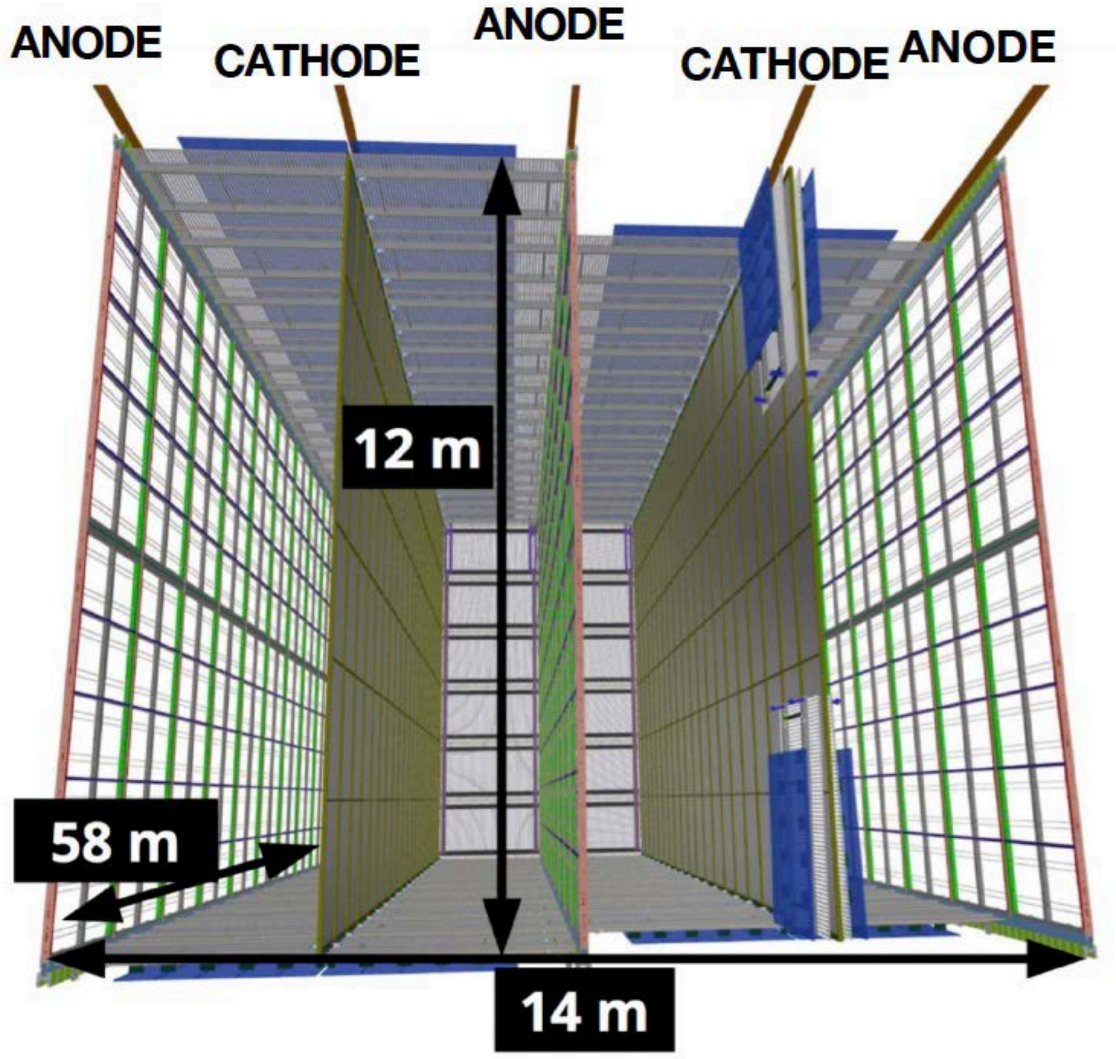


CRP** Vertical Drift

** Charge Readout Planes

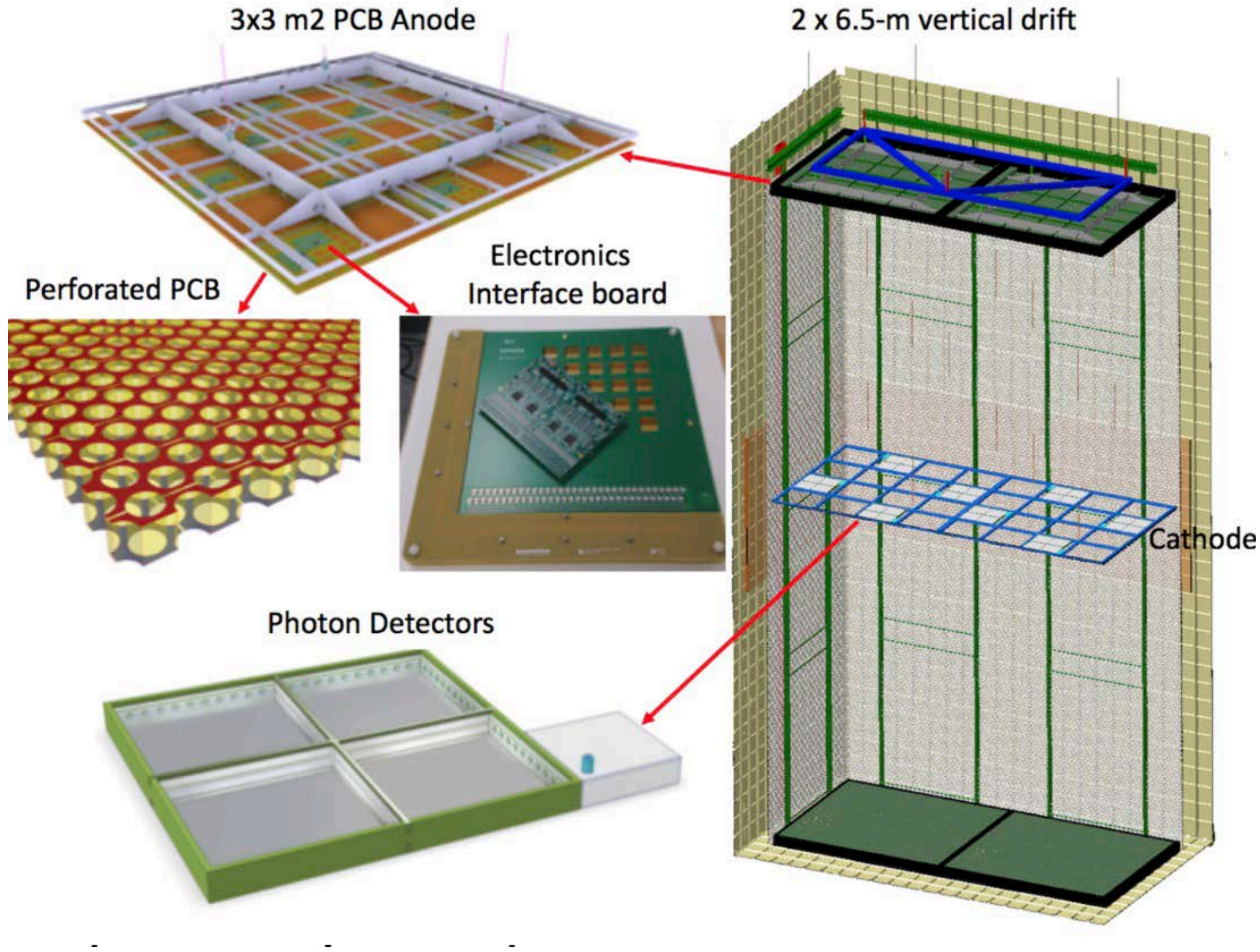
FD1-HD

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

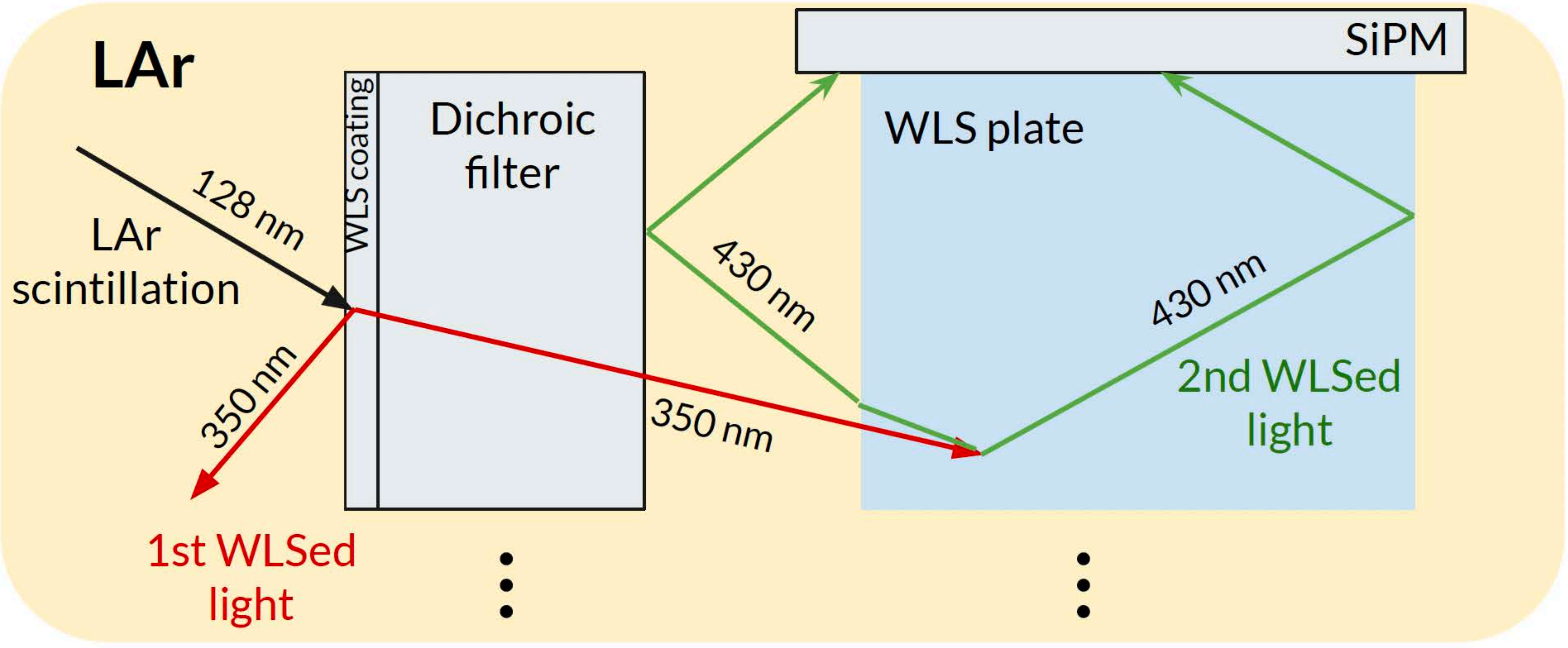


FD2-VD

- 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



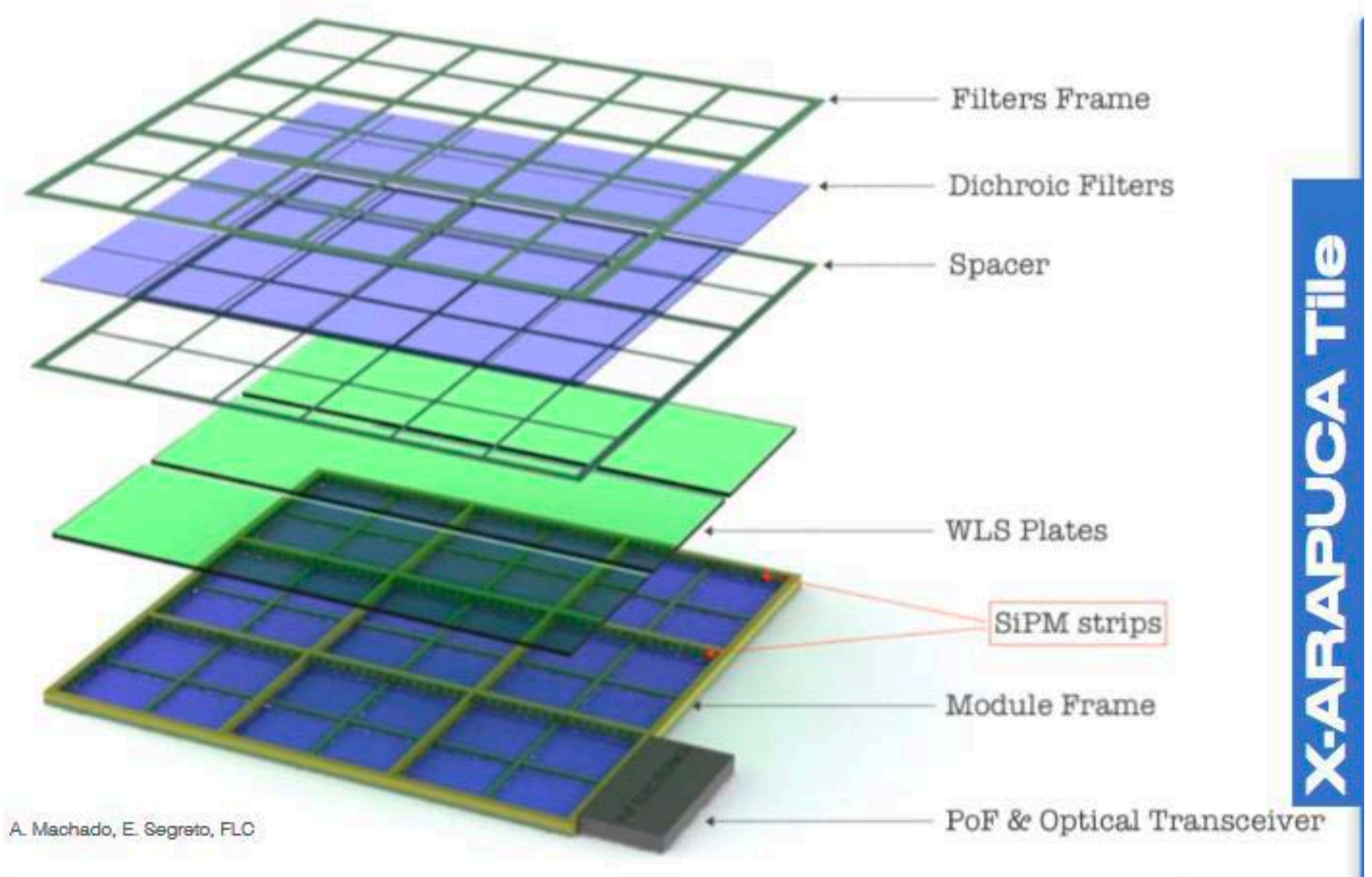
DUNE PHOTON DETECTION SYSTEM (PDS)



Detection Efficiency between 1.5% and 3%

Supercell 209×12×2 cm
48 SiPMs

MEGACELL 60×60×0.8 cm
2 r/o channels
(160 SiPMs)



X-ARAPUCA Tile

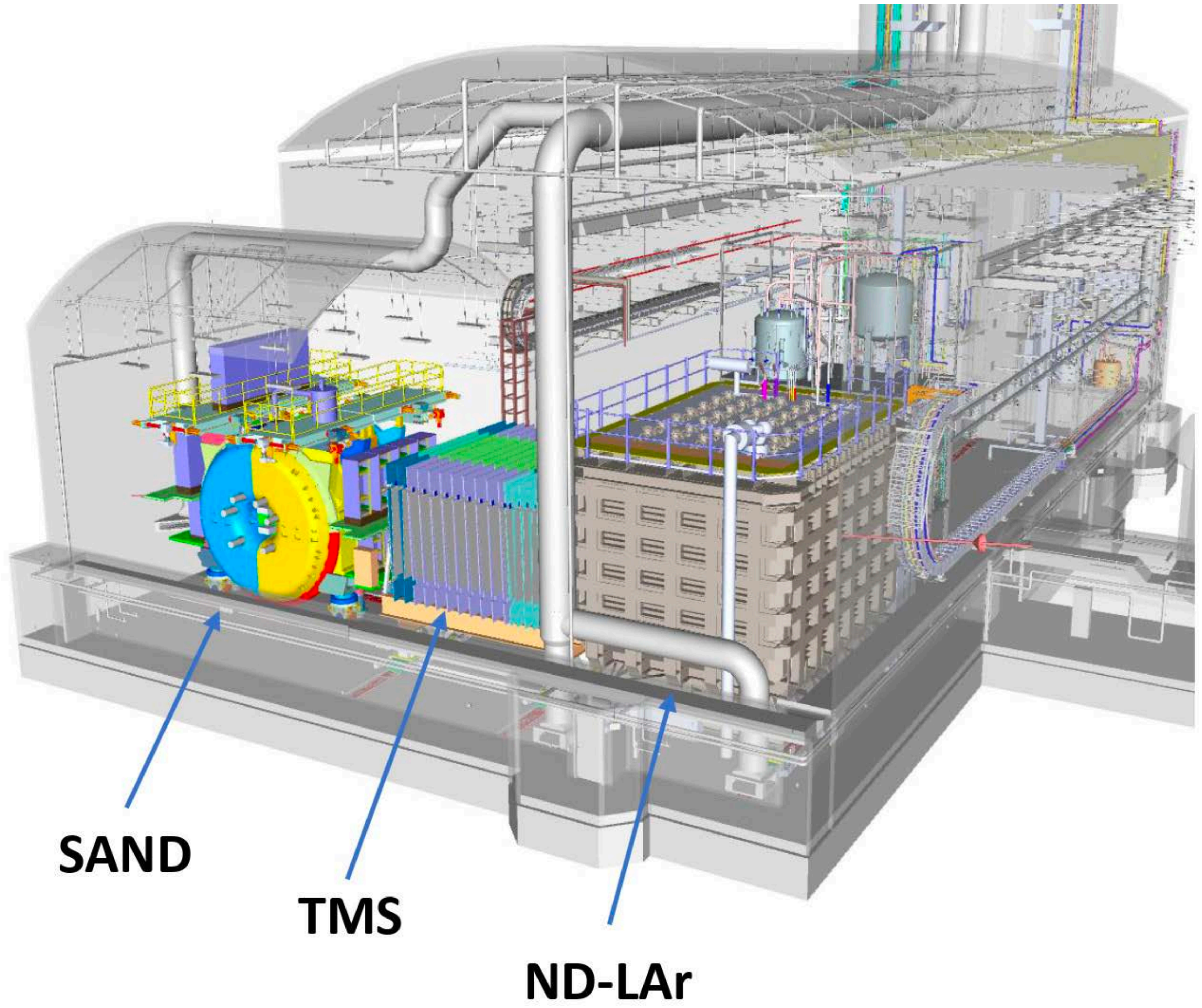
X-ARAPUCA light trap:

- Photon collector to expand coverage and trapping mechanism to give photons more than one chance of being detected
- Trapping through combination of a well defined cut off filter and two different WLSs
- Trapped photons reflected several times eventually reach a SiPM

Test @ Naples CRYOLAB

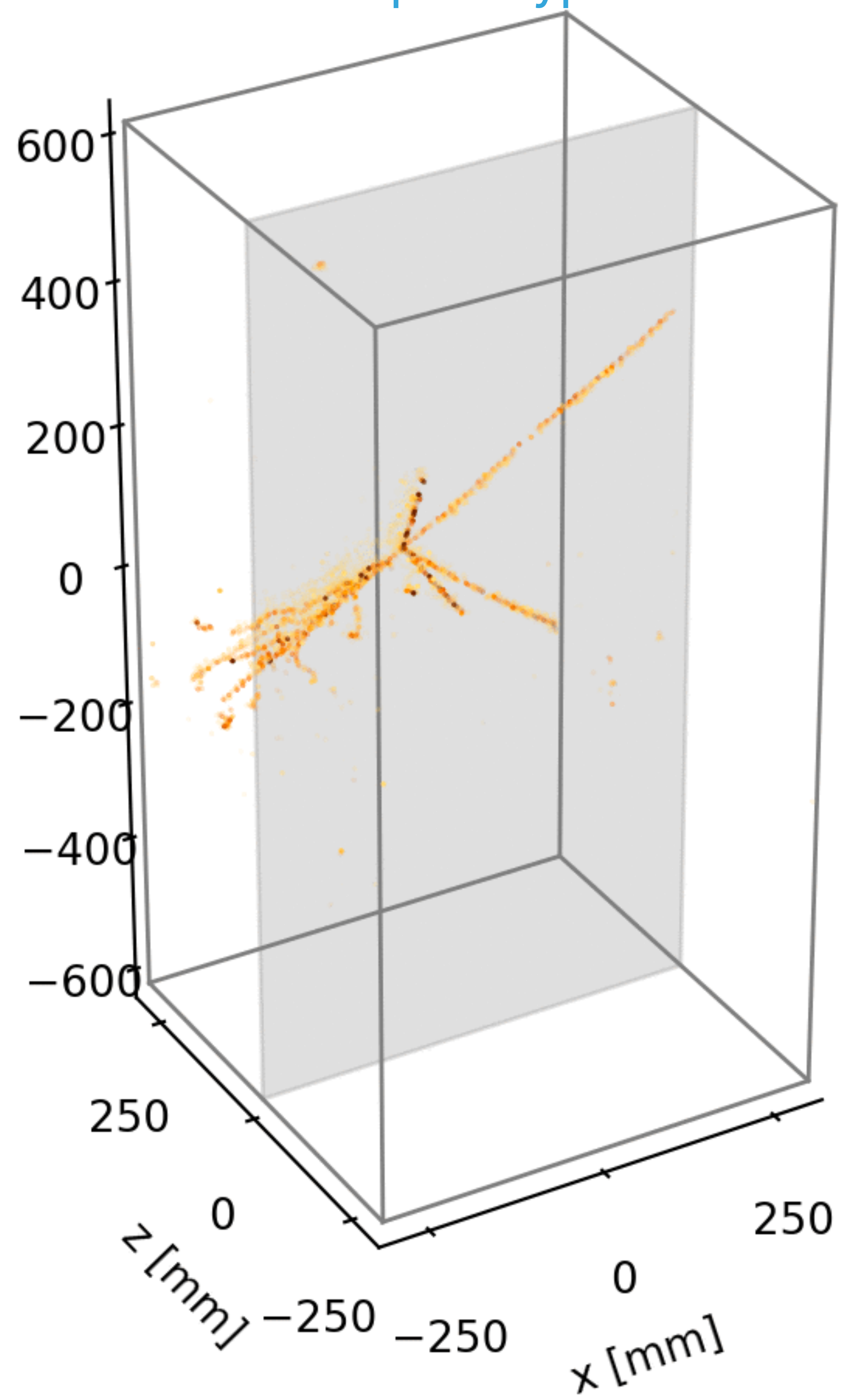
DUNE NEAR DETECTOR COMPLEX (PHASE I)

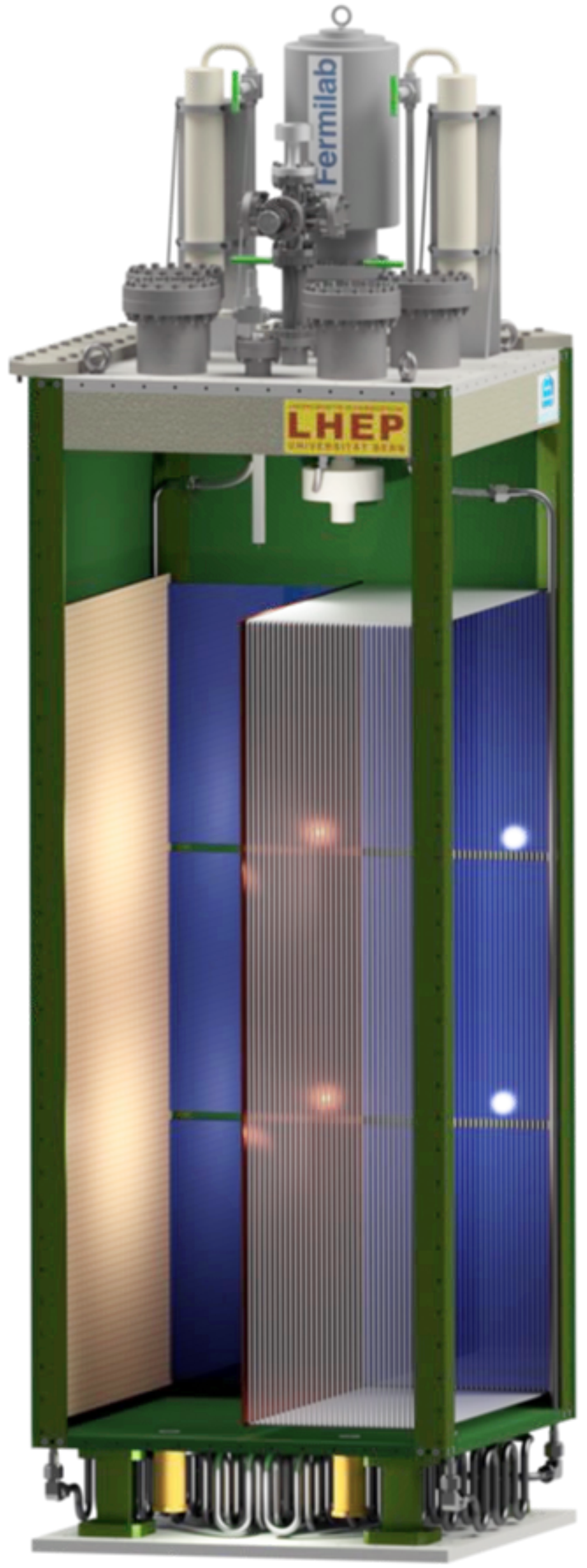
- Measures the neutrino beam rate and spectrum to predict unoscillated event rates in the far detector
- Constrains systematic uncertainties (flux, cross sections, detector response) for oscillation measurements
- Additional physics program



- 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)

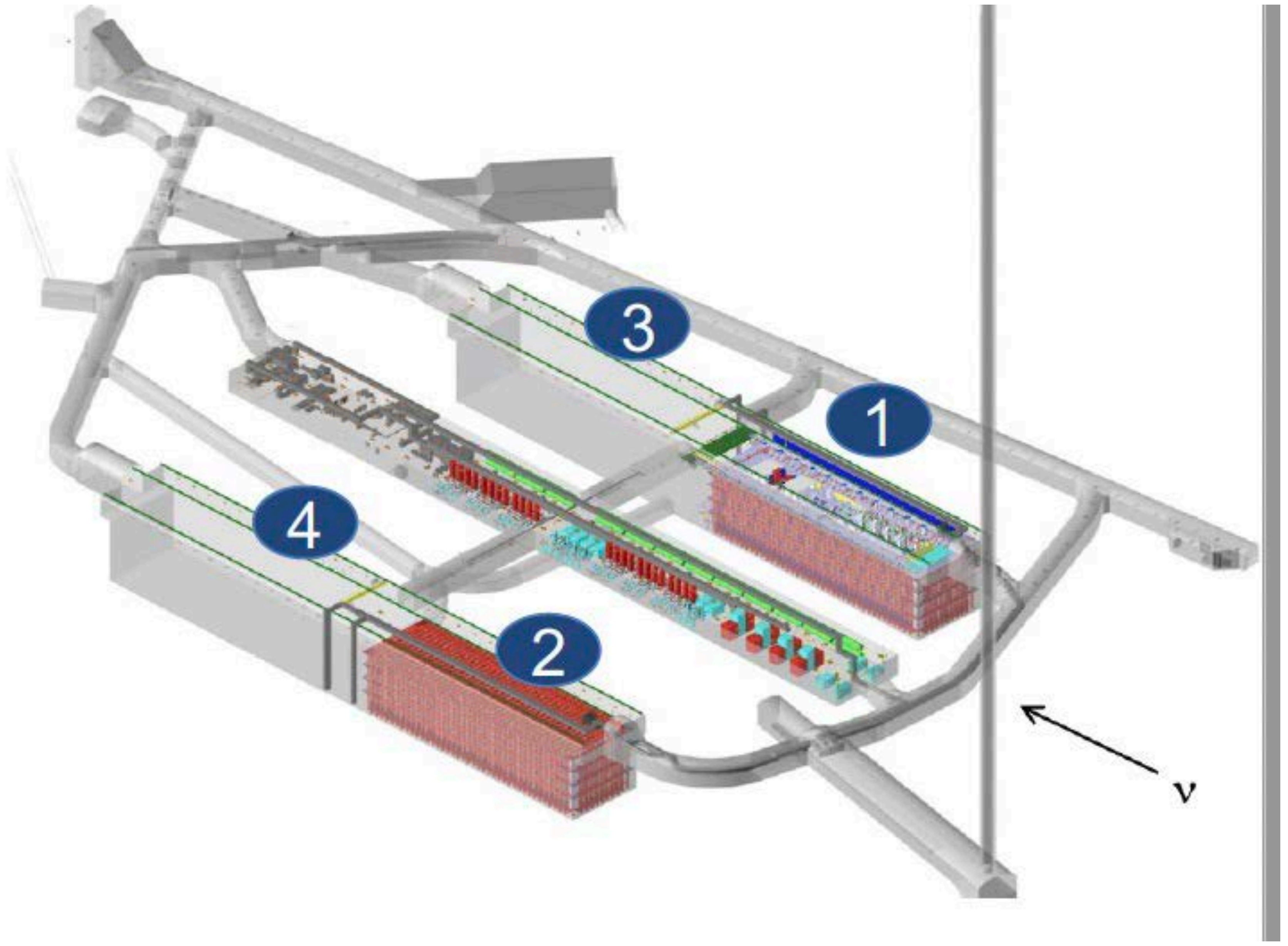
Raw 3D images of cosmic rays in ton-scale prototype



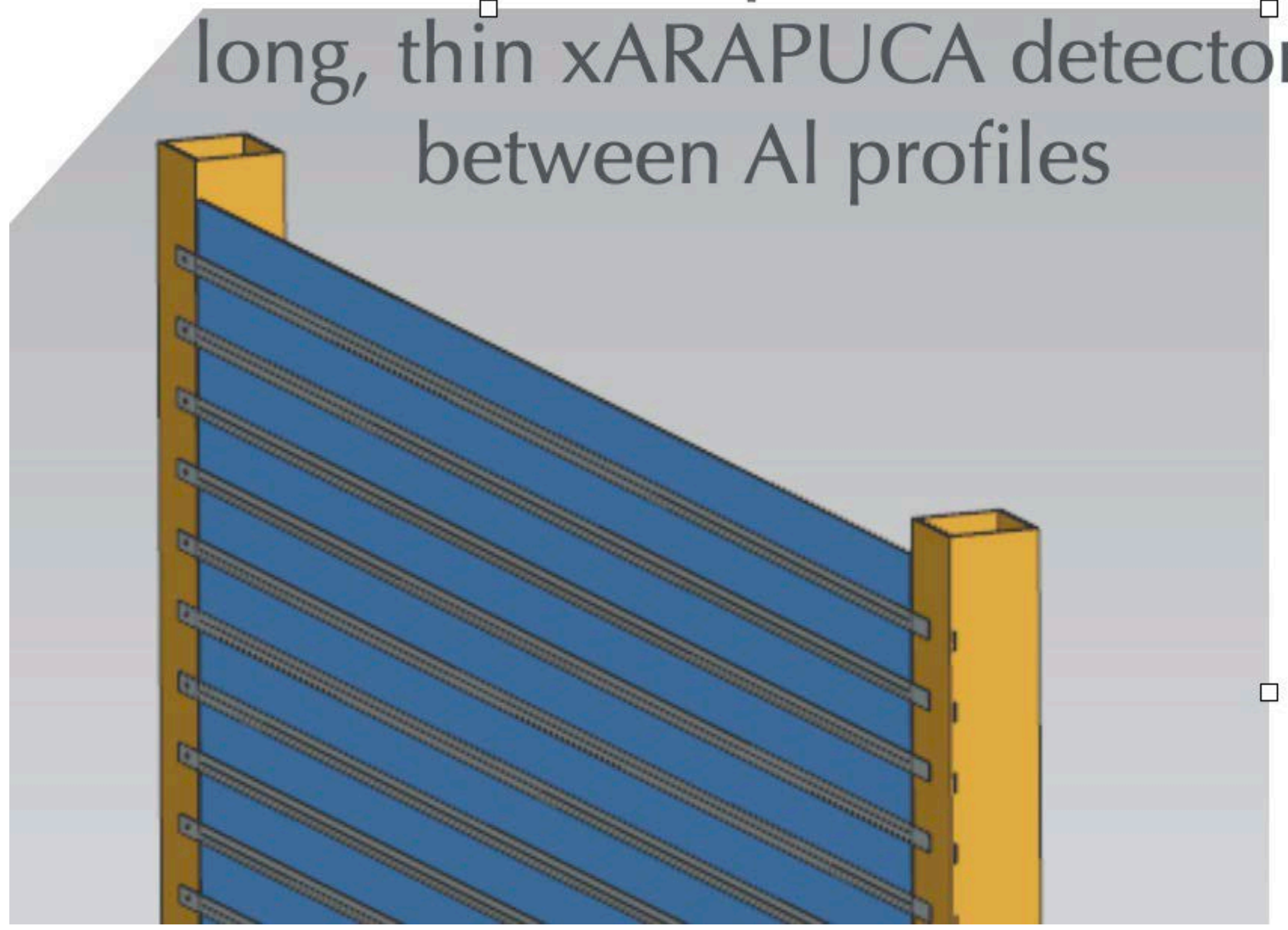


DUNE PHASE II

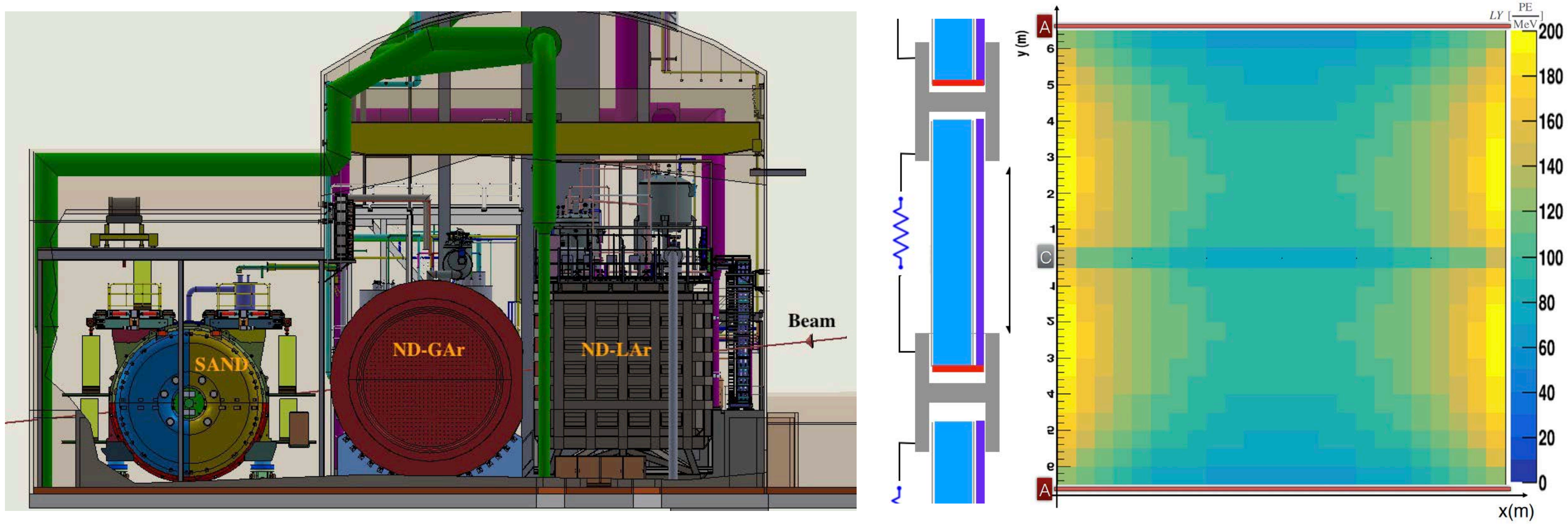
- **Far Detector with 4 modules**
  - FD-3 SP LArTPC enhanced VD 4π concept TBD (by 2027),
  - FD-4 : «module of opportunity»: decision by 2028
- **Beam power upgrade to 2.4 MW**
- **Near Detector: TMS replaced by ND-GAr**
  - ND-LAr
  - ND-GAr important for higher precison ν-Ar measurements and when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



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

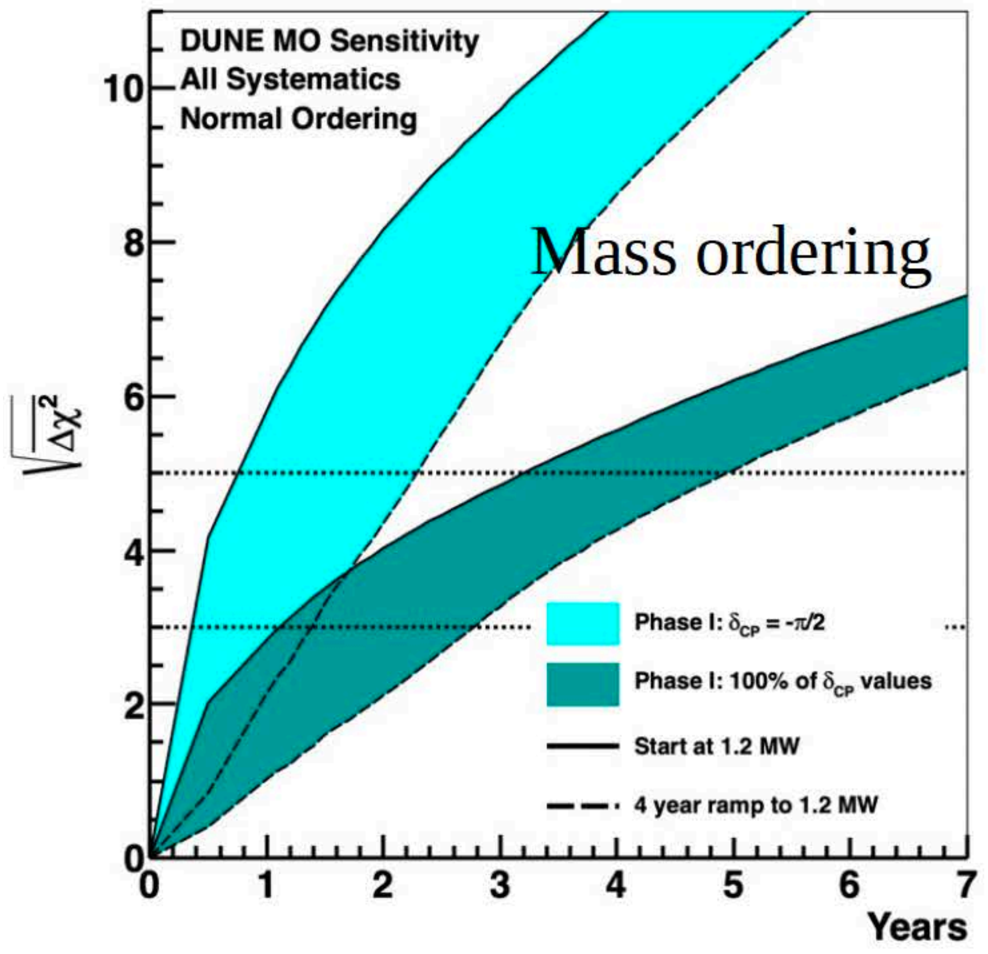


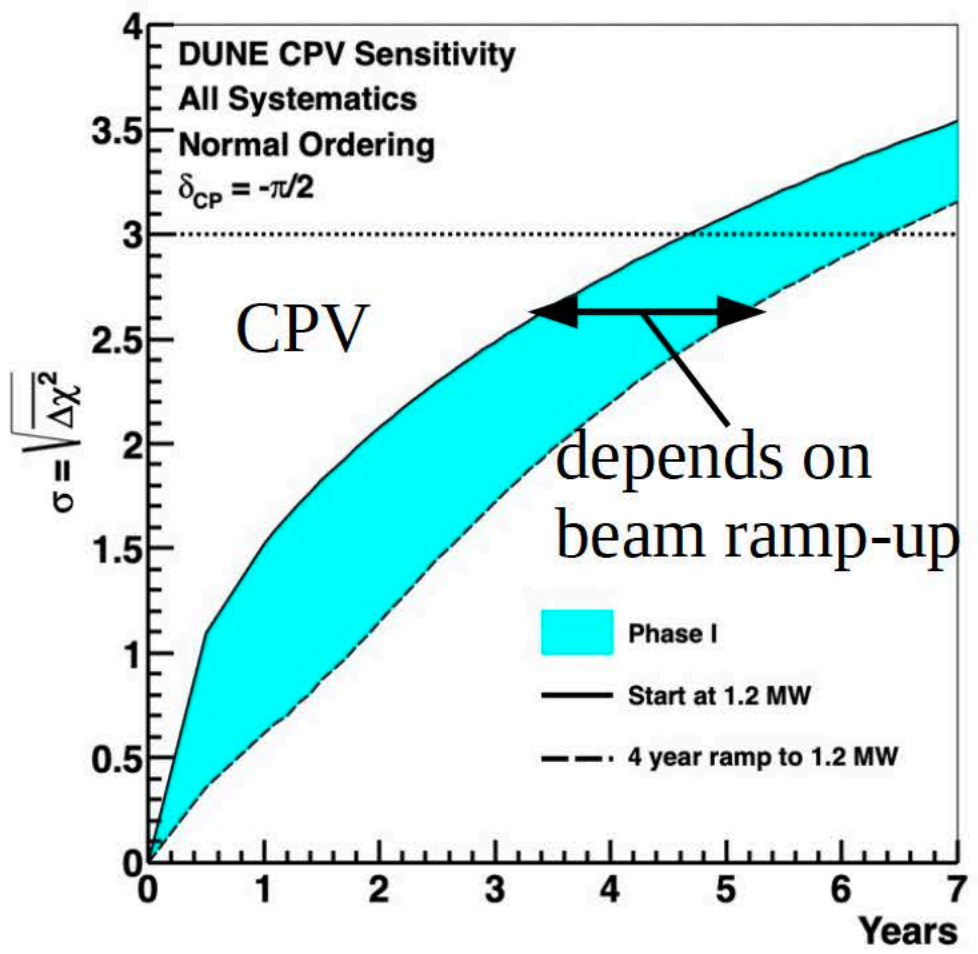
convert TPC Field Cage structure into a fully active PDS → LY ×2

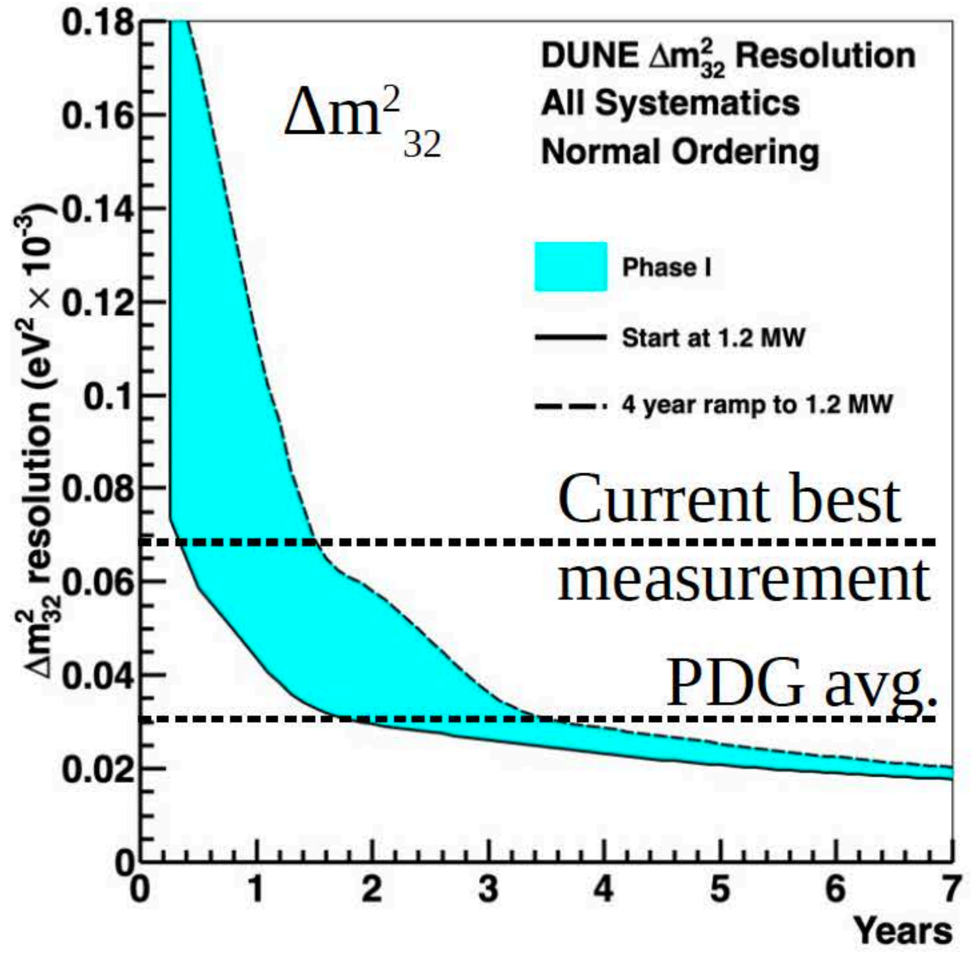


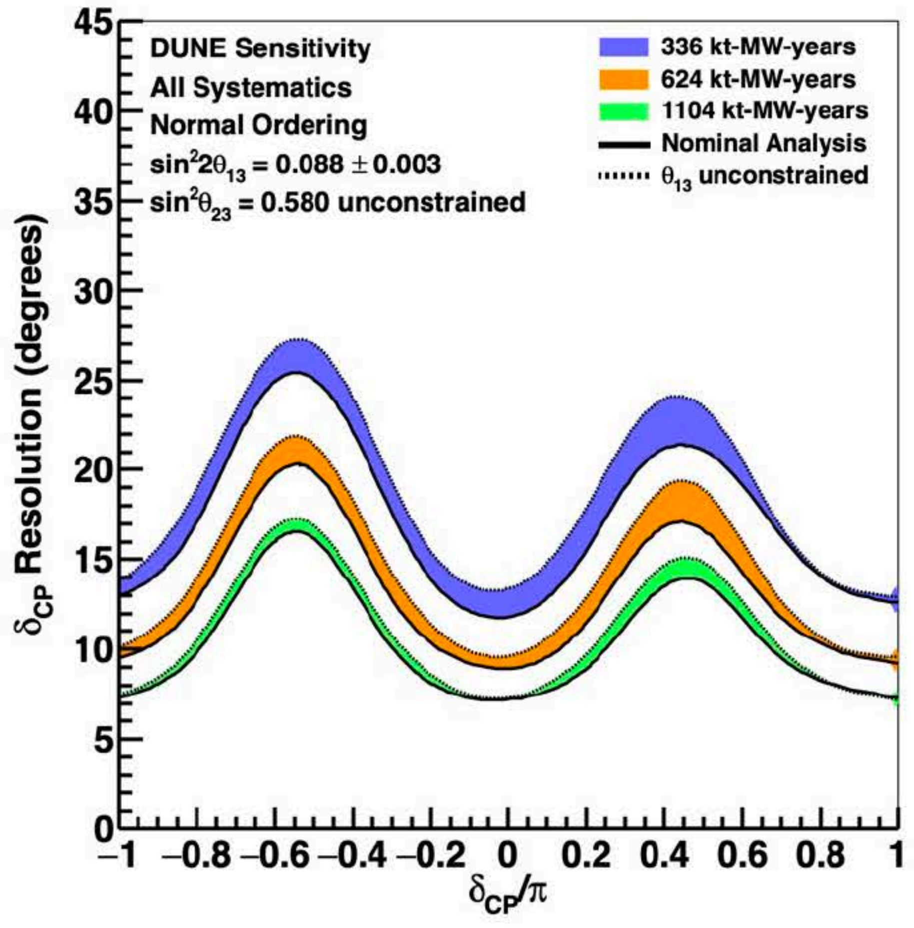
DUNE SENSITIVITIES: PHASE I & PHASE II

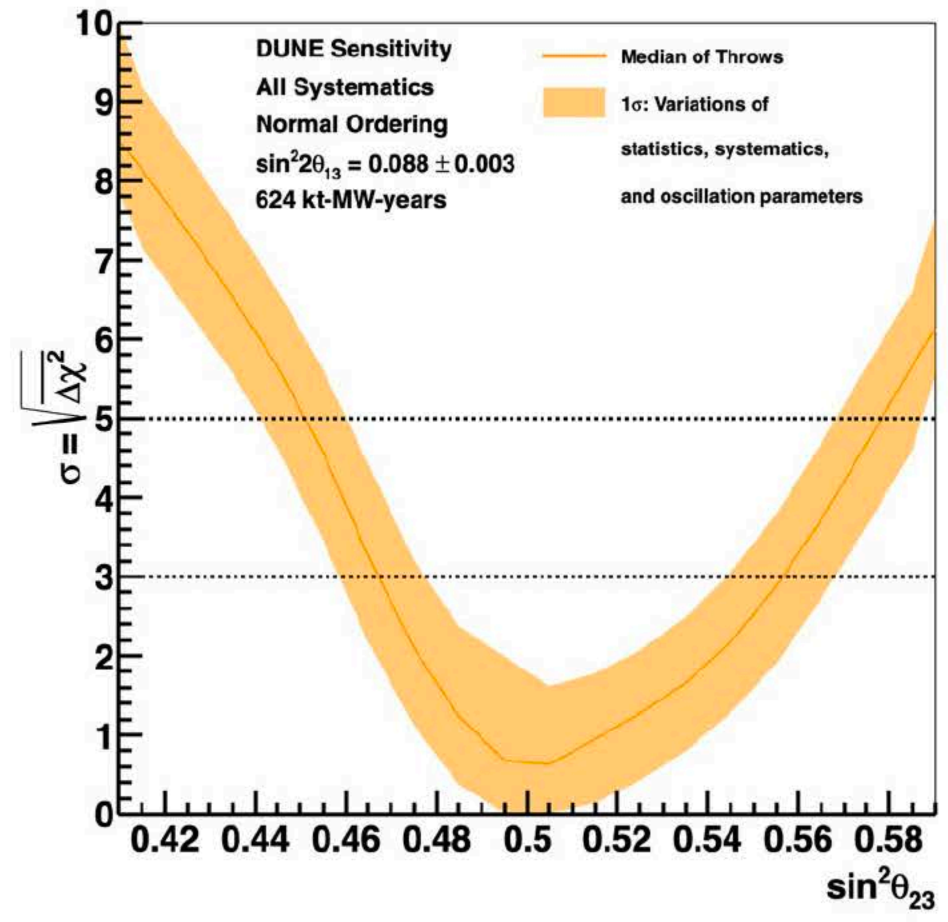
- DUNE Phase I:
  - will be able to establish the **neutrino mass ordering** at the 5σ level for 100% of δ_{CP} values
  - **CP violation** (CPV) can be observed with 3σ significance after about 7 years if $\delta_{CP} = -\pi/2$ and after about 10 years for 50% of δ_{CP} values.
  - Δm^2_{32} can be measured with the resolution better than any other measurements after 2 years
- DUNE Phase II:
  - Measure δ_{CP} to 6-16° → **>5σ CPV** over >50% of δ_{CP} values
  - Measure θ_{23} and Δm^2_{32} → **resolve θ_{23} octant** if non-maximal
  - Measure θ_{13} with precision comparable to reactors → indirect **test of PMNS non-unitarity**

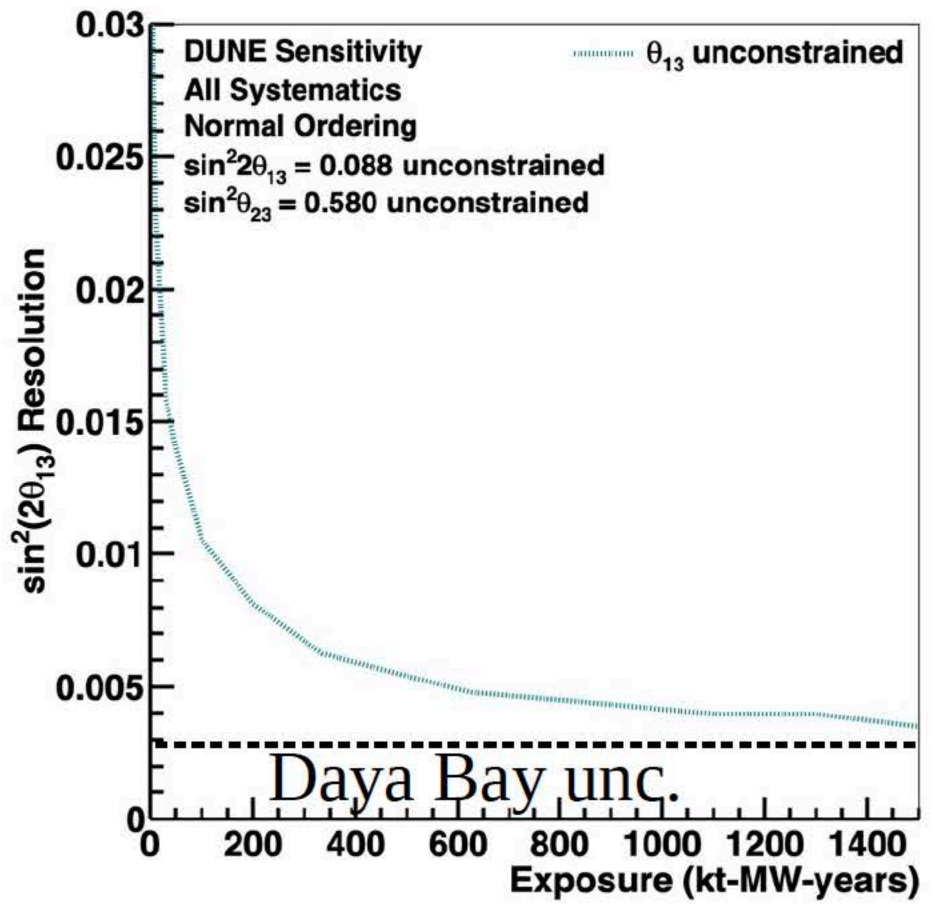












DUNE PHASE II: EXPAND PHYSICS GOALS

Low-Energy Physics

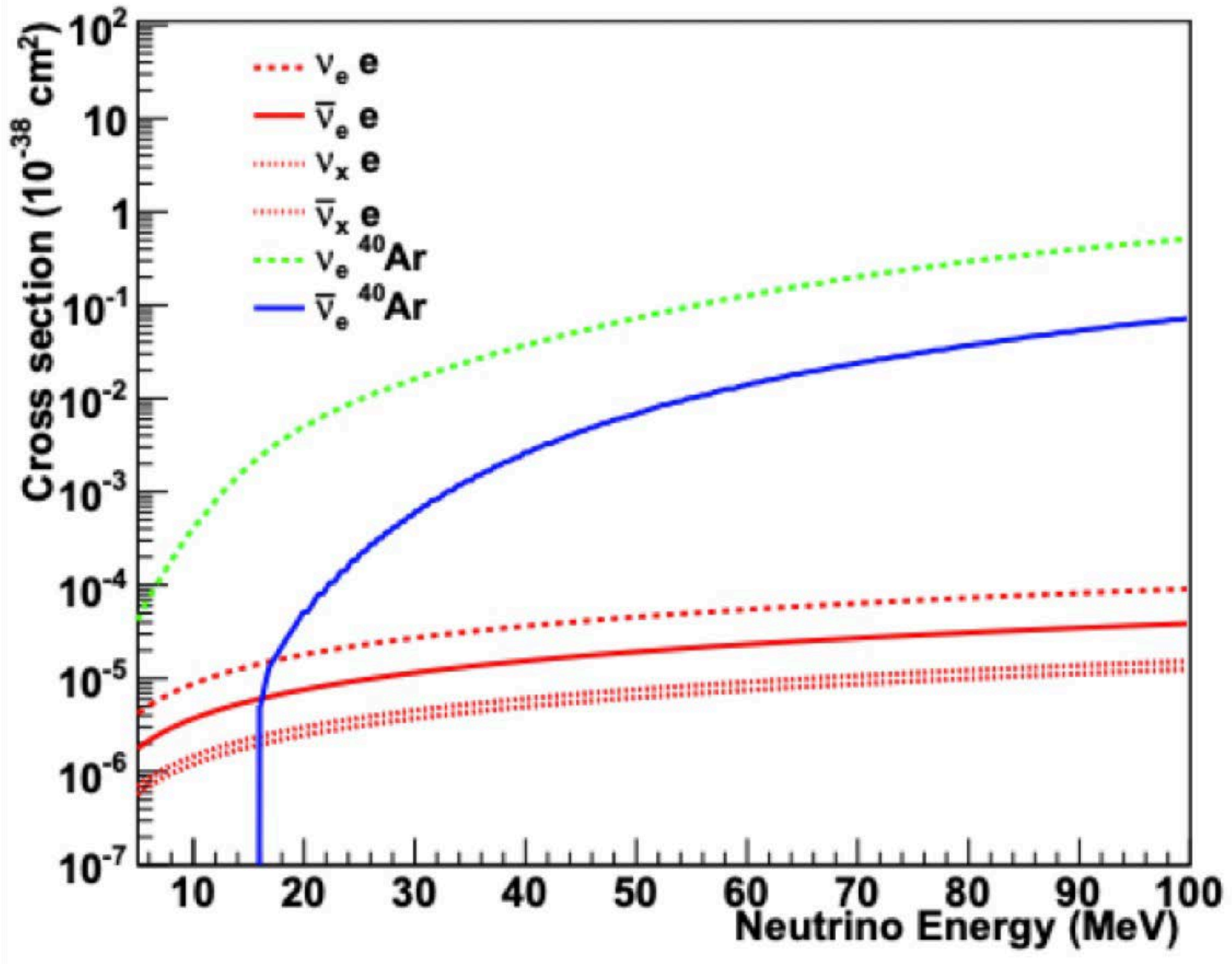
- Interaction channels in argon:
  - Charged current (CC) interactions on Ar

    $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$

    $\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$
  - ES on electrons

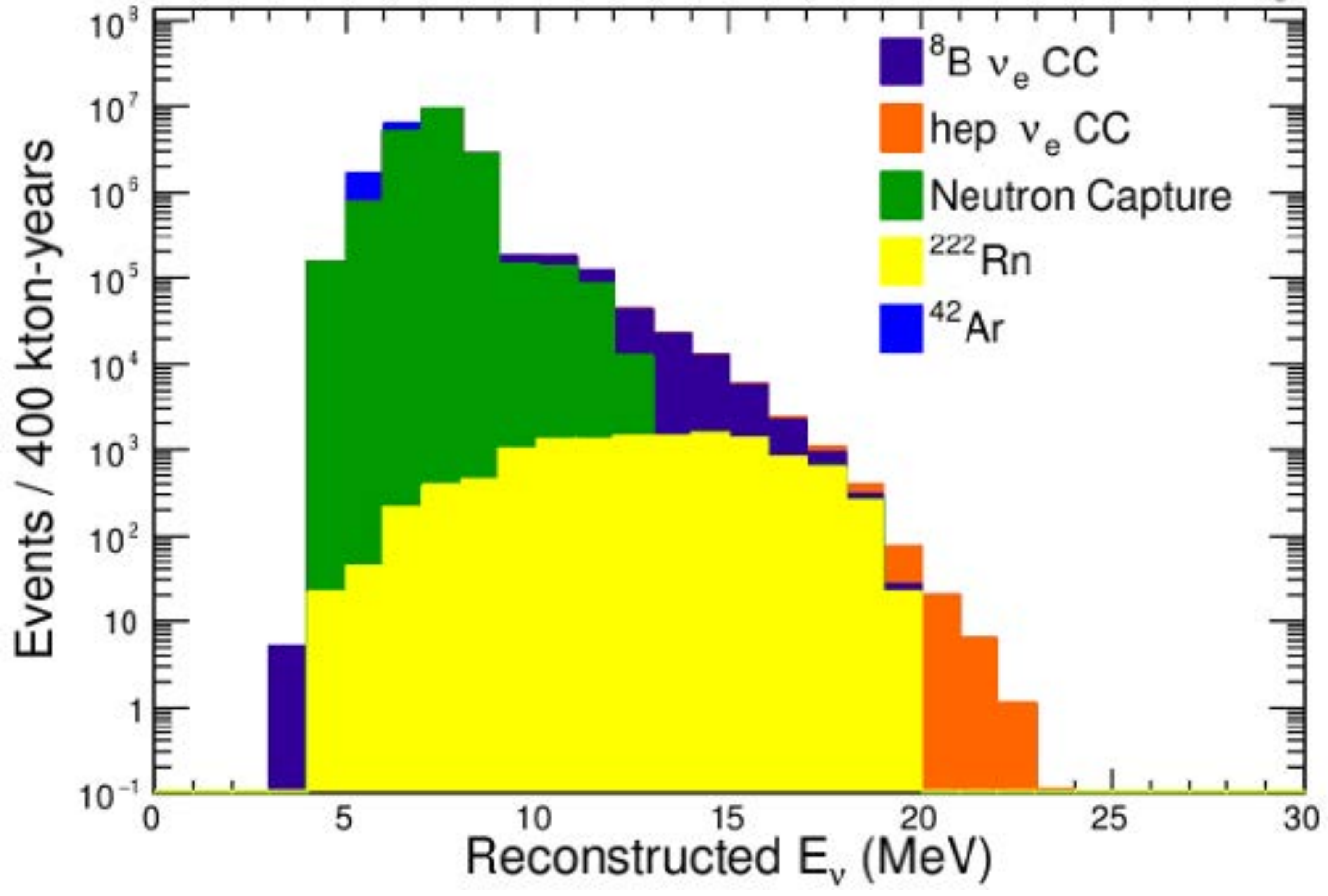
    $\nu_x + e^- \rightarrow \nu_x + e^-$
  - Neutral current (NC) interactions on Ar

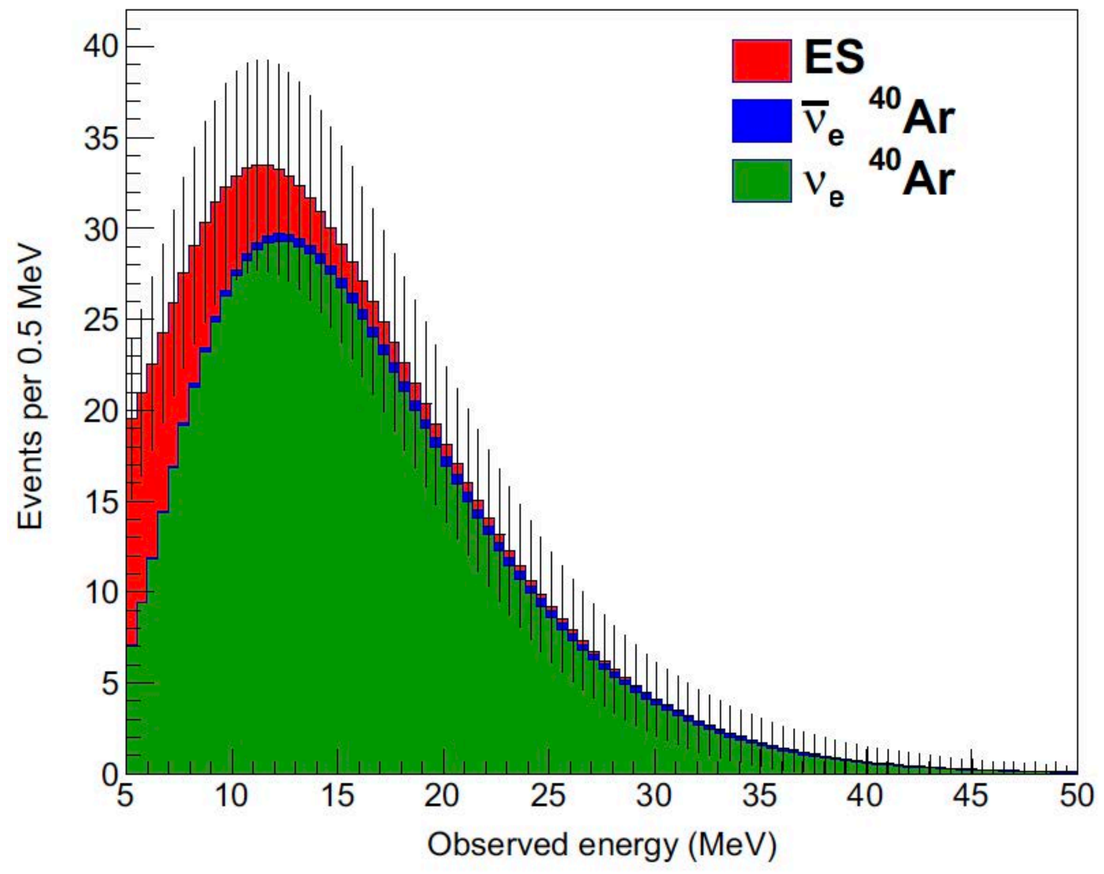
    $\nu_x + {}^{40}\text{Ar} \rightarrow \nu_x + {}^{40}\text{Ar}^*$
- Astrophysical neutrinos
  - Solar neutrinos:
    - potential for first detection of hep flux
    - precision θ_{12} and Δm^2_{21} measurements
  - Supernova neutrino burst detection
    - unique capability of observing neutralization phase
  - Diffuse supernova background

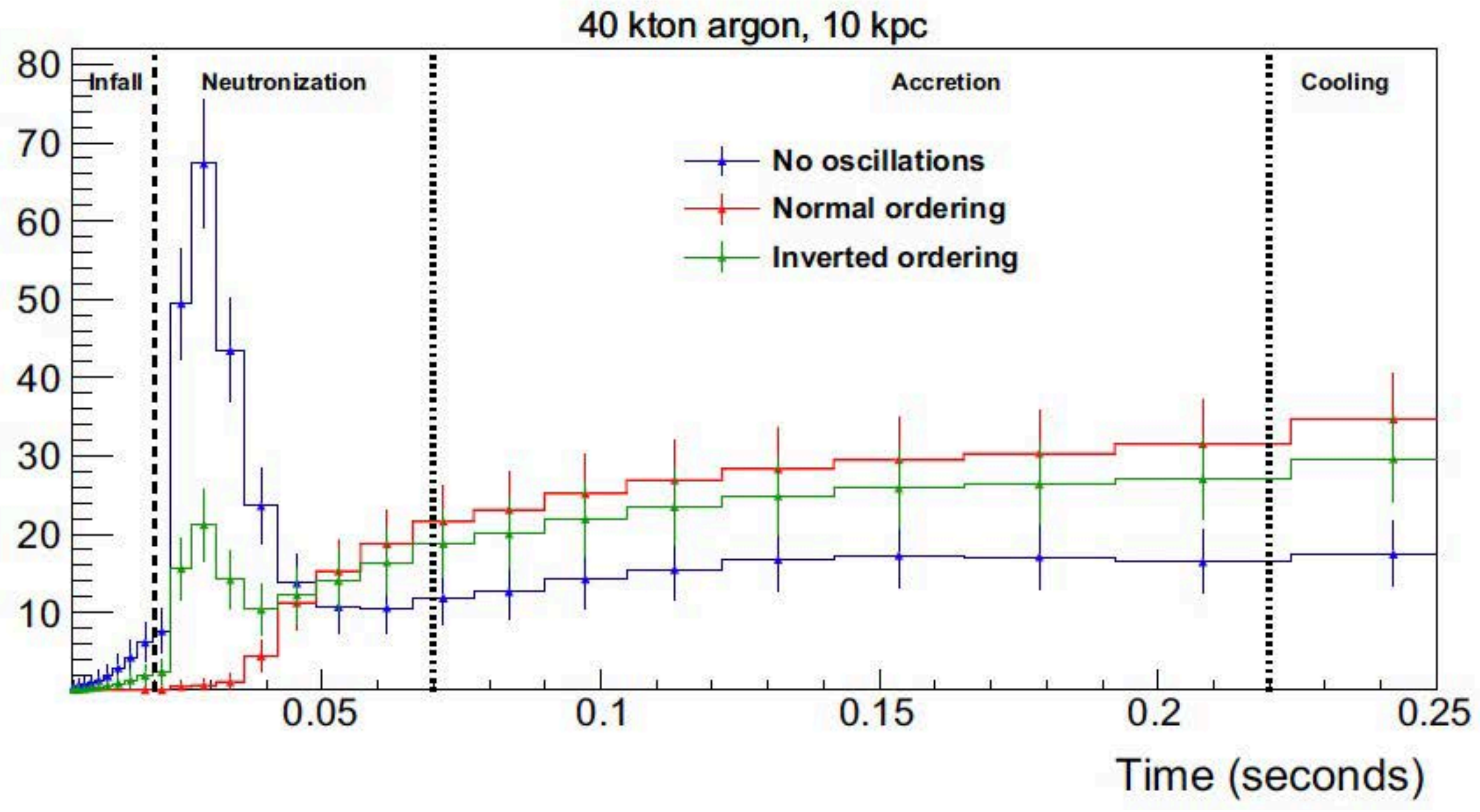


arXiv:2301.04526

DUNE Preliminary



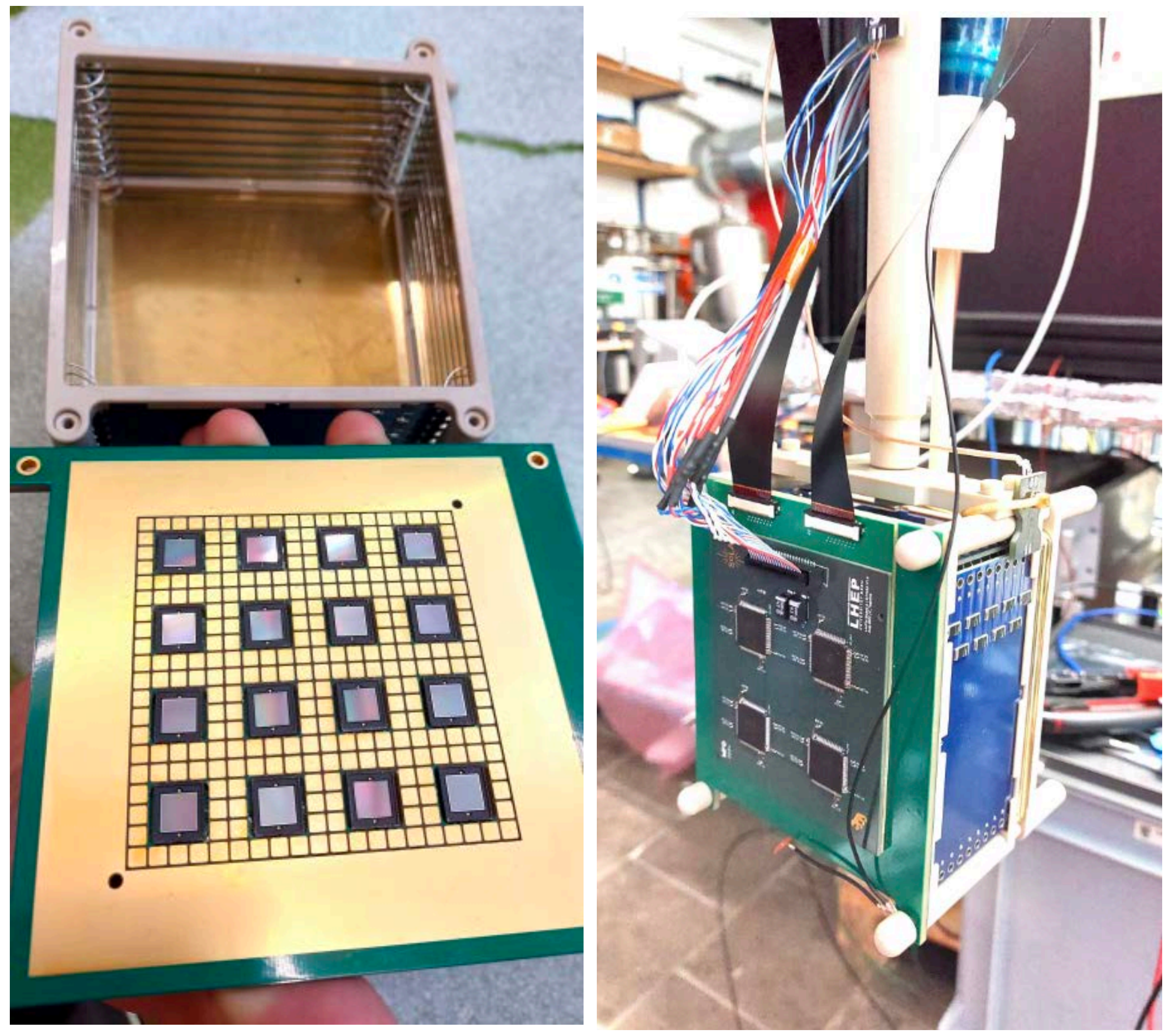




Eur. Phys. J. C (2021) 81:423

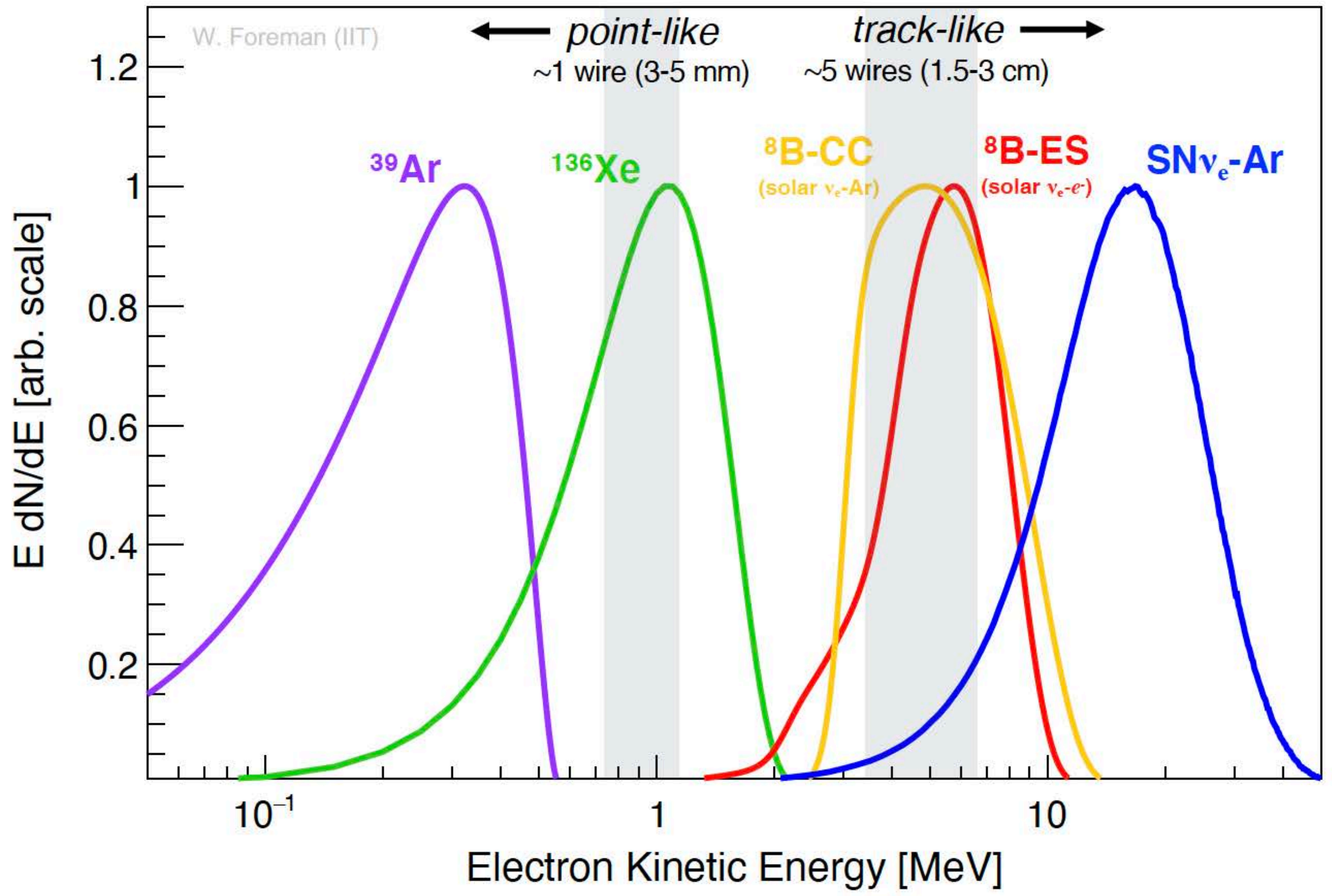
DUNE PHASE II: EXPLORE NEW TECHNOLOGIES

- **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

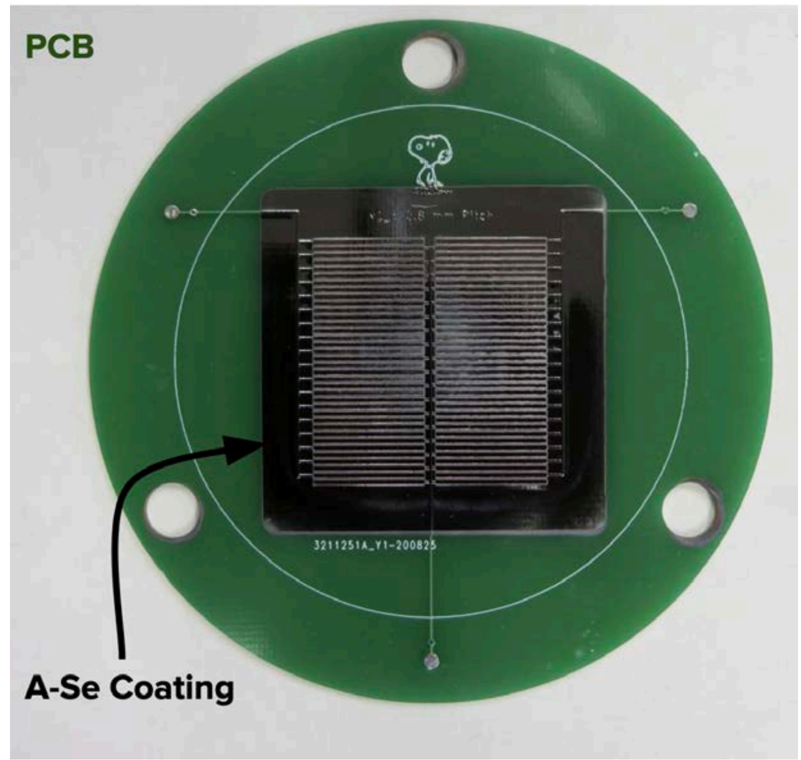


SOLAR prototype

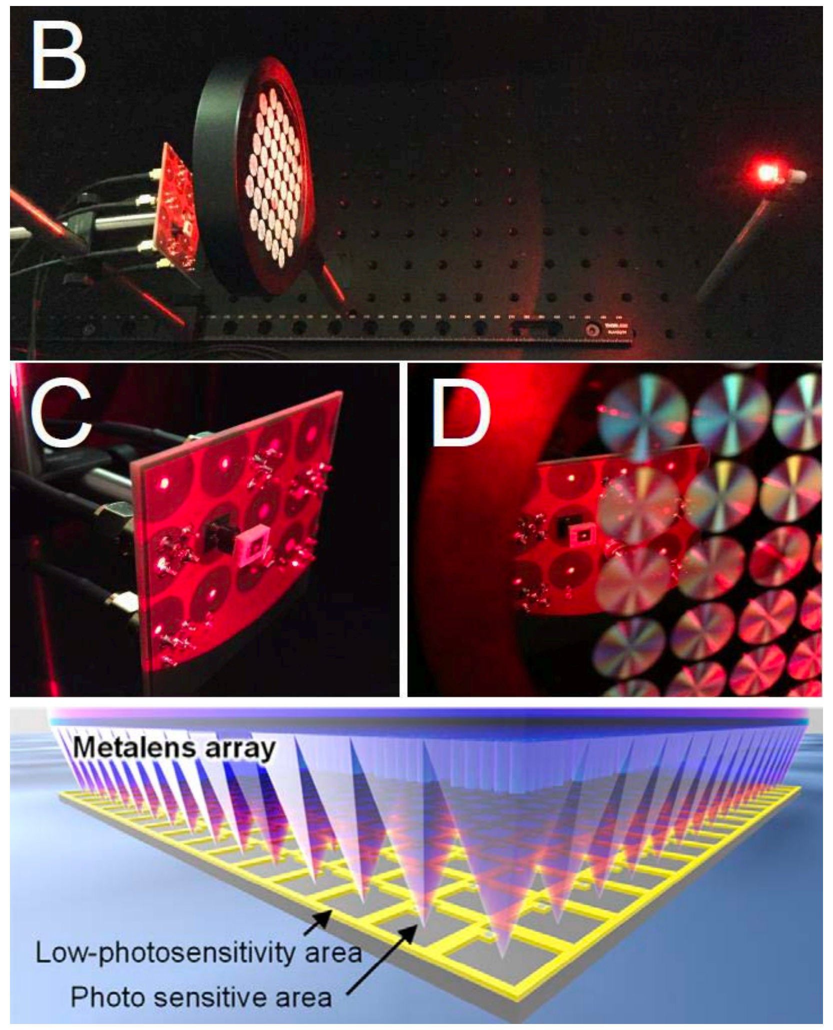
J. Phys. G: Nucl. Part. Phys. 50 033001

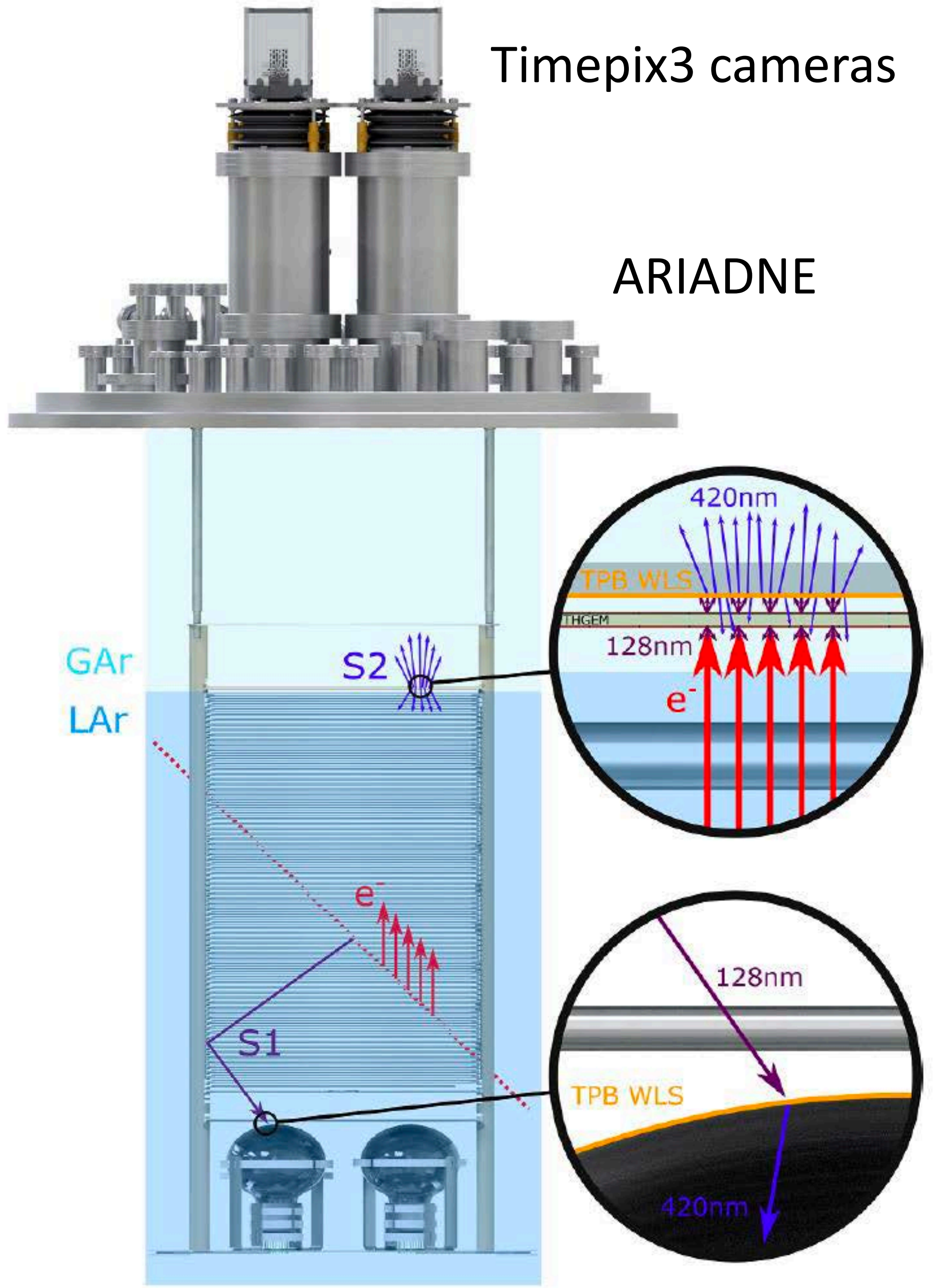


Multiple modality pixels



Metalenses

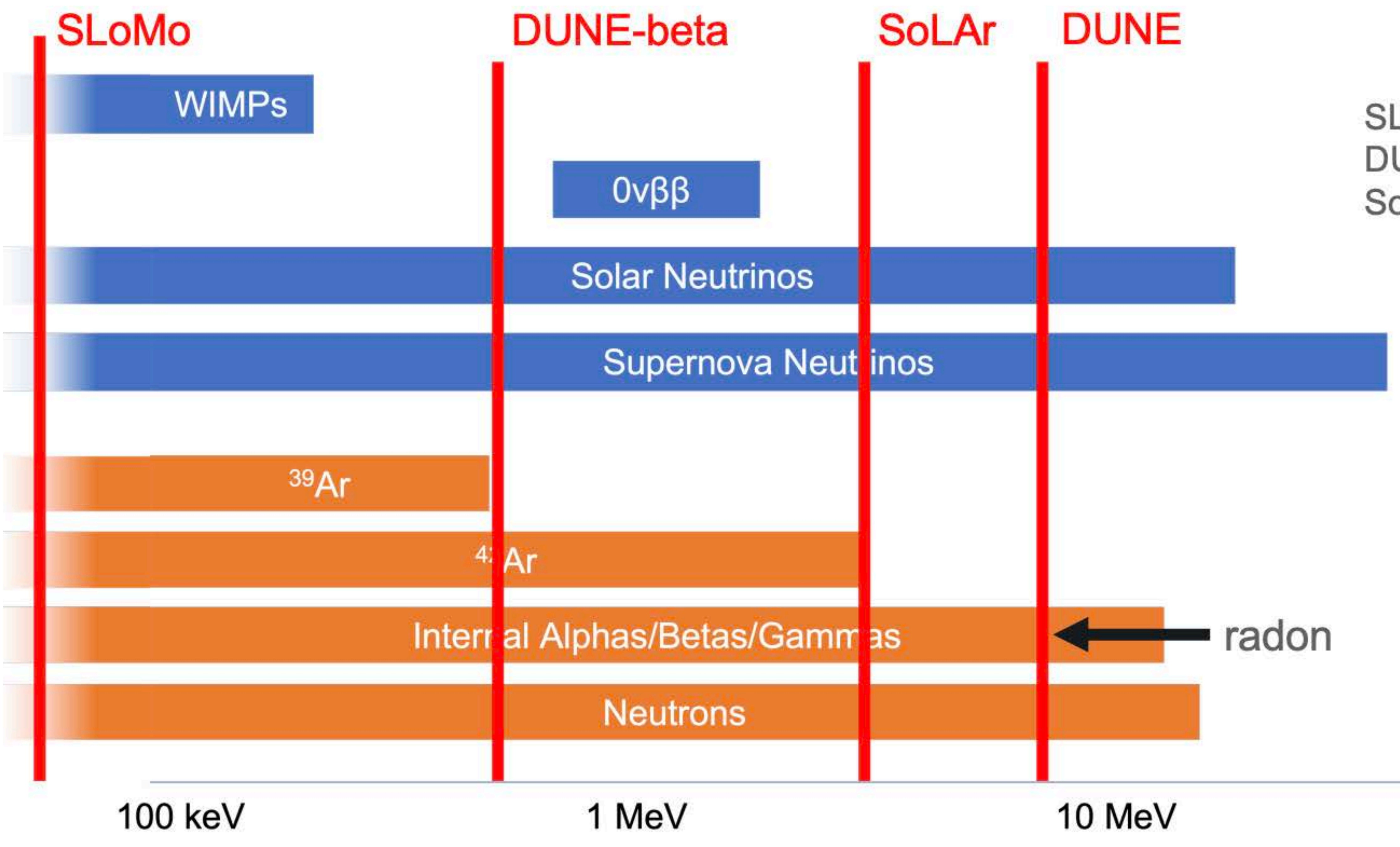




DUNE PHASE II: BLUE SKY

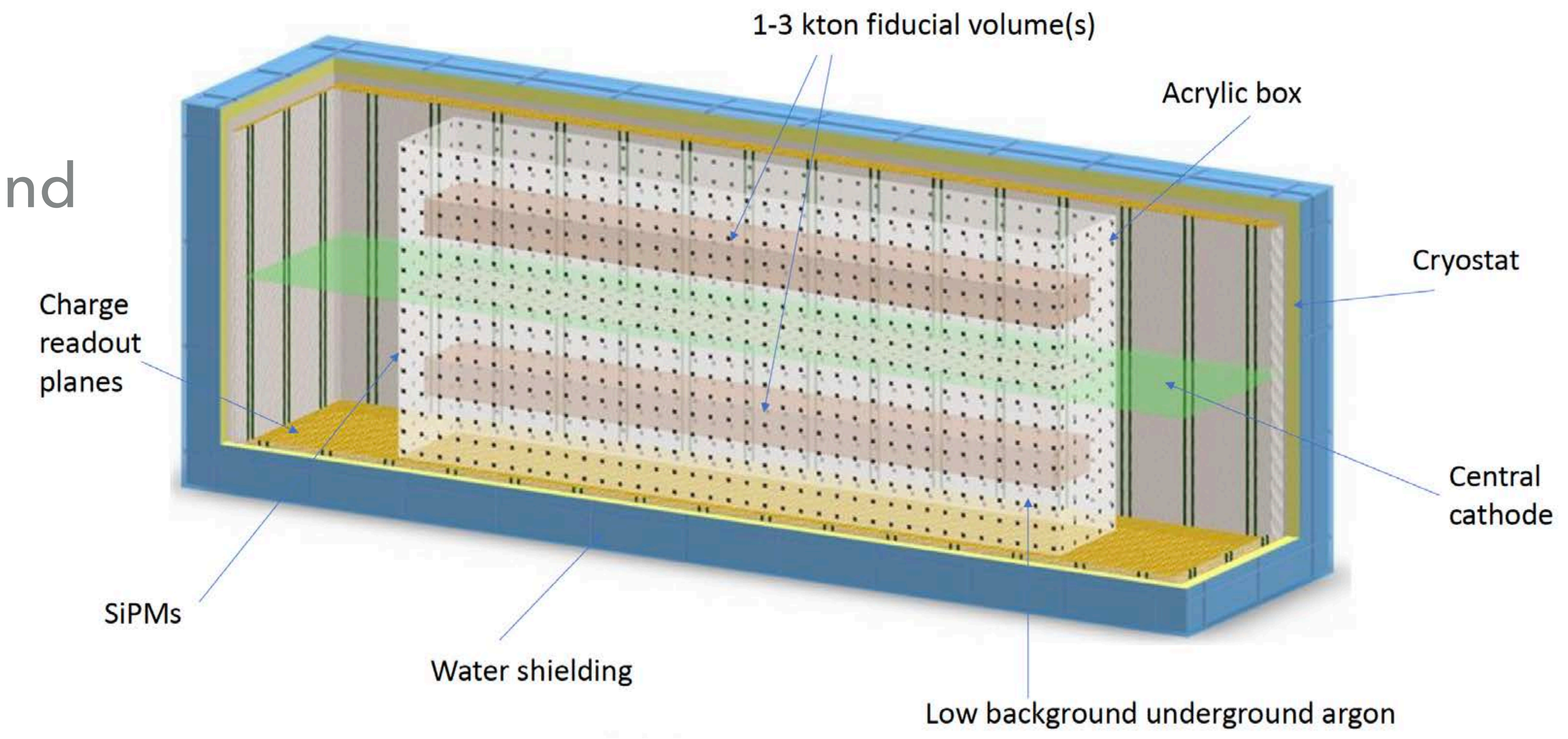
- **Further Low-Energy Physics goals:**
  - Measurement of lower-energy neutrinos in real time with high statistics
  - $0\nu\beta\beta$
  - WIMP dark matter
  - CEvNS…
- **Higher detector challenges:**
  - External shielding
  - Materials selection QA/QC
  - Radon reduction
  - Low-radioactivity underground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

Chris Jackson, Seattle Snowmass Summer Meeting 2022

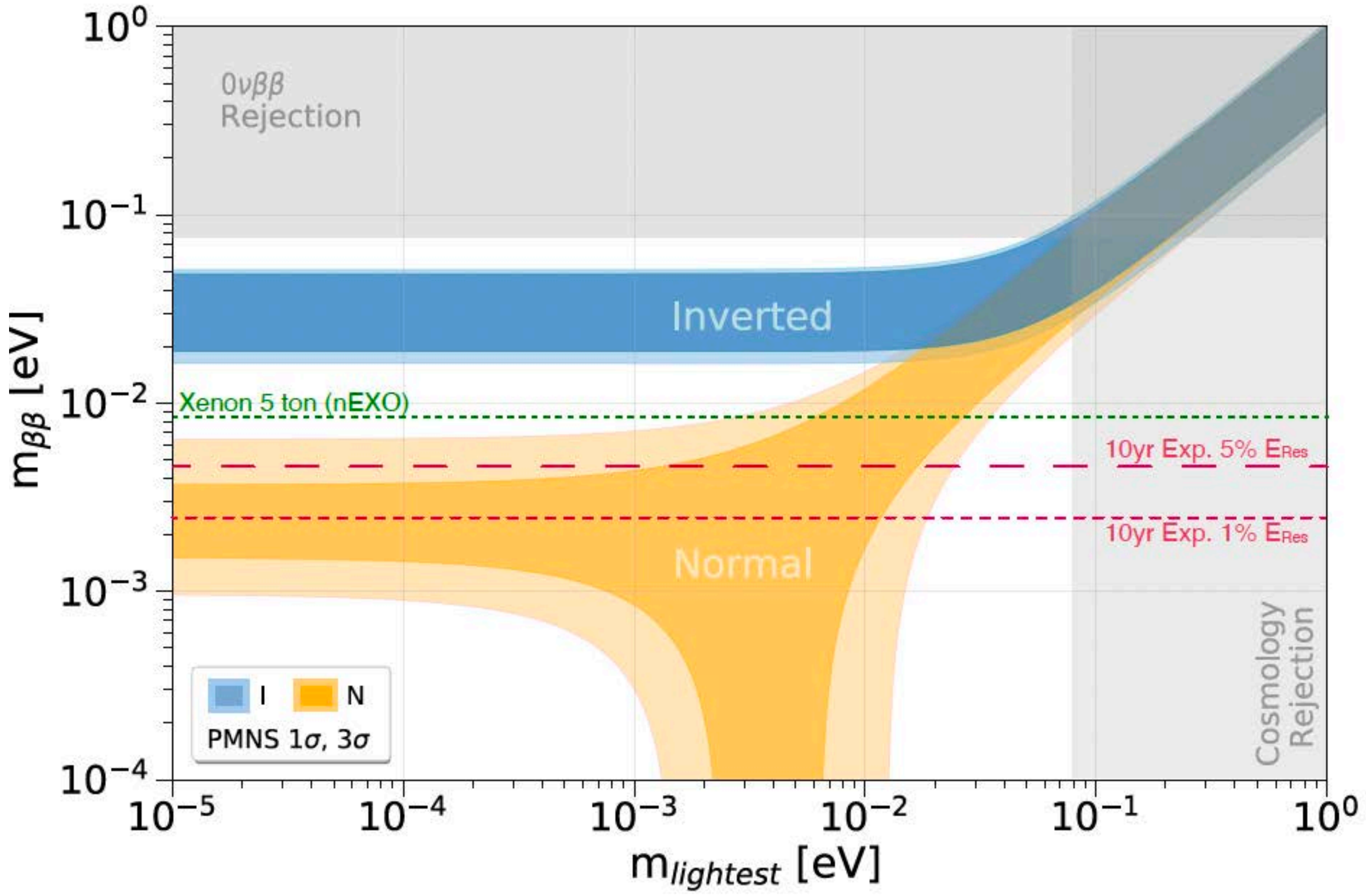


SLoMo: arxiv:2203.08821
DUNE-beta: arxiv:2203.14700
SoLAr: arxiv:2203.07501

Also:
Low-Energy Physics in Neutrino LArTPCs: arxiv:2203.00740
DUNE as the Next-Generation Solar Neutrino Experiment Phys. Rev. Lett. 123, 131803 (2019)

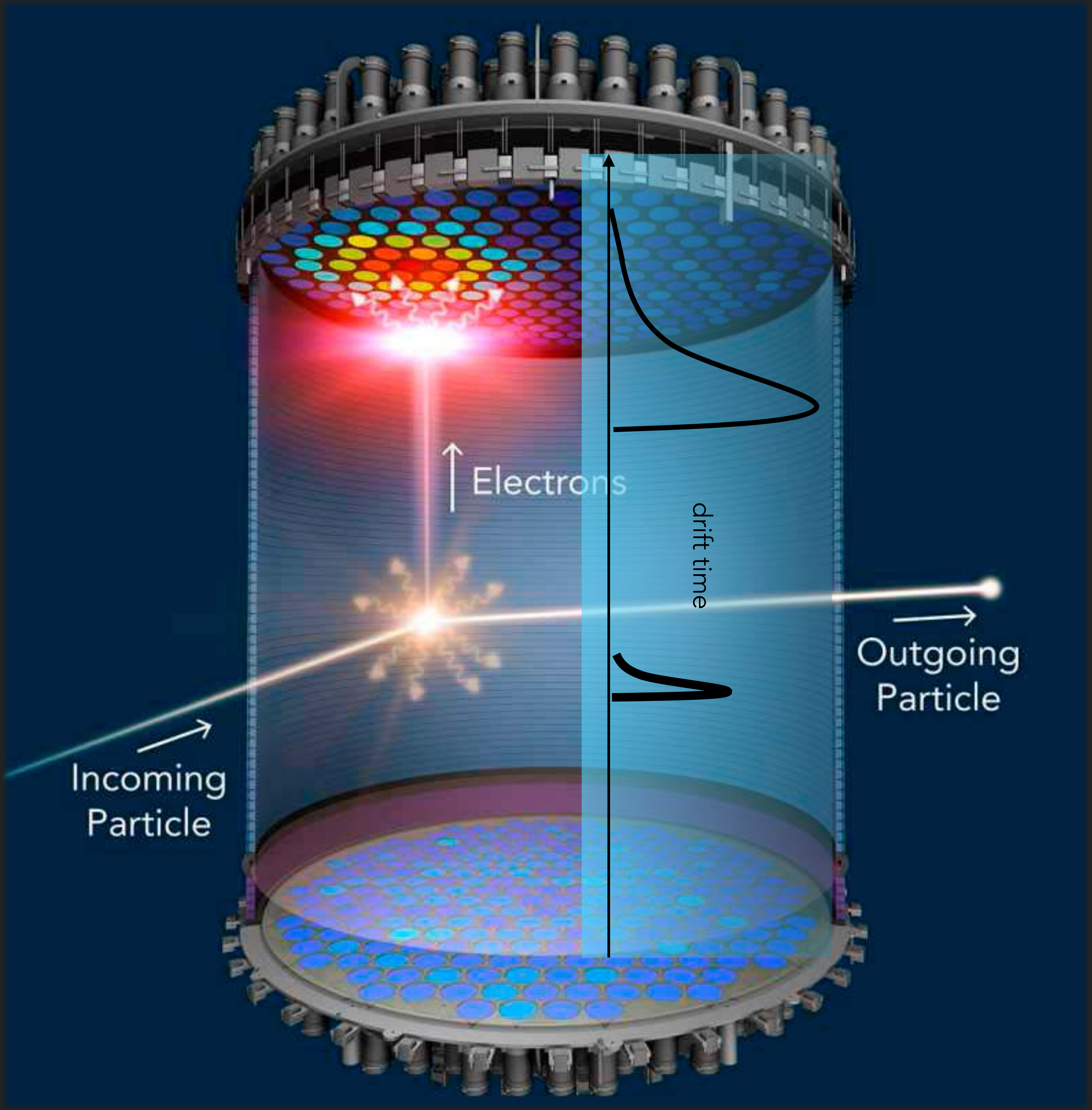


arXiv:2203.14700



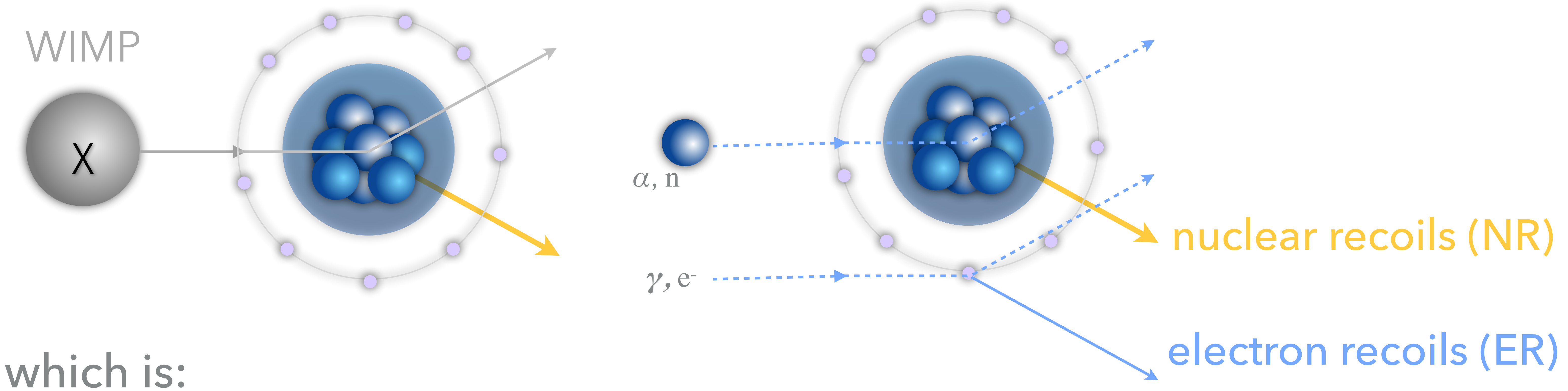
DUAL-PHASE TIME PROJECTION CHAMBERS

- dual-phase Time Projection Chambers with multi-tonne liquid Xe, Ar targets
- read out primary scintillation: “S1” + proportional gas scintillation from drifted electrons: “S2”
- 3D position reconstruction:
  - time difference between S1 and S2 gives Z position (few mm resolution)
  - pattern of S2 light gives XY position (~1cm resolution)
- background identification + passive suppression
- zeptobarn (10^{-45} cm^2) to yoctobarn (10^{-48} cm^2) sensitivity to WIMP dark matter



Credit: SLAC National Accelerator Laboratory

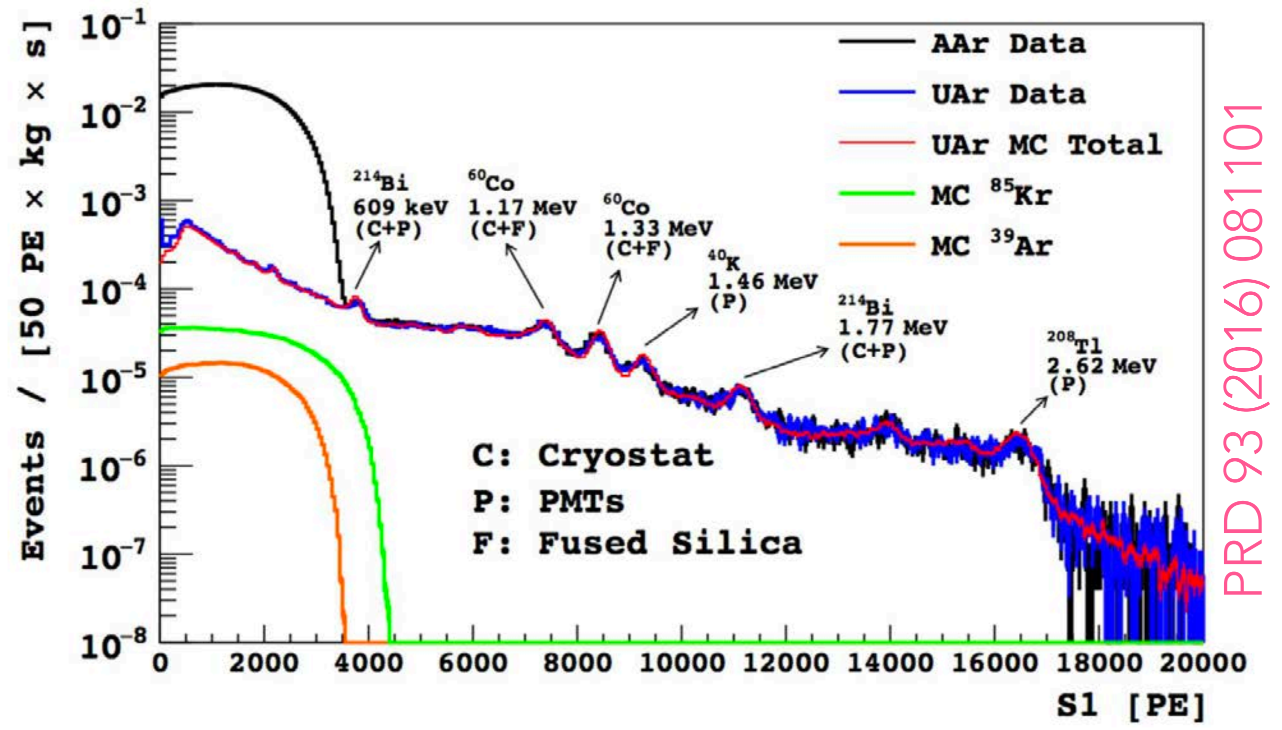
EXPERIMENTAL CHALLENGE: DETECTING NUCLEAR RECOILS

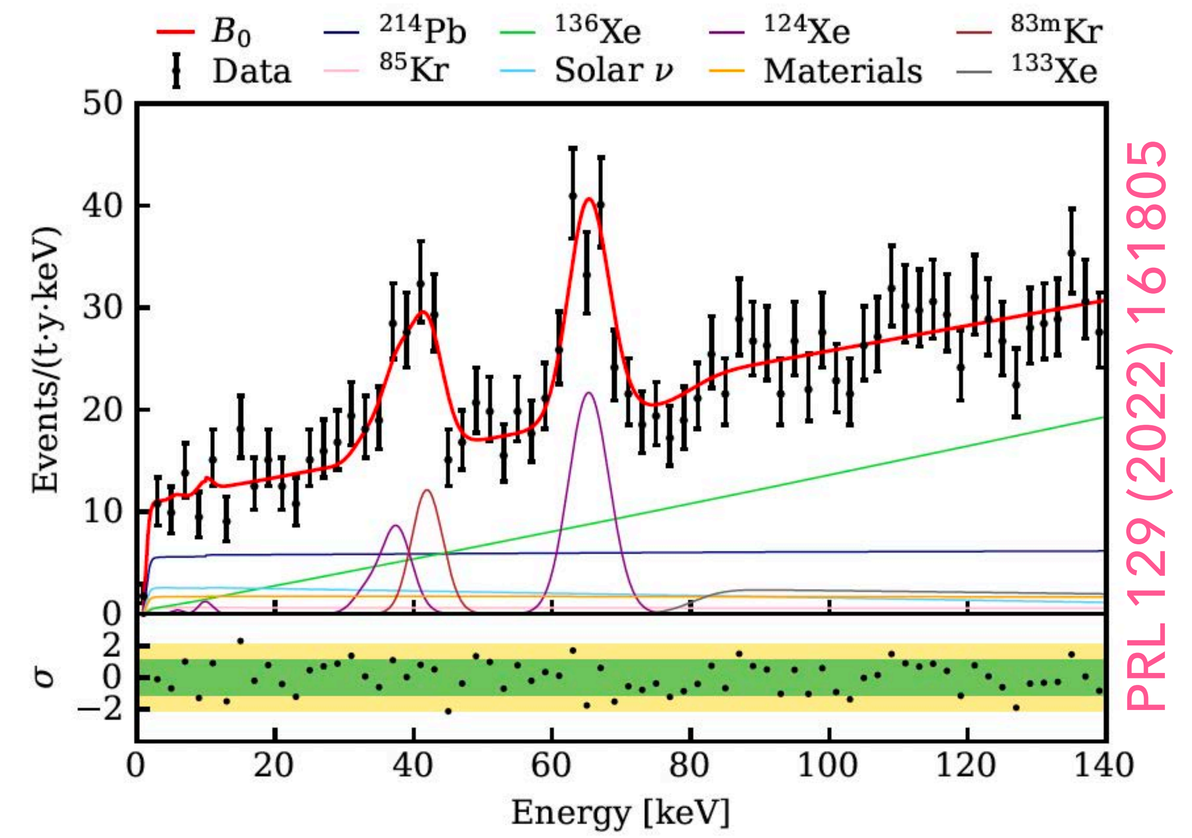


- DM detectors designed to observe a signal which is:
  - very small: low recoil energies < 100 keV
  - very rare: <1 ev/(kg y) at low masses and < 1 ev/(t y) at high masses
  - buried in **backgrounds** from:
    - Muon-induced neutrons: NRs
    - Cosmogenic activation of materials/targets: ERs
    - Radioactivity of detector materials: NRs and ERs
    - Target intrinsic isotopes: ERs
    - Neutrinos (solar, atmospheric, DSNB): NRs and ERs

Internal backgrounds:

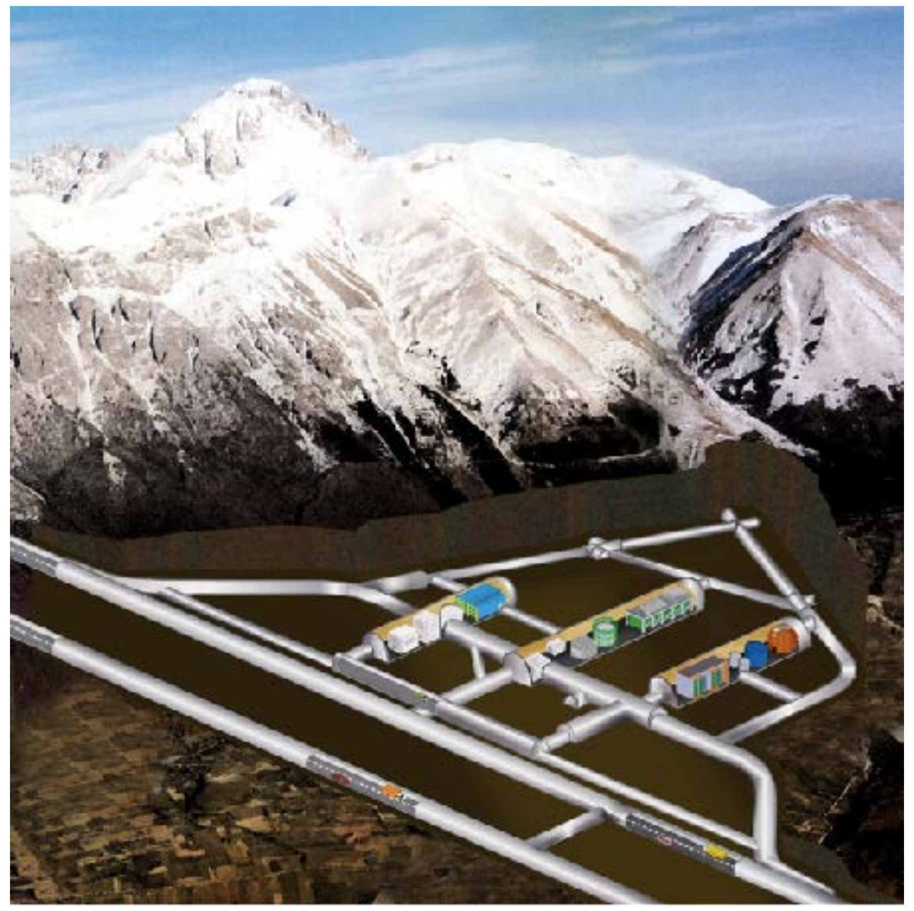
- ^{39}Ar: 1 Bq/kg in AAr to <1 mBq/kg in UAr
- ^{85}Kr: ~1 mBq/kg in commercially available xenon to 0.01 µBq/kg by dedicated removal devices
- ^{222}Rn: <1 µBq/kg achieved in LXe, 2–0.2 µBq/kg in LAr



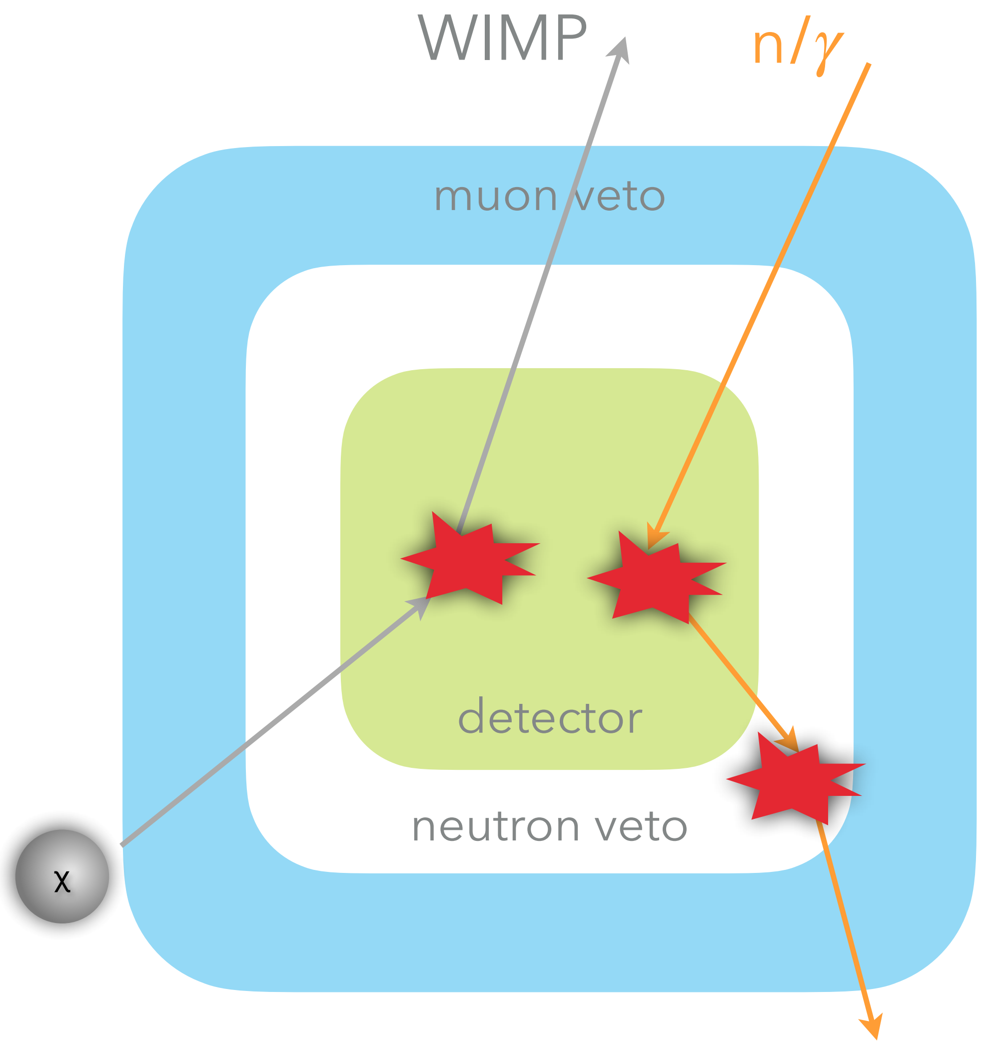


EXPERIMENTAL CHALLENGE: DEFEATING BACKGROUNDS

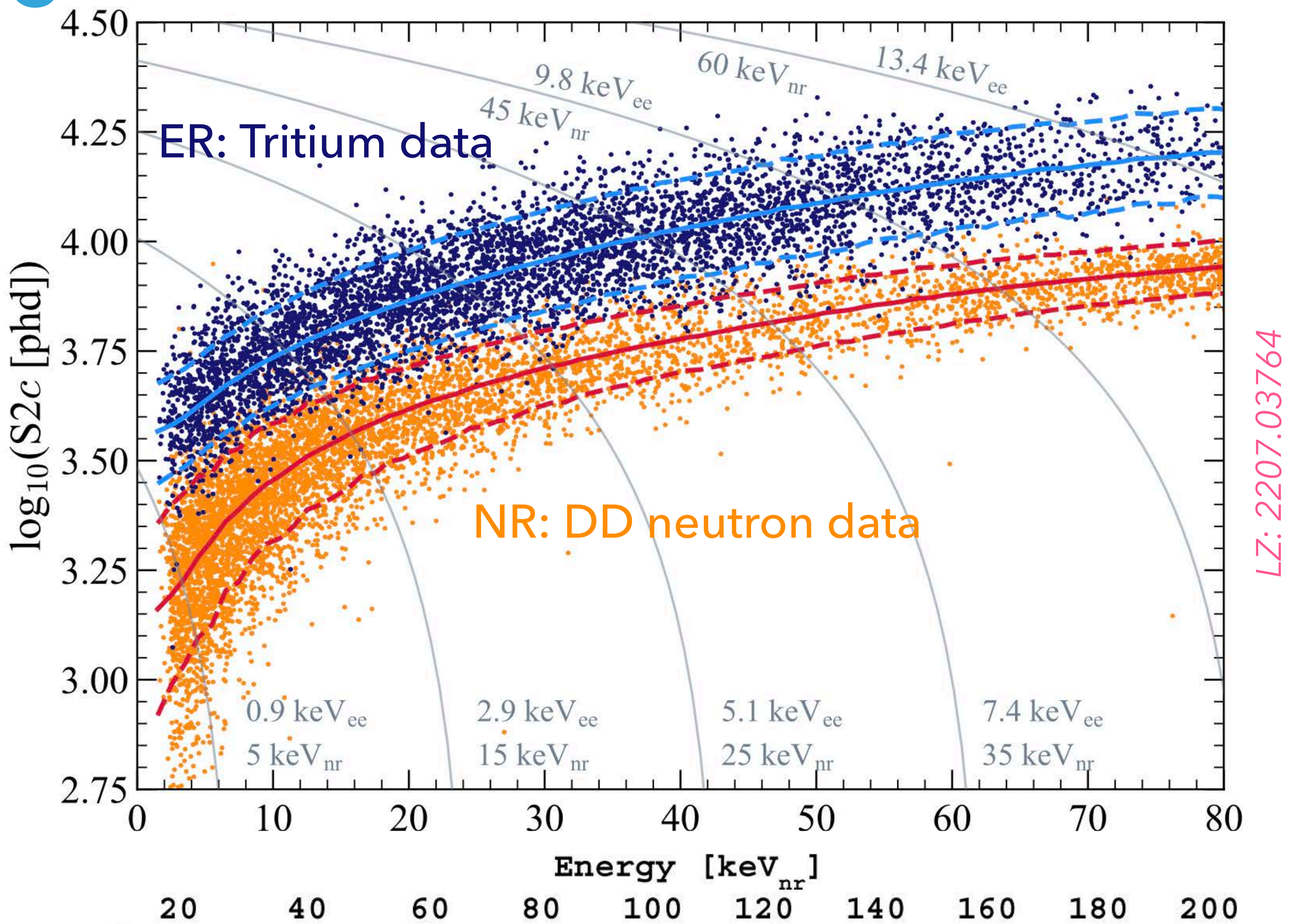
- **Background reduction:**
  - Underground location
  - Clean environment
  - Material screening & selection
  - Purification of target materials
- **Background rejection**
  - Active veto shield
  - ER/NR identification

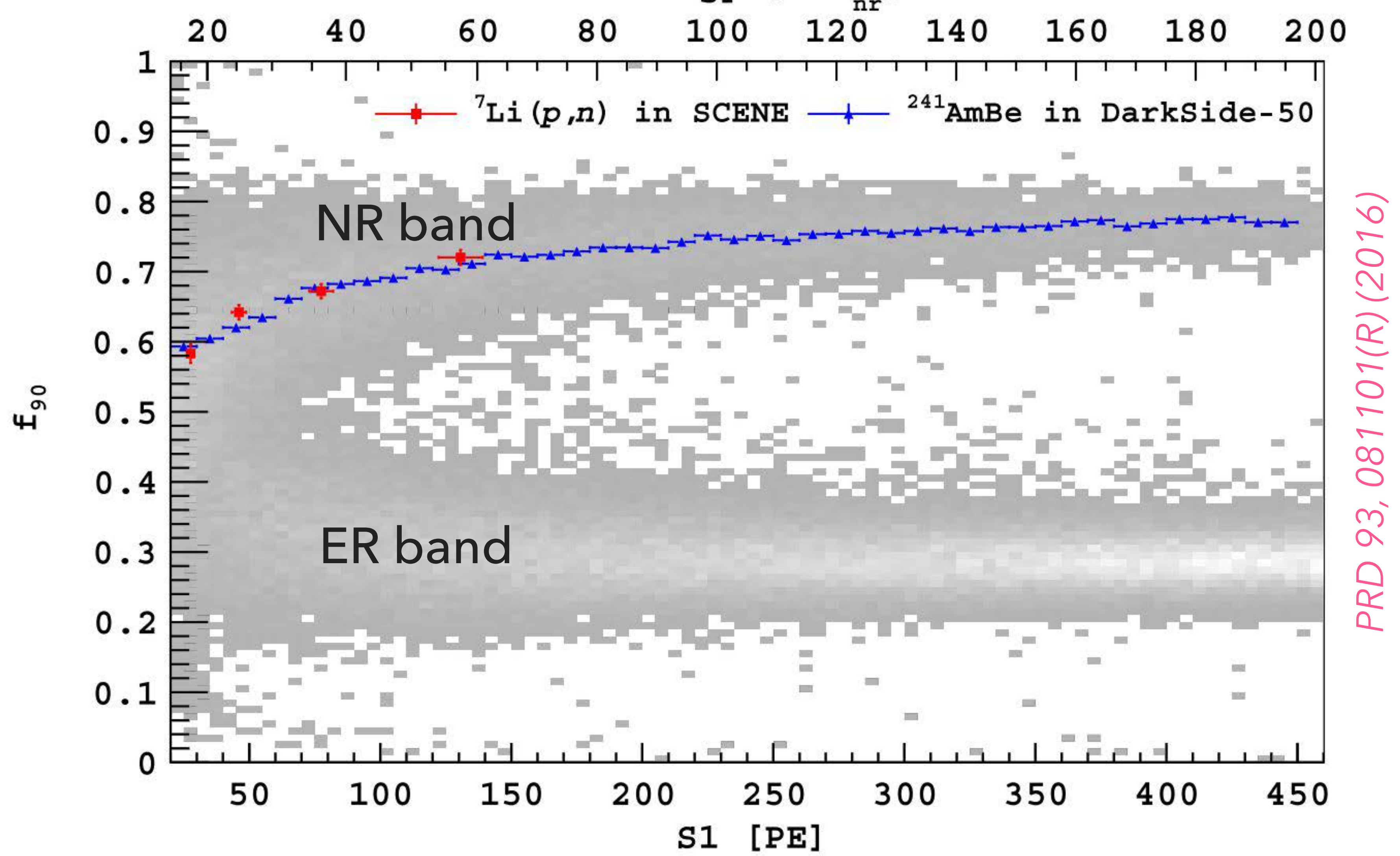


Active veto shield

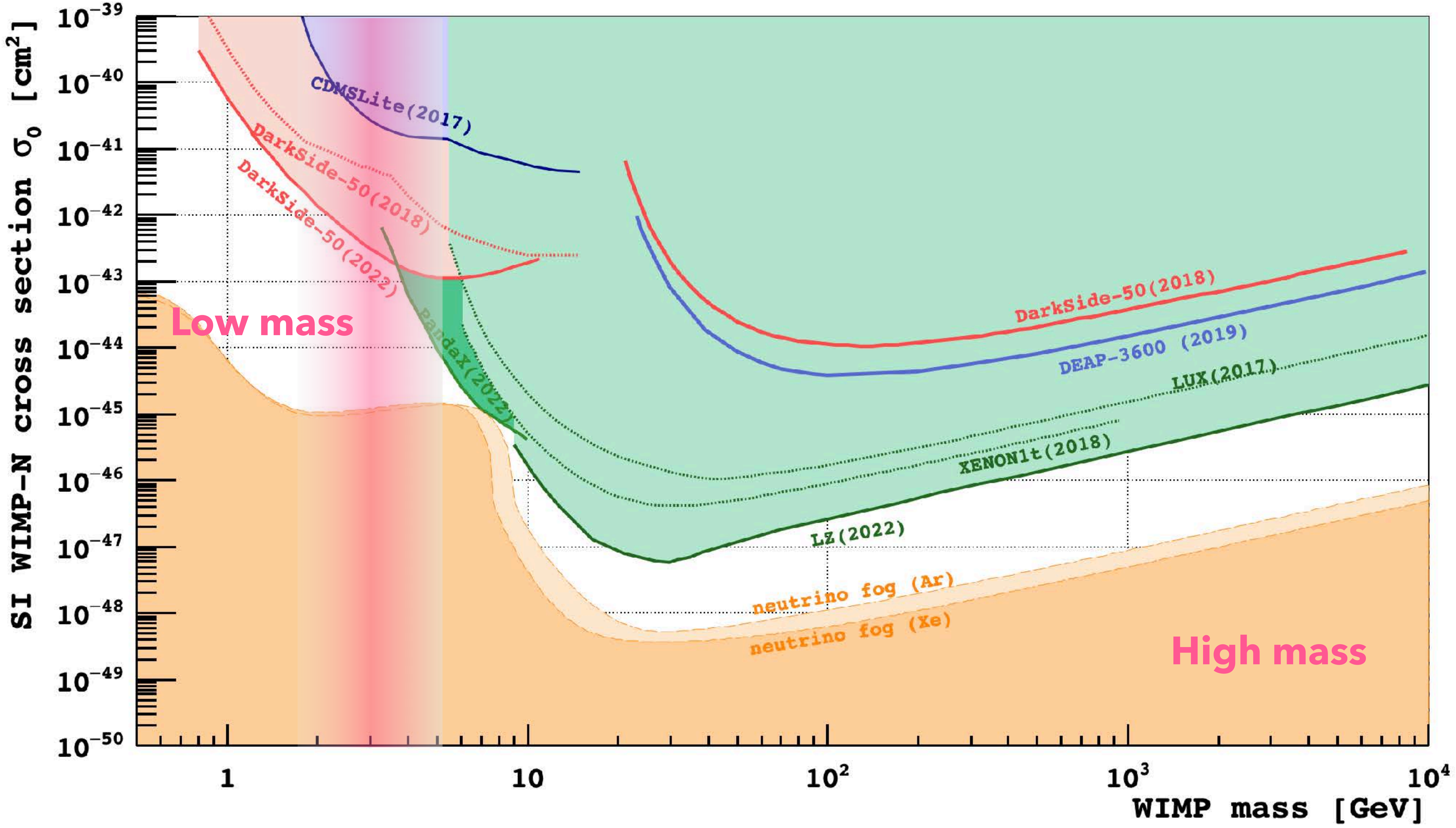


ER/NR identification





NOBLE LIQUID DETECTORS SENSITIVE TO A BROAD RANGE OF WIMP MASSES



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

XENON DETECTORS

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

10 kg

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)

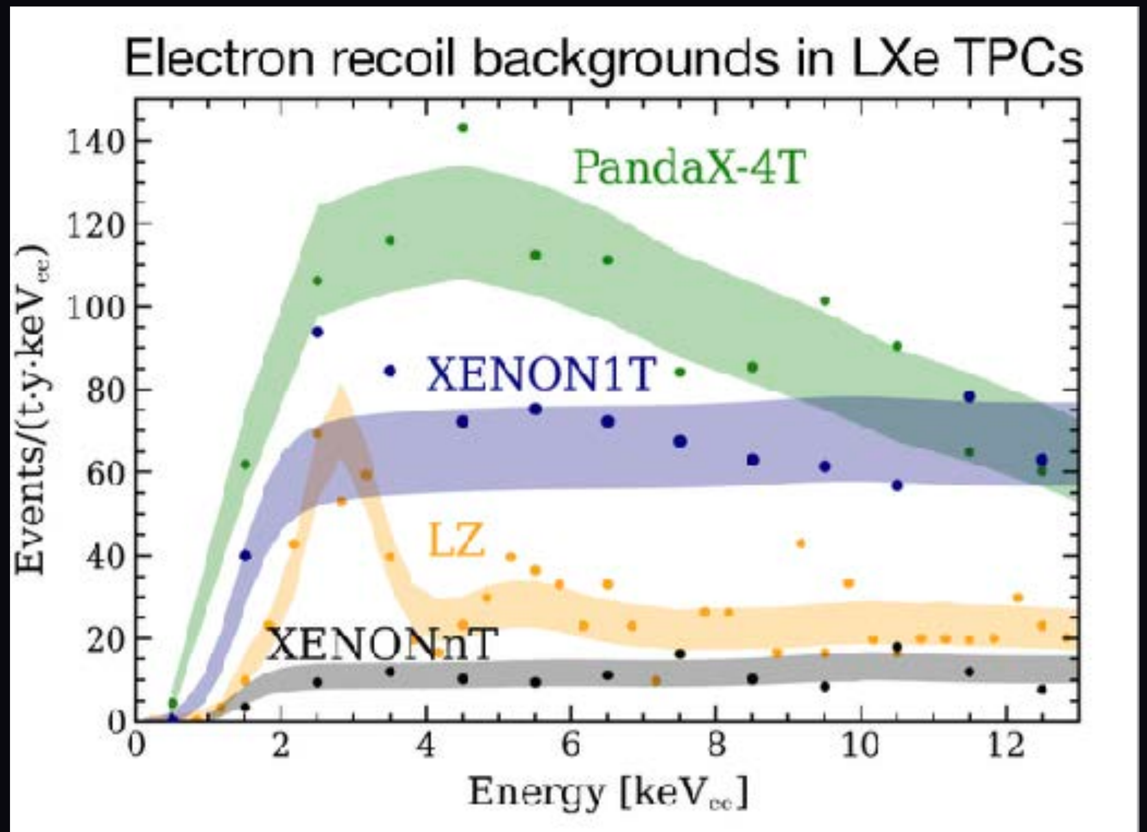
XENONnT: (6t, LNGS)
LZ: (7t, SURF)

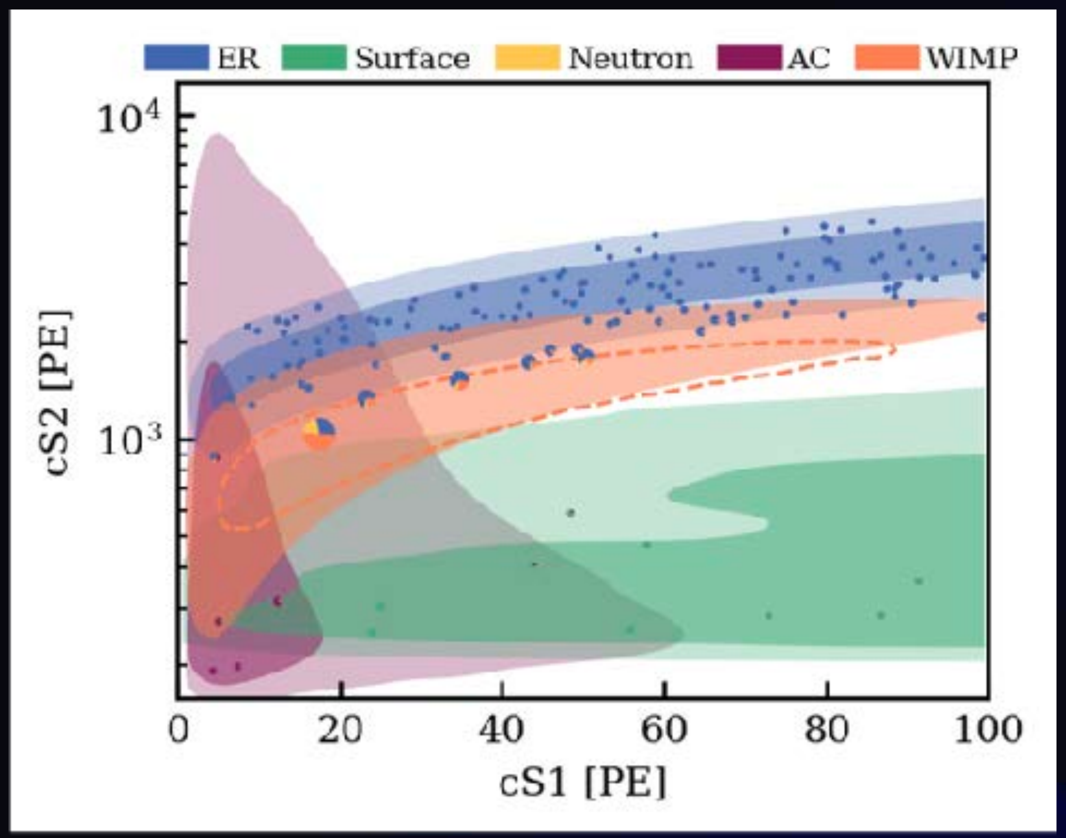
2020

10000 kg

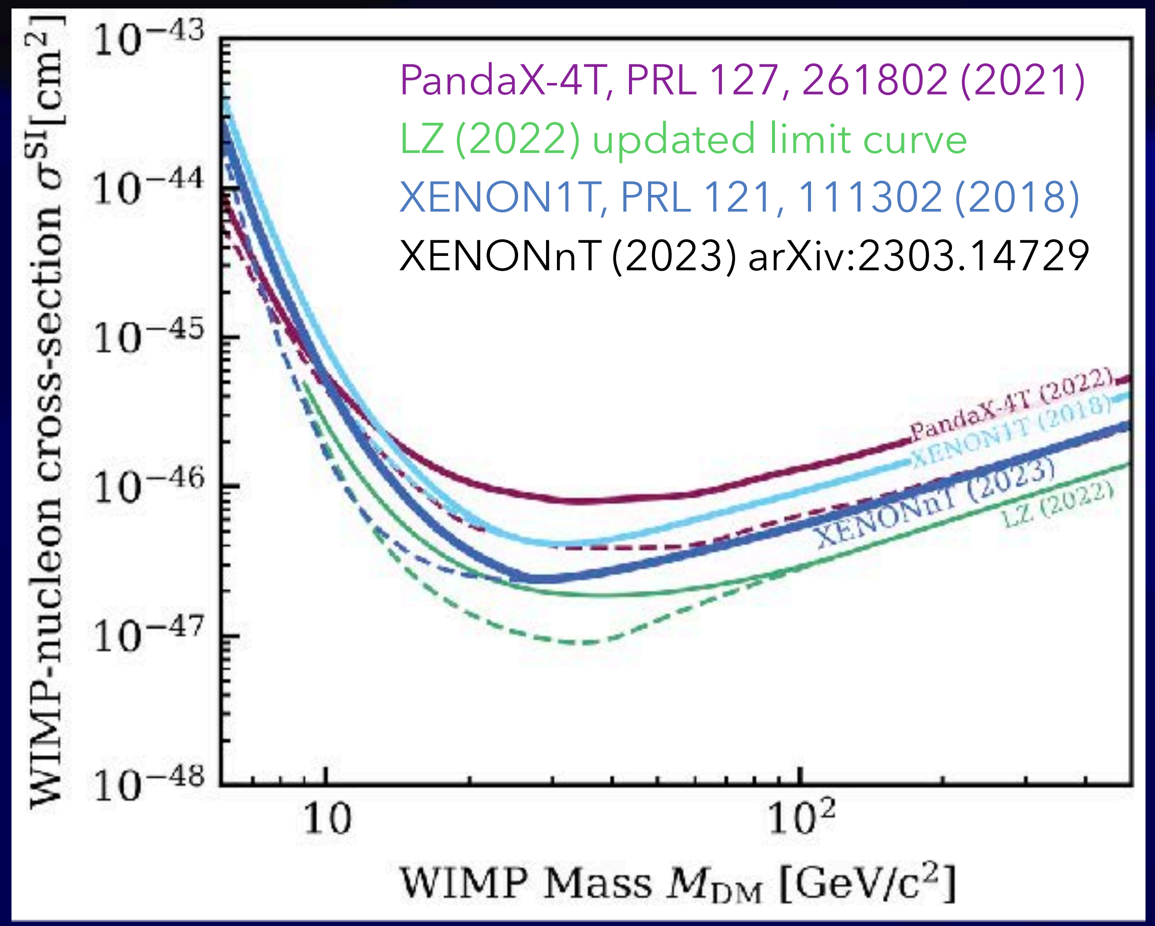
DARWIN, PandaX-xT: 50 t
arXiv:2203.02309v1

XENON:2303.14729

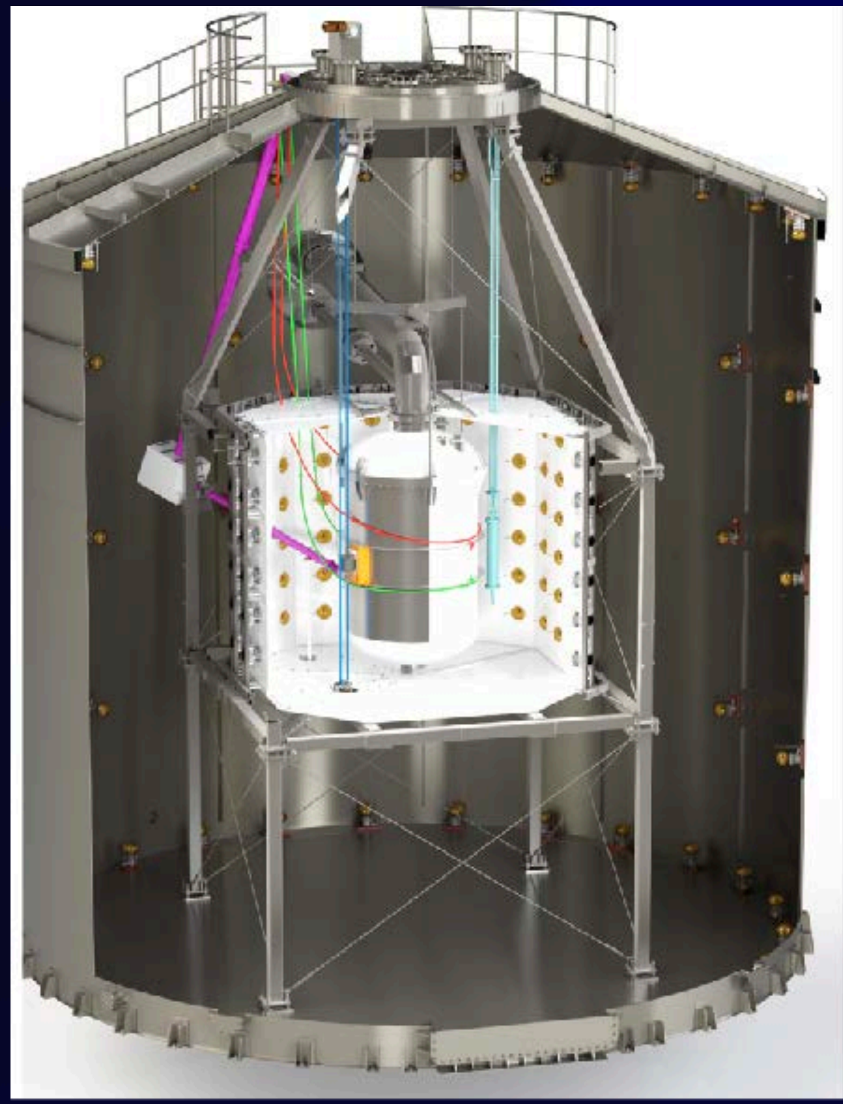




E. Aprile UCLA DM2023



XLZD Consortium formed



Credits: Jocelyn Monroe, ESPP, Granada 2019

KEY TECHNOLOGIES: XENON EXPERIMENTS

- Cryogenic distillation "online" to reduce Kr concentration in Xe and suppress radioactive ^{85}Kr
  - delivering gas with a ^{nat}Kr concentration of < 0.05 ppt
- Ultra-low (Rn) background gas pumps developed in context of XENON and nEXO
- Continuous Rn removal by cryogenic distillation (XENONnT and PandaX) or by gas chromatography (LZ)
  - Rn-222/Xe = 1.8 µBq/kg (GXe-only mode)
  - Rn-222/Xe = 0.8 µBq/kg (GXe+LXe mode)

ARGON DETECTORS

2010

10 kg

DarkSide-50
(50 kg, LNGS)

100 kg

ArDM
(1t, LSC)

1000 kg

2015

DEAP-3600
(3.6t, SNOLAB)

10000 kg

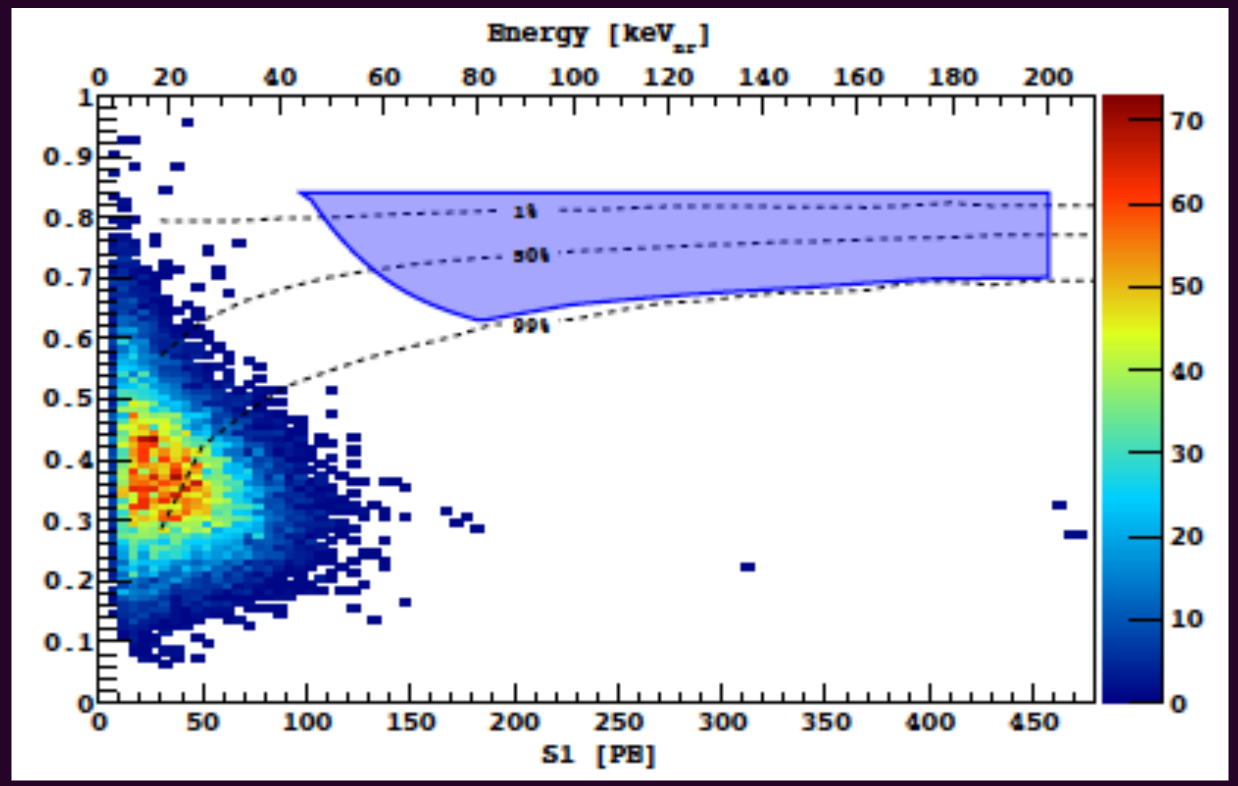
Global Argon Dark Matter Collaboration formed

2020

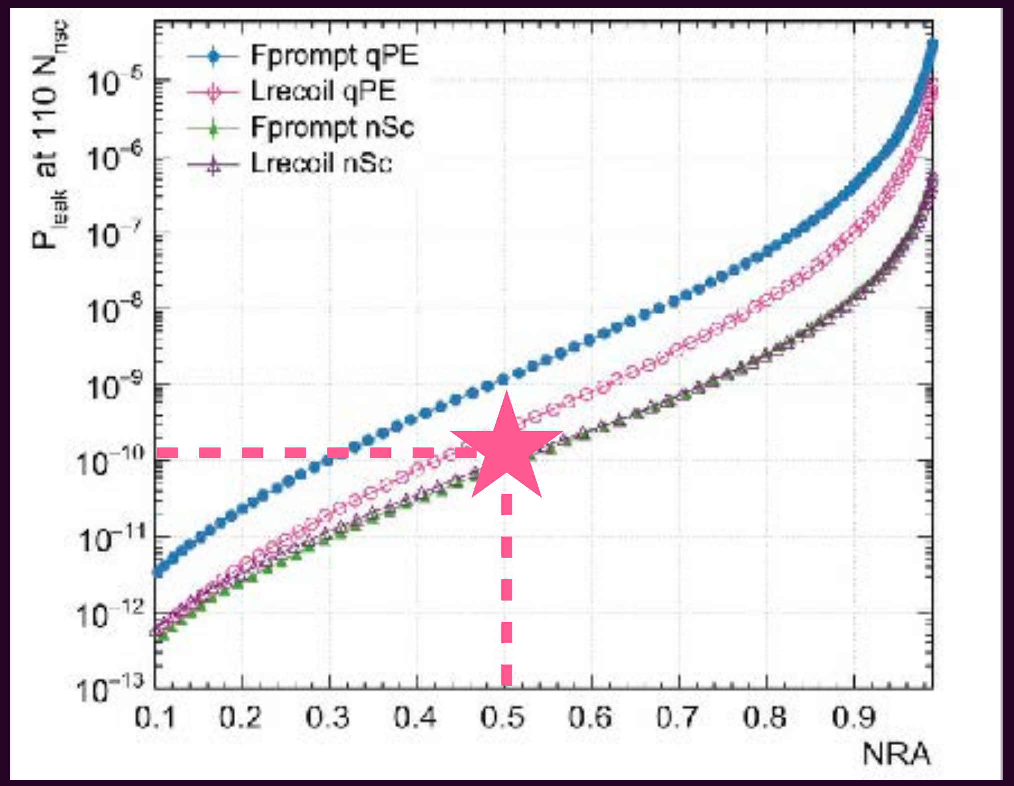
DarkSide-20k
(50t, LNGS)

100000 kg

ARGO: 400 t, SNOLAB

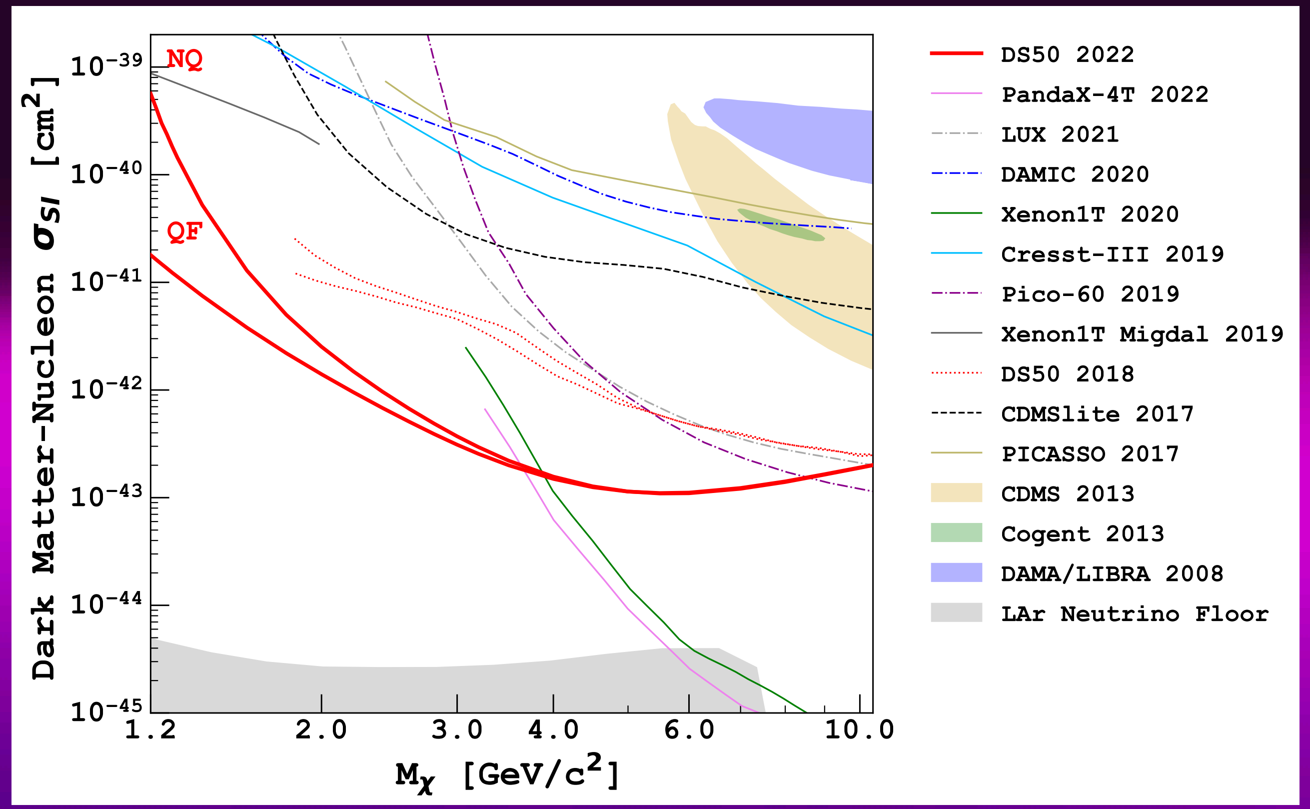


PRD 98, 102006 (2018)

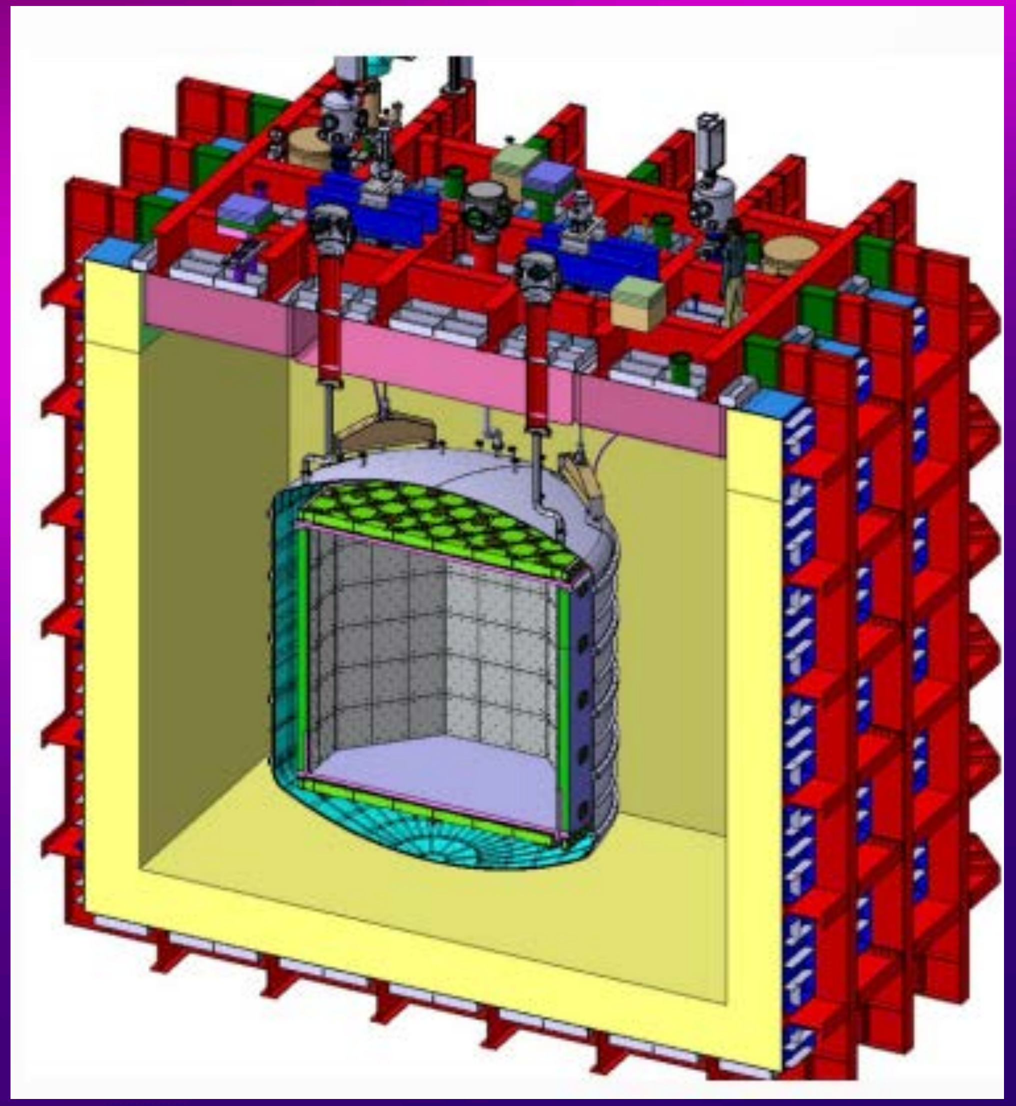


EPJ C 81, 823 (2021)

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



PRD 107, 063001 (2023)



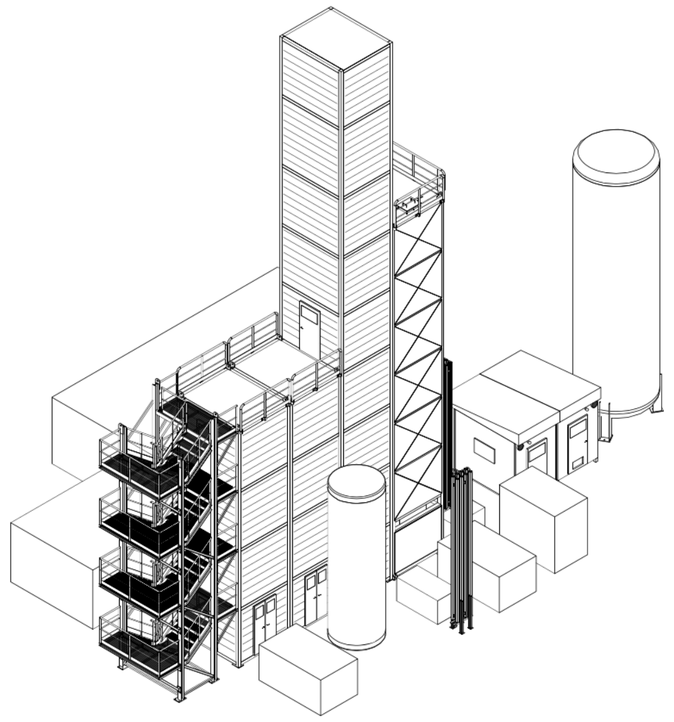
Credits: Jocelyn Monroe, ESPP, Granada 2019

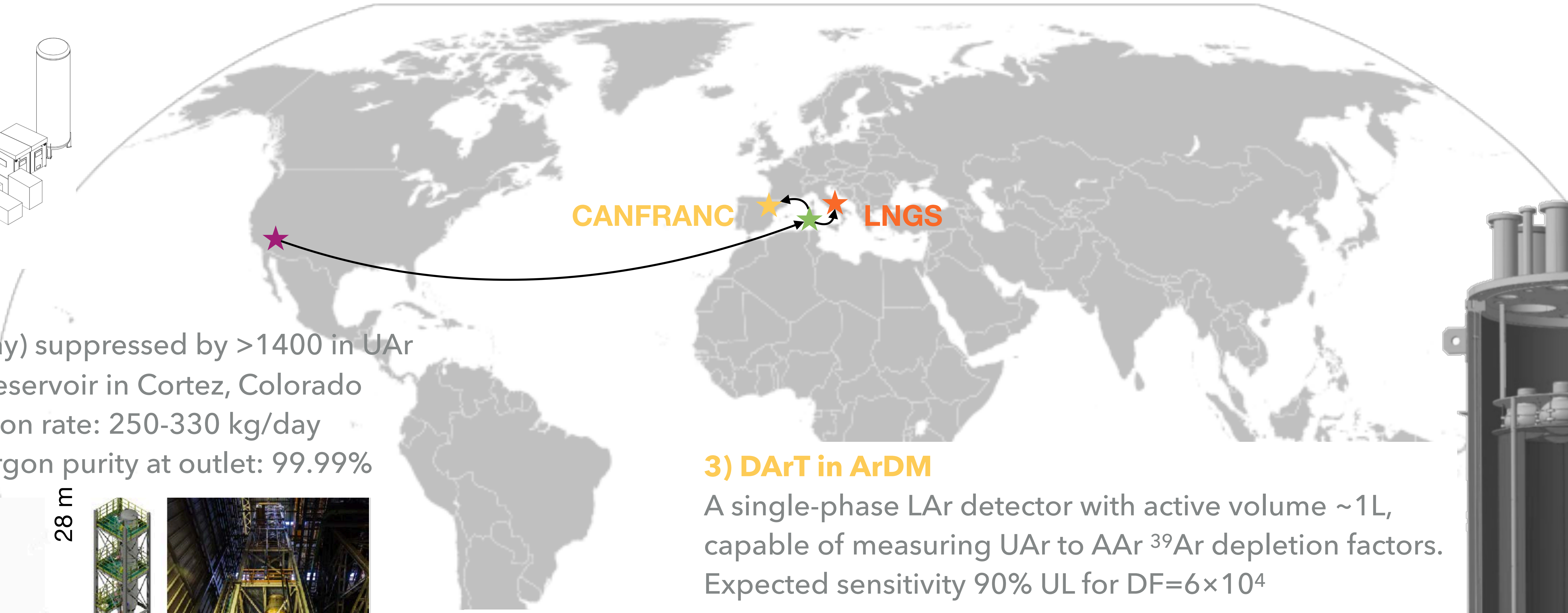
KEY TECHNOLOGIES: ARGON EXPERIMENTS

DarkSide-20k cornerstones:

1. Pulse shape discrimination for complete electron recoil rejection
2. Underground argon for pile-up avoidance *R.Santorelli in E4*
3. DUNE-like cryostat for shielding and cryogenic buffer protection of isotopic-enhanced target
4. Use of PMMA vessel for containment of active volume coupled - ultrapure PMMA for anode and cathode window and Gd-PMMA barrel for enhancement of neutron vetoing *Y.Wang in F3*
5. Custom SiPM-based photosensors for maximal photon collection *F.Di Capua in F3*

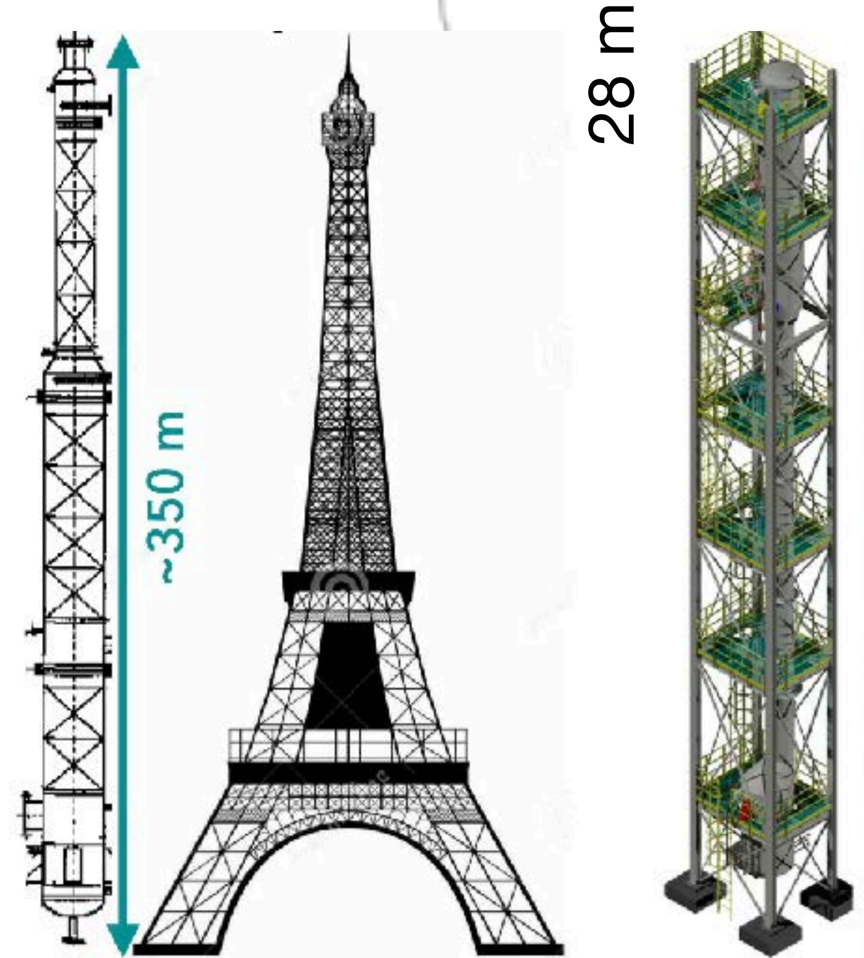
LOW RADIOACTIVITY ARGON: URANIA & ARIA PLANTS

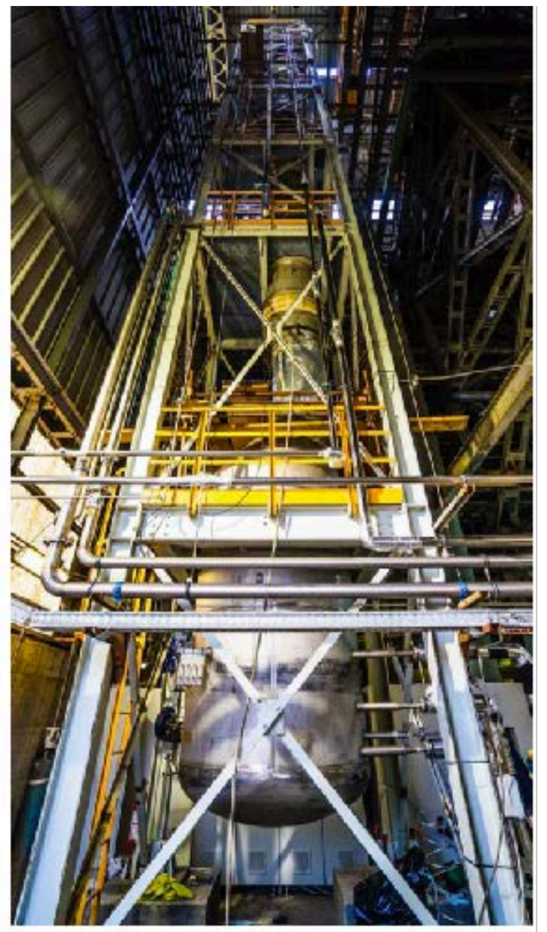




1) URANIA

^{39}Ar (β-decay) suppressed by >1400 in UAr
from CO2 reservoir in Cortez, Colorado
UAr extraction rate: 250-330 kg/day
Expected argon purity at outlet: 99.99%





Eur. Phys. J. C (2021) 81:359
Eur.Phys.J.C 83 (2023) 5, 453

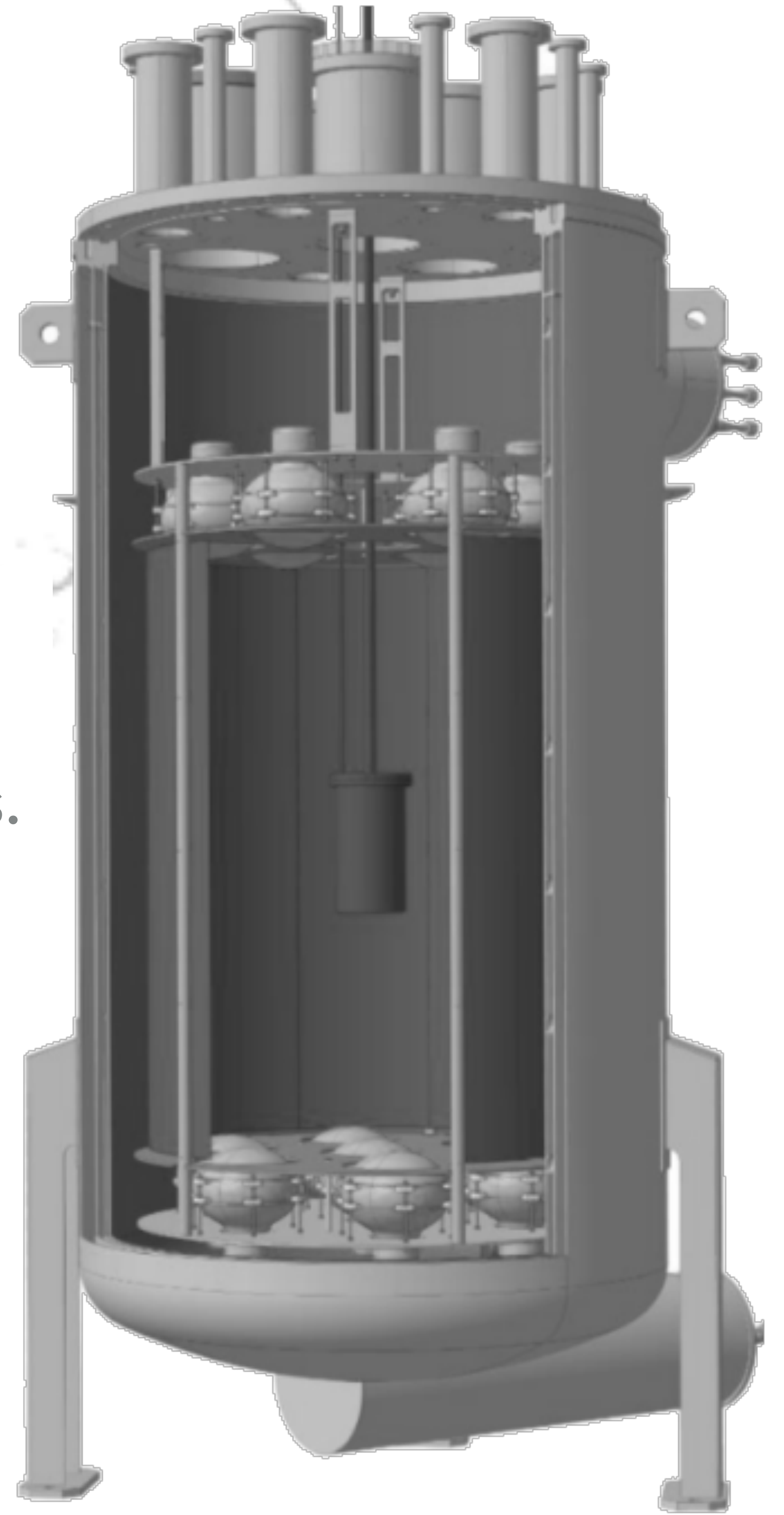
3) DArT in ArDM

A single-phase LAr detector with active volume ~1L,
capable of measuring UAr to AAr ^{39}Ar depletion factors.
Expected sensitivity 90% UL for DF=6×10^{4}

2) ARIA

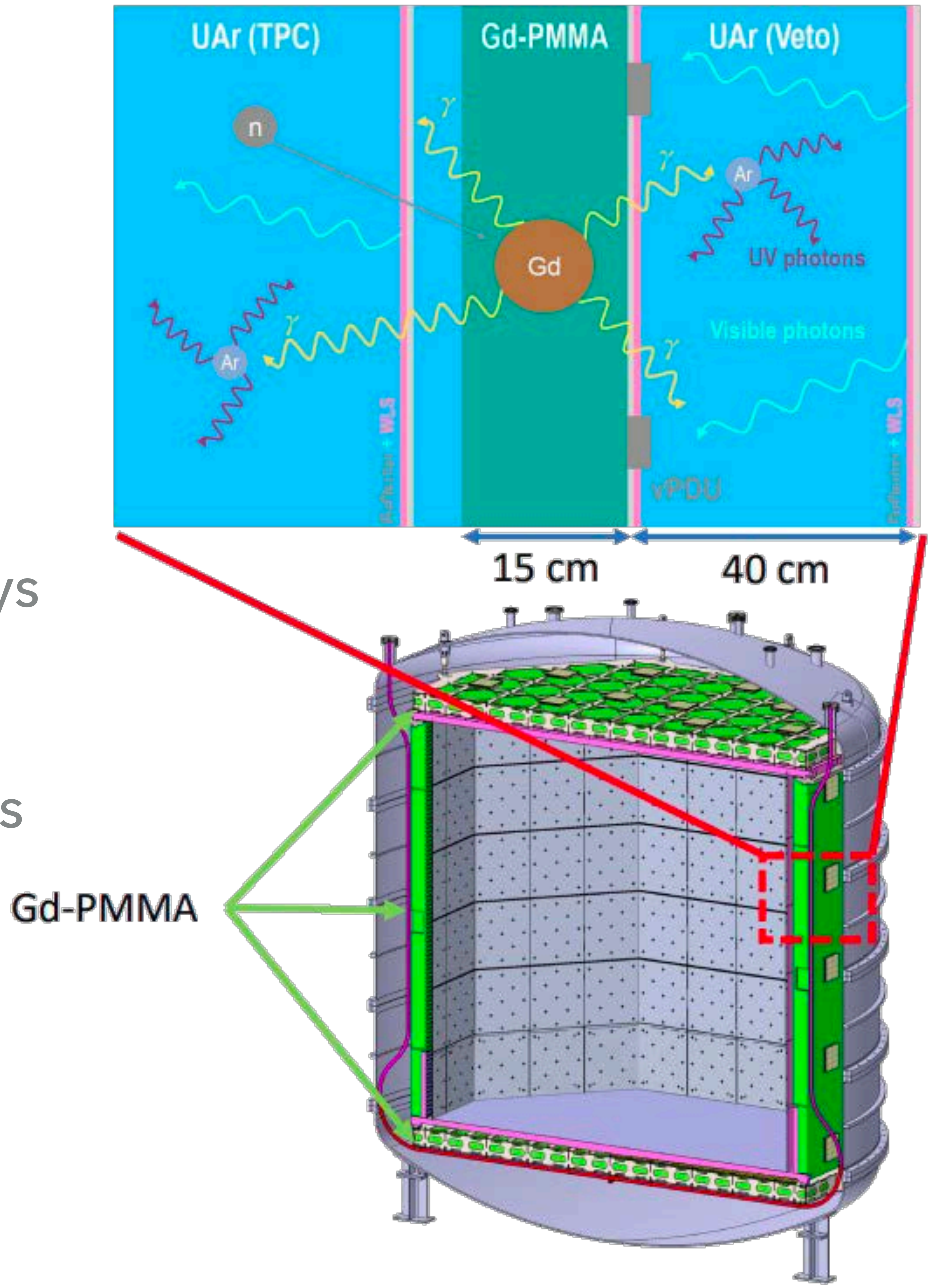
Installed in the shaft of a coal mine in Sardinia, Italy
Chemical purification rate: 1 t/day
Designed for the isotopic distillation of ^{39}Ar
First module operated according to specs with nitrogen
Run completed with Ar

JINST 15 (2020) P02024

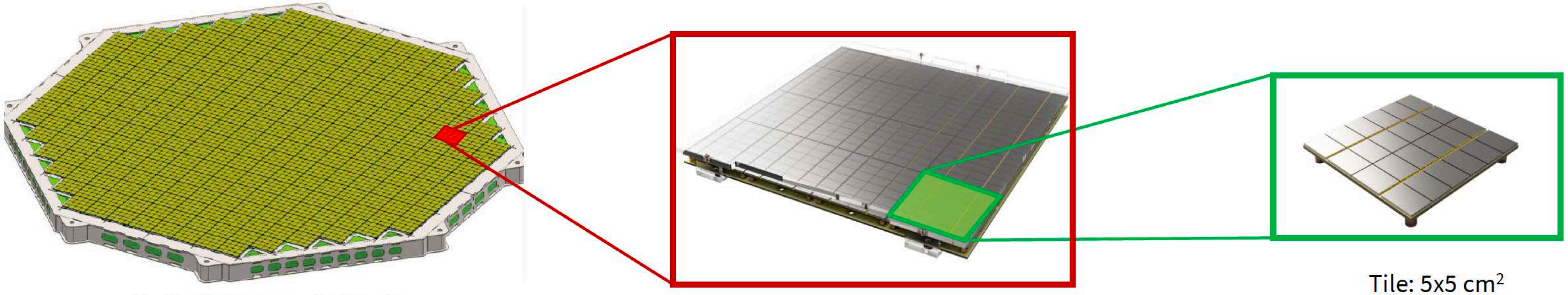


ULTRAPURE AND Gd-LOADED ACRYLIC

- Dual-phase LAr TPC
  - contained in pure & Gd-doped (1 wt%) acrylic;
  - field maintained by conductive Clevios coatings, ESR reflector + TPB wavelength shifter; viewed by SiPM arrays
- Inner Veto
  - contained in stainless steel vessel, viewed by SiPM arrays
  - neutron tagging via Gd-Loaded Acrylic
    - detection of γ-rays (<8 MeV) from n capture by Gd
    - n-tagging efficiency ~90%



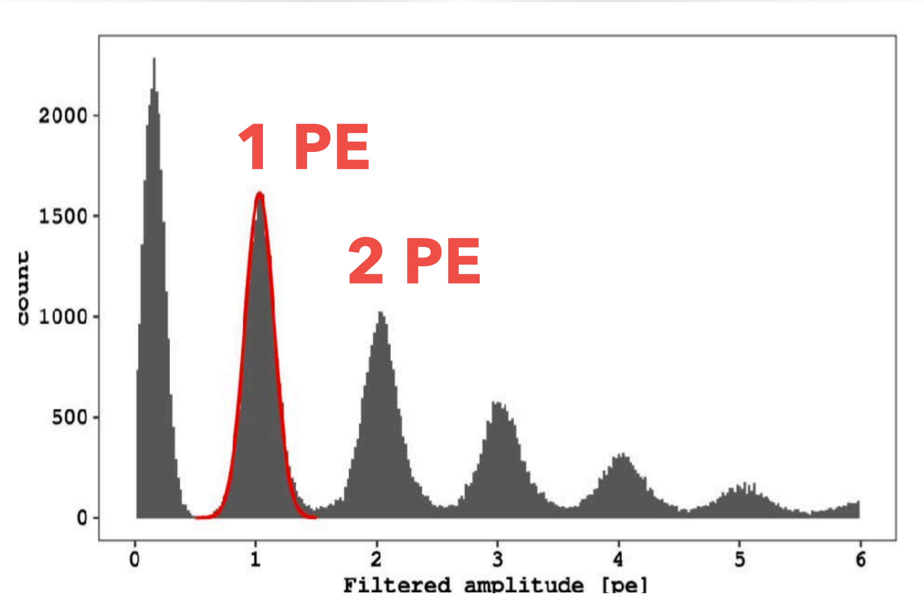
LOW RADIOACTIVITY, HIGH EFFICIENCY SiPM PHOTOSENSORS

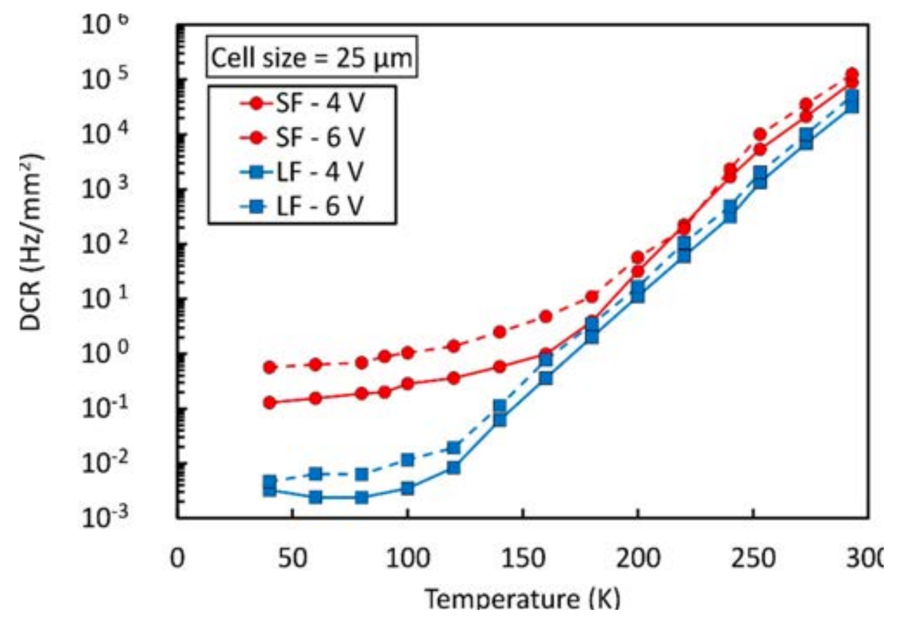


Optical planes: ~2x10 m²
Total PDUs used: 525
100% coverage

PDU: 20x20 cm²
16 Tiles assembled on a Motherboard
4 Readout Channel

Tile: 5x5 cm²
24 SiPMs directly mounted on a FEB
SiPM: NUV-HD-CRYO developed by FBK and produced by LFoundry





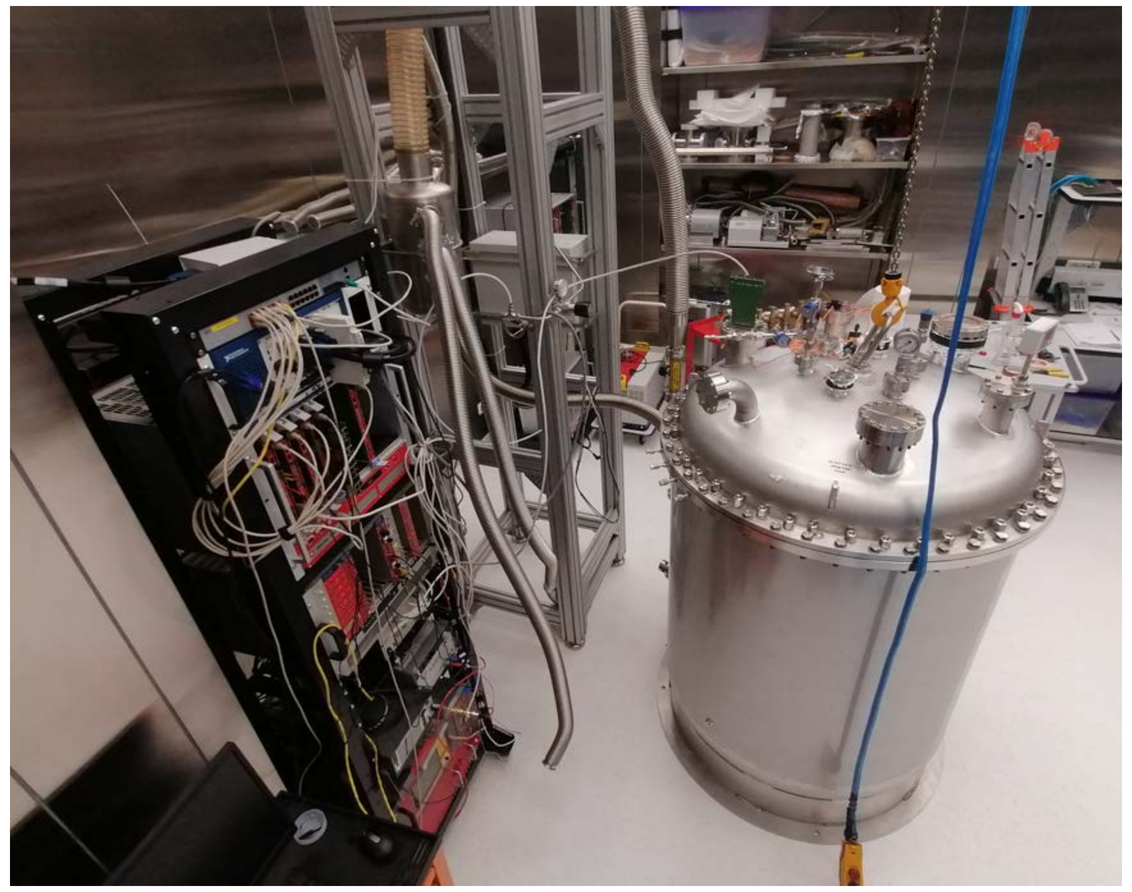
- Photon detection efficiency PDE > 40% at 77 K
- Dark count rate DCR < 0.01 Hz/mm² at 77 K

PDU: Photon Detection Unit

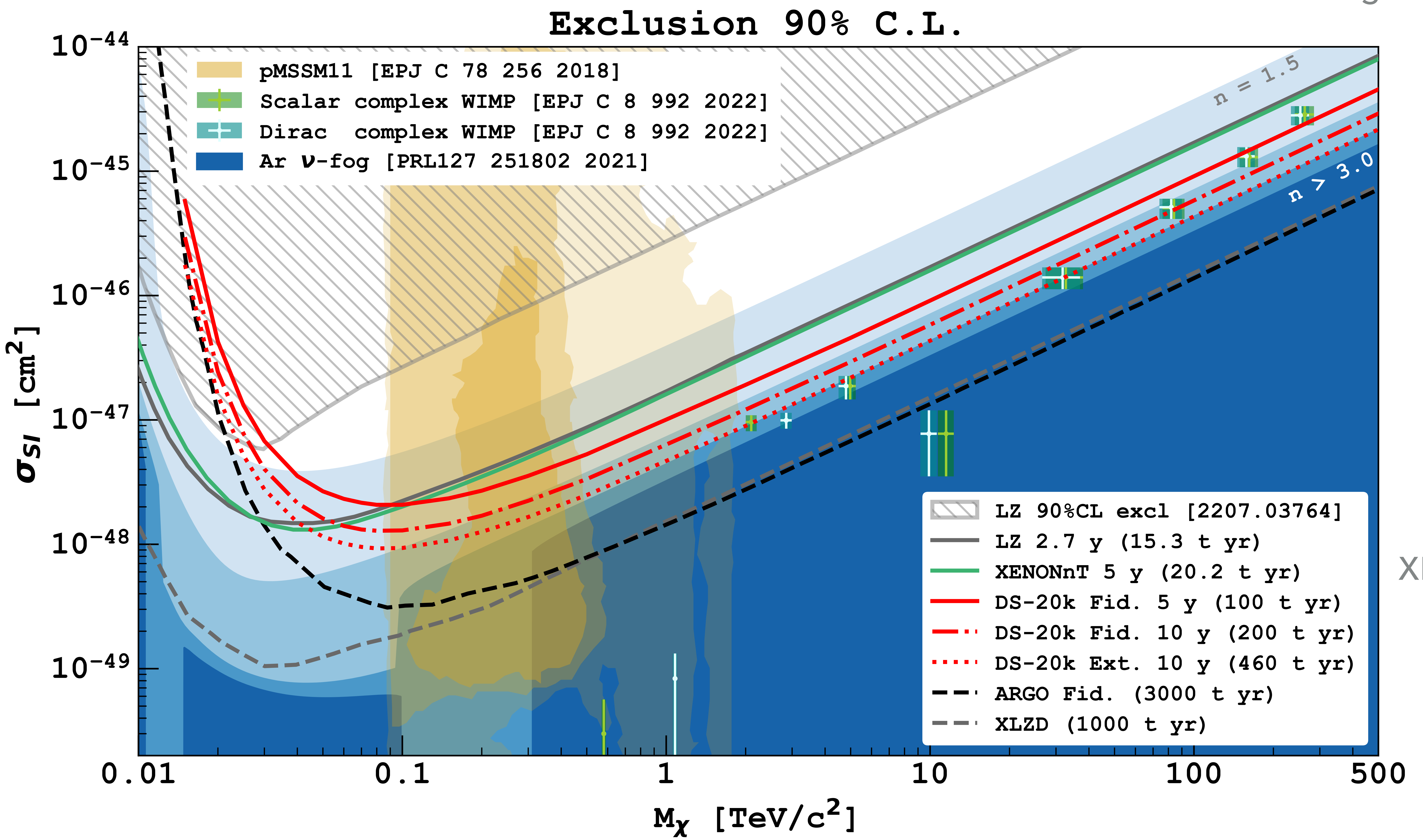
- TPC PDU: assembled in **Nuova Officina Assergi (NOA)**
  - NOA is a 420 m² ISO-6 Rn-free cleanroom at LNGS
  - 528 TPC PDUs to be tested at the **Naples Test Facility**
- VETO PDU: assembled in UK
  - 120 VETO PDUs to be tested in multiple facilities in UK and Poland

NOA cleanroom

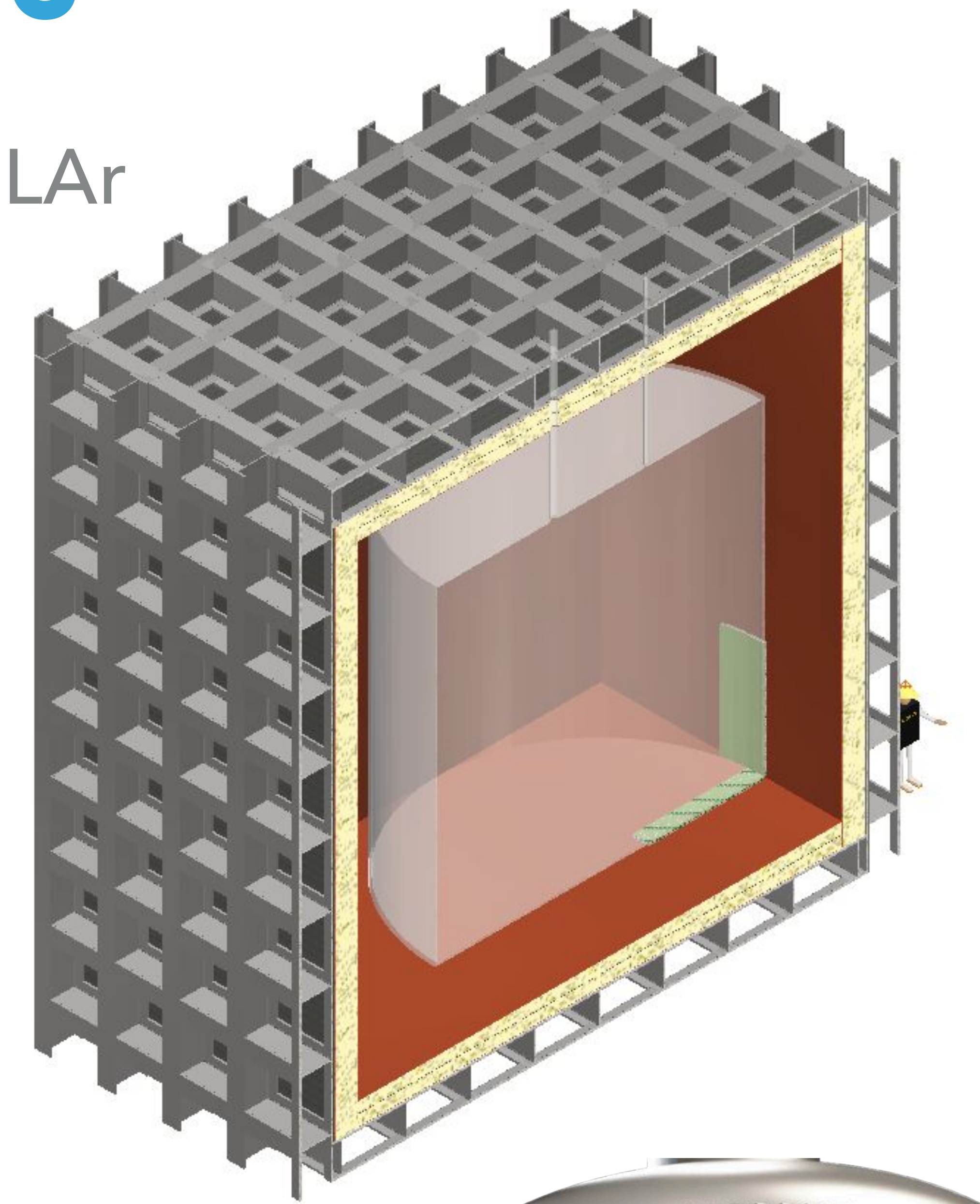
Napoli PDU Test Facility



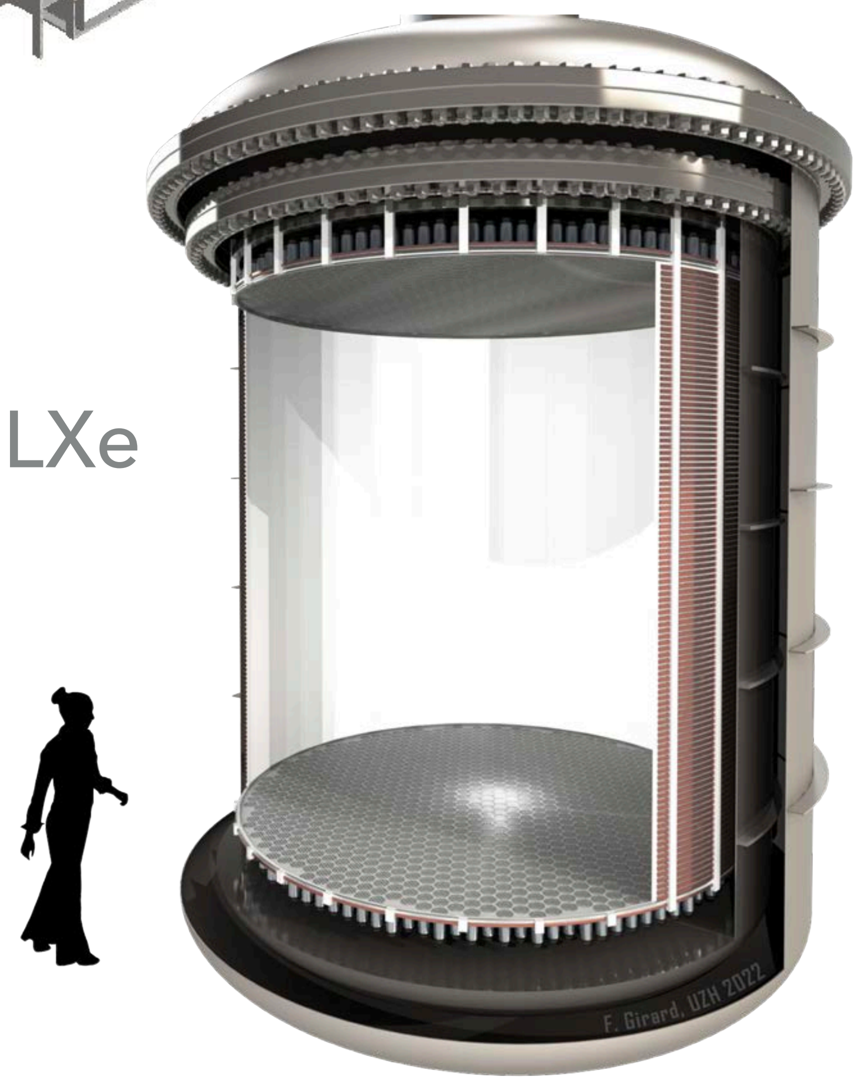
HIGH MASS WIMP SI INTERACTION EXCLUSION LIMITS PROSPECTS



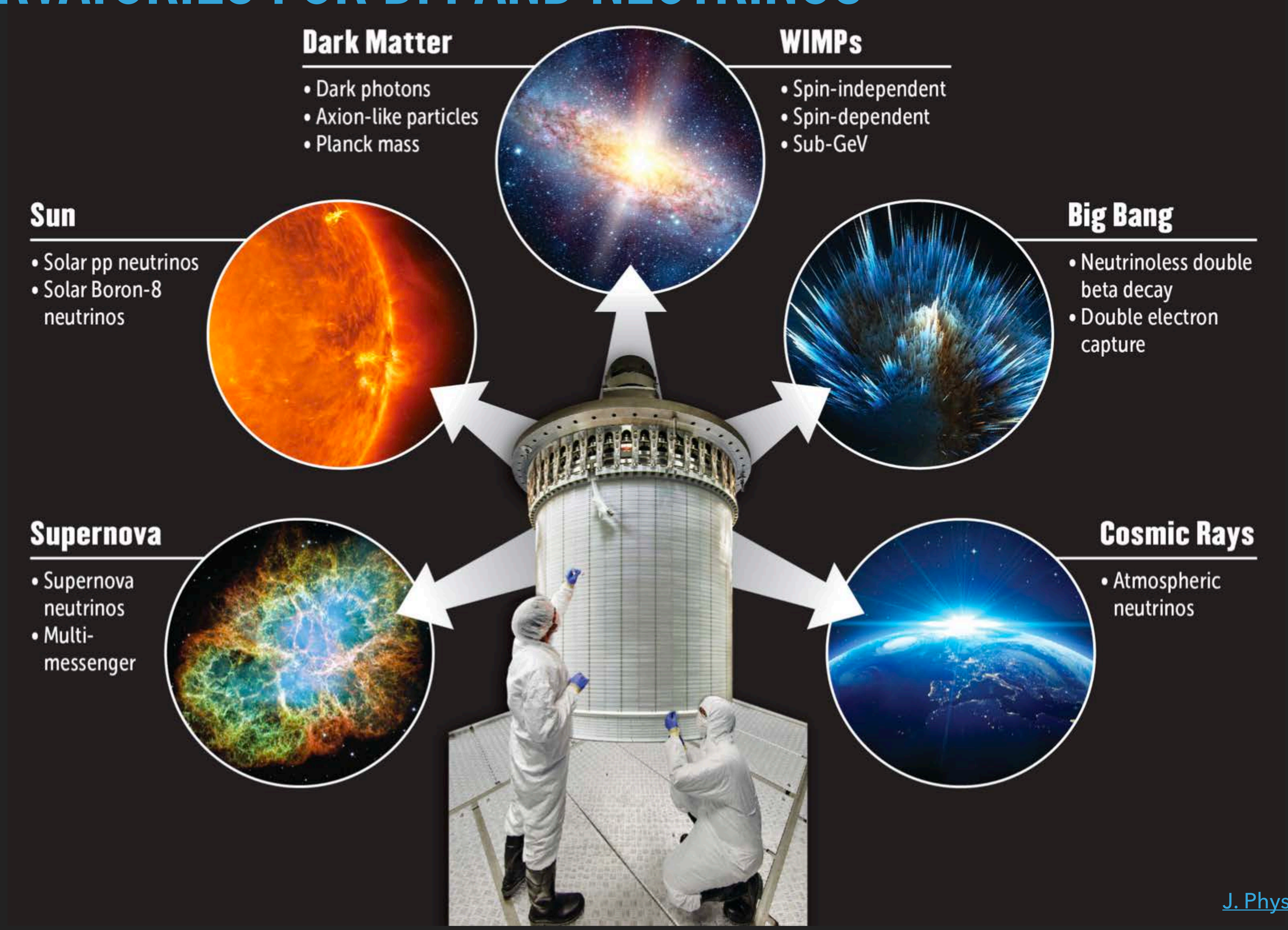
Argo: 400 ton LAr



XLZD: 40-60 ton LXe



FUTURE OBSERVATORIES FOR DM AND NEUTRINOS



J. Phys. G: Nucl. Part. Phys. 50 (2023) 013001

SUMMARY & OUTLOOK

- 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, …

➟ *several topics not covered here*