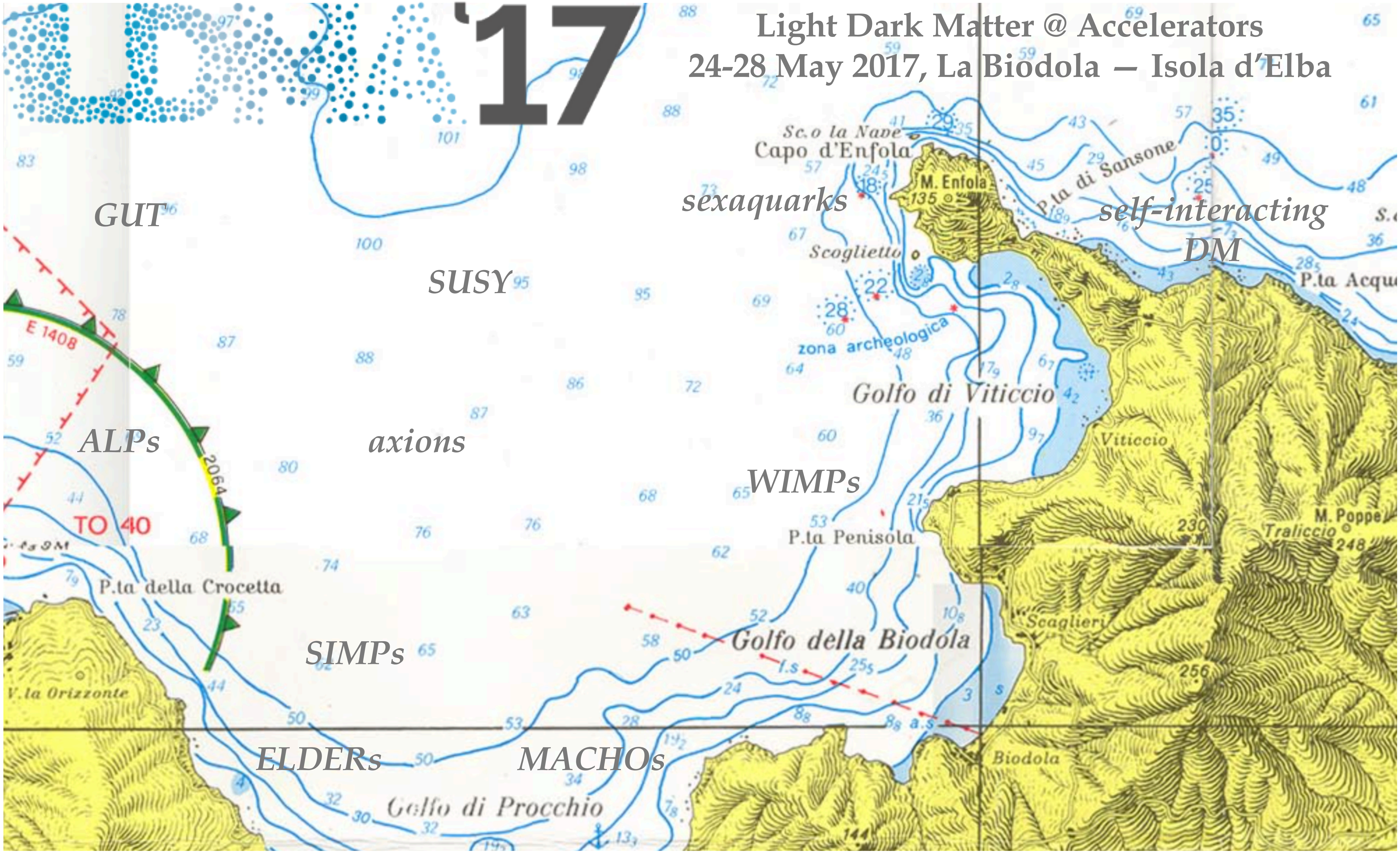
Light Dark Matter @ Accelerators

24-28 May 2017, La Biodola — Isola d'Elba



Andrea Pocar

University of Massachusetts, Amherst

Amherst Center for Fundamental Interactions

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

Liquid xenon (LXe) and liquid argon (LAr) for low-background physics

Noble liquid detectors have risen to be a leading technology in low-energy rare event searches over the past ~decade (WIMP dark matter, $0\nu\beta\beta$ decay)

Scintillating calorimeters

- XMASS (LXe)
- DEAP-3600 (LAr)
- miniCLEAN (LAr)

all growing larger

TPCs

dual phase:

- ZEPLIN
- XENON 10/100/1T/nT
- LUX / LZ
- PandaX I-II

(LXe)

- WaRP
- ArDM
- DarkSide-50 / DS-20k

(LAr)

single phase:

- EXO-200 nEXO (LXe)

General features, requirements

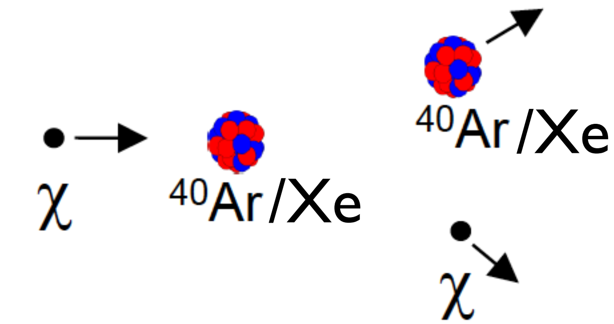
Strenghts:

- Powerful combination of low energy threshold, energy resolution, event ID
- LXe/LAr are excellent scintillators
- Background discrimination (technique-specific)
- Scalability
- Inline purification

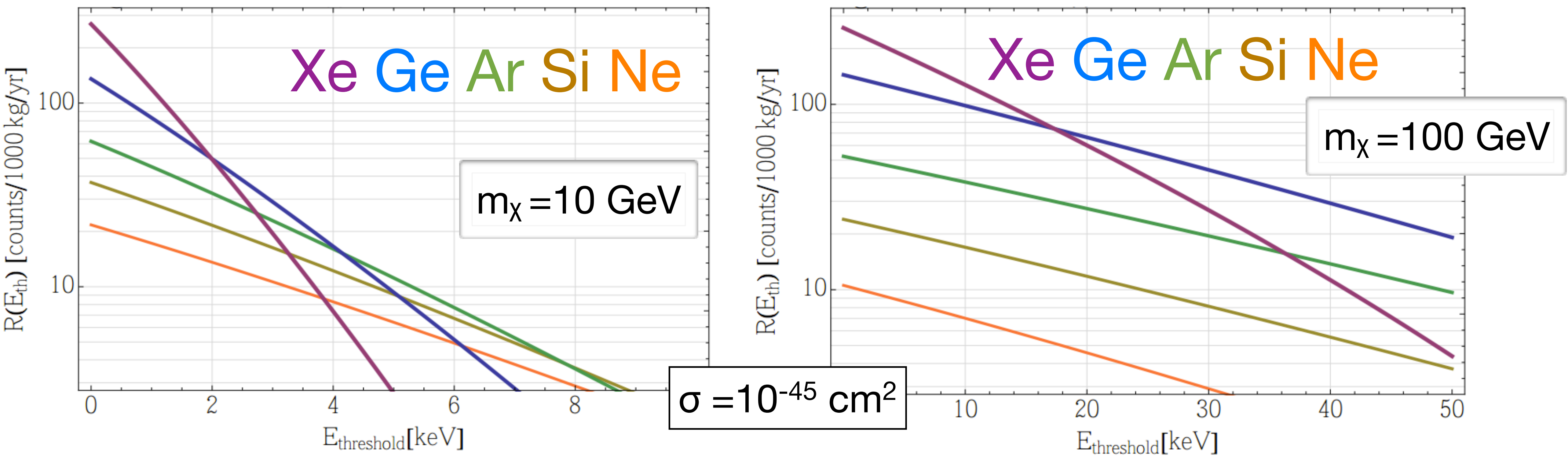
- Large ‘empty’ volume filled with clean, re-purifiable LXe/LAr
- ‘Dirty’ components pushed away from fiducial volume (self-shielding)
- Selected materials, reduce mass where possible
- Apply detector design concepts developed for low energy neutrinos to searches for WIMPs

Direct dark matter search: what we measure

➛ *look for excess of nuclear-like recoil events*

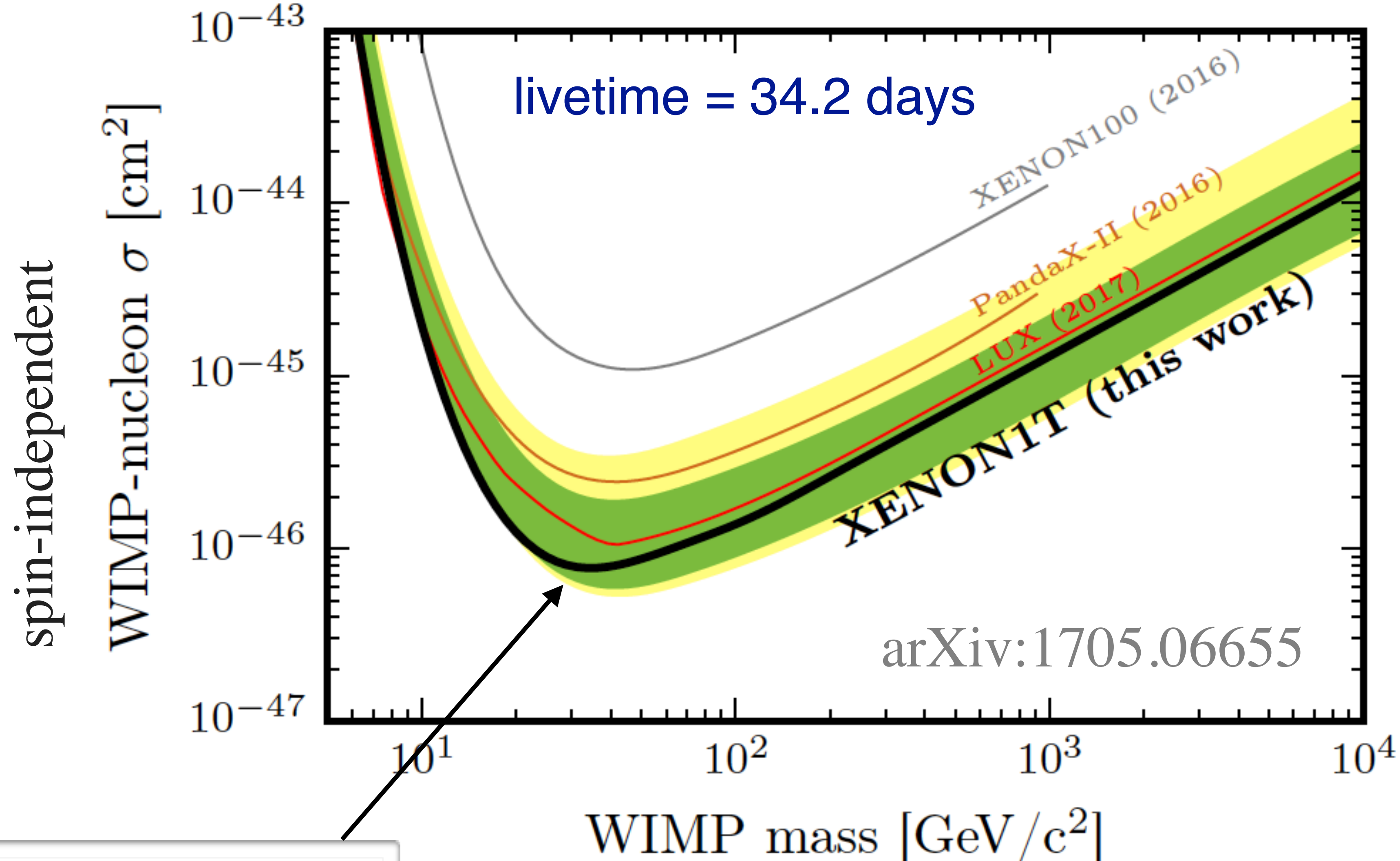


arXiv:1310.8327



Noble liquids are very powerful WIMP-searching machines with mass larger than a few GeV/c²

Fresh from the press: new results from XENON1T



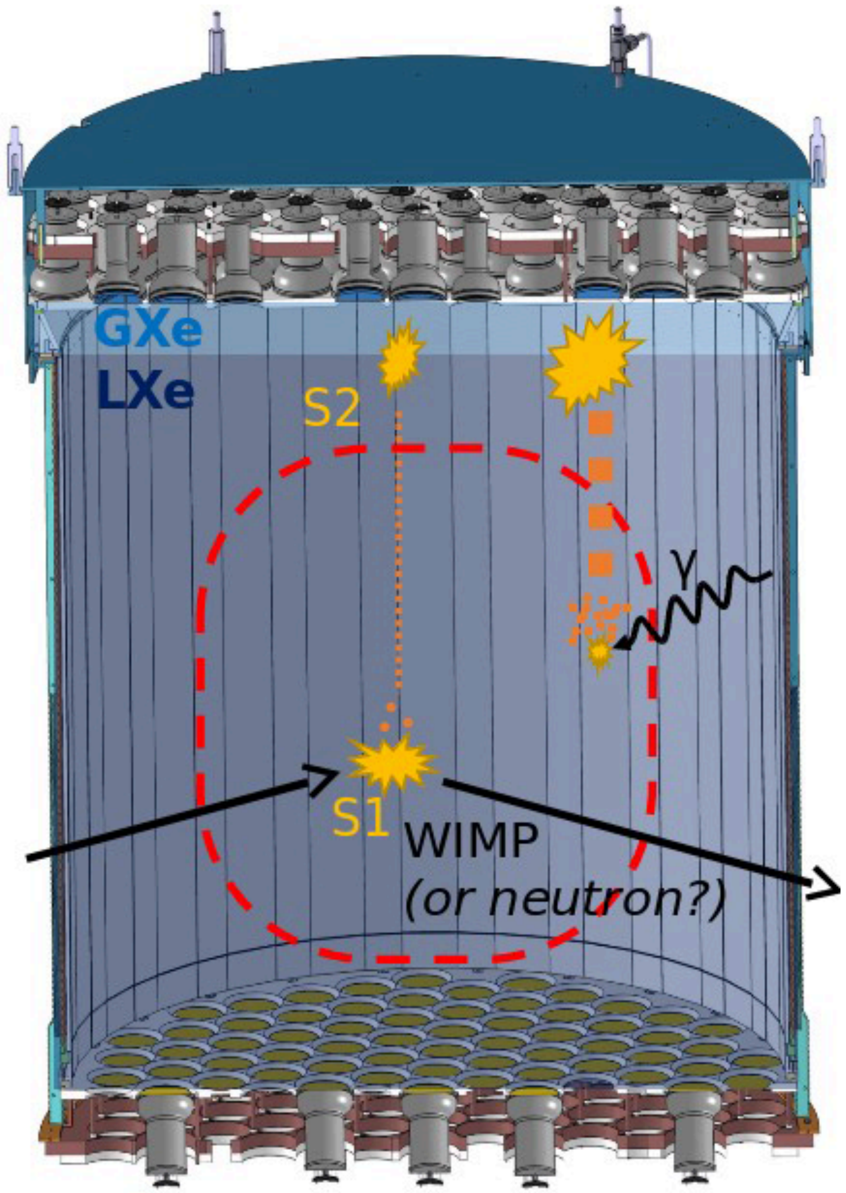
fiducial mass:
1042 ± 12 kg

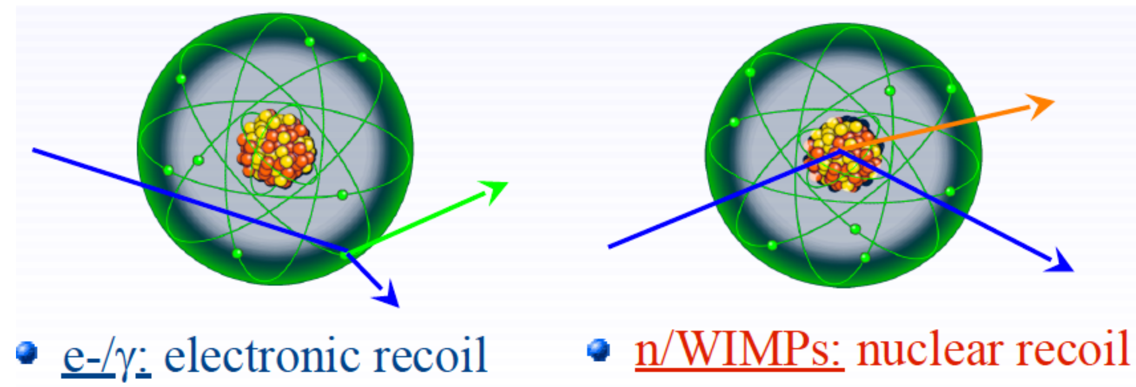
$7.7 \times 10^{-47}\ \mathrm{cm}^2$

dual phase LXe: current leaders for WIMP searches

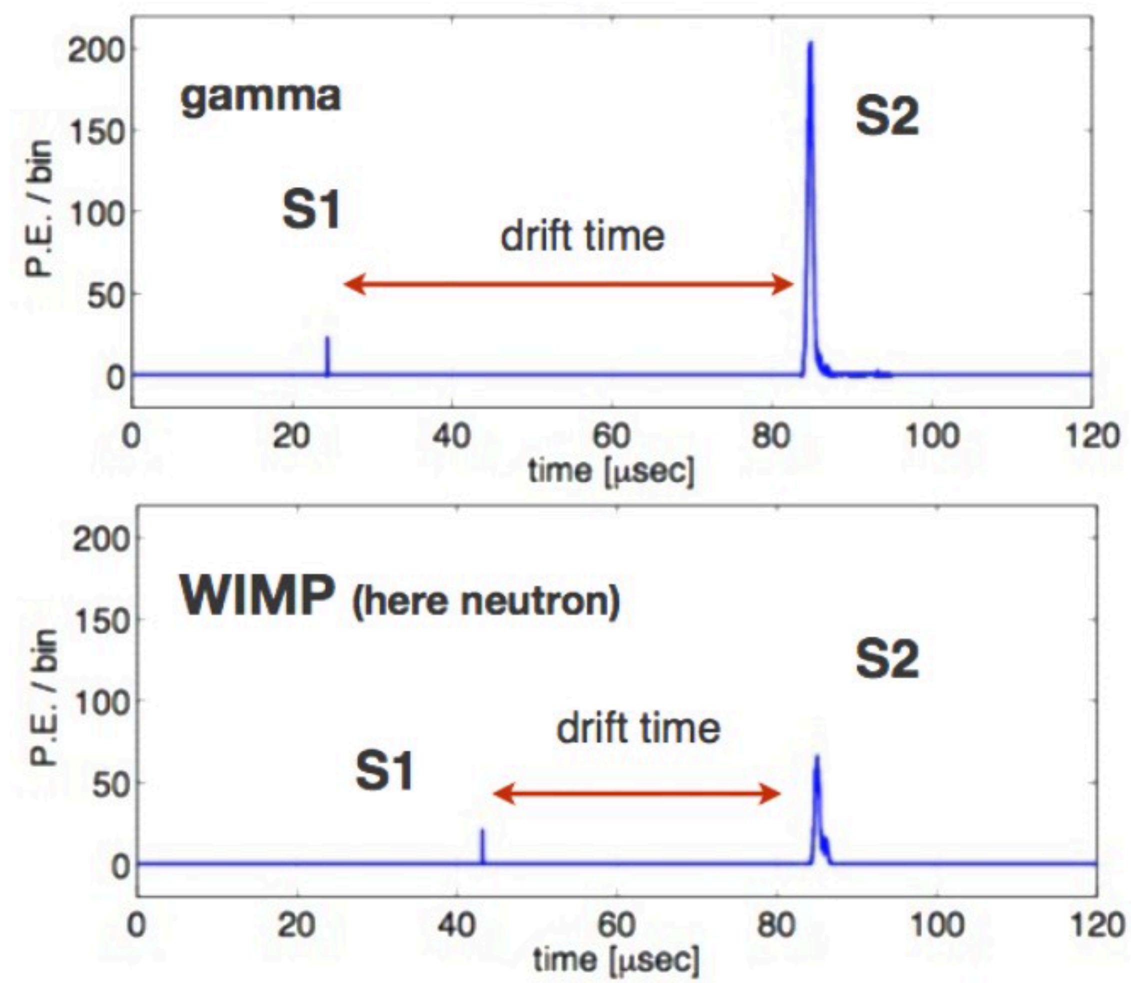
Dual-phase LXe TPC

adapted from
Gianmarco Bruno and Ethan Brown





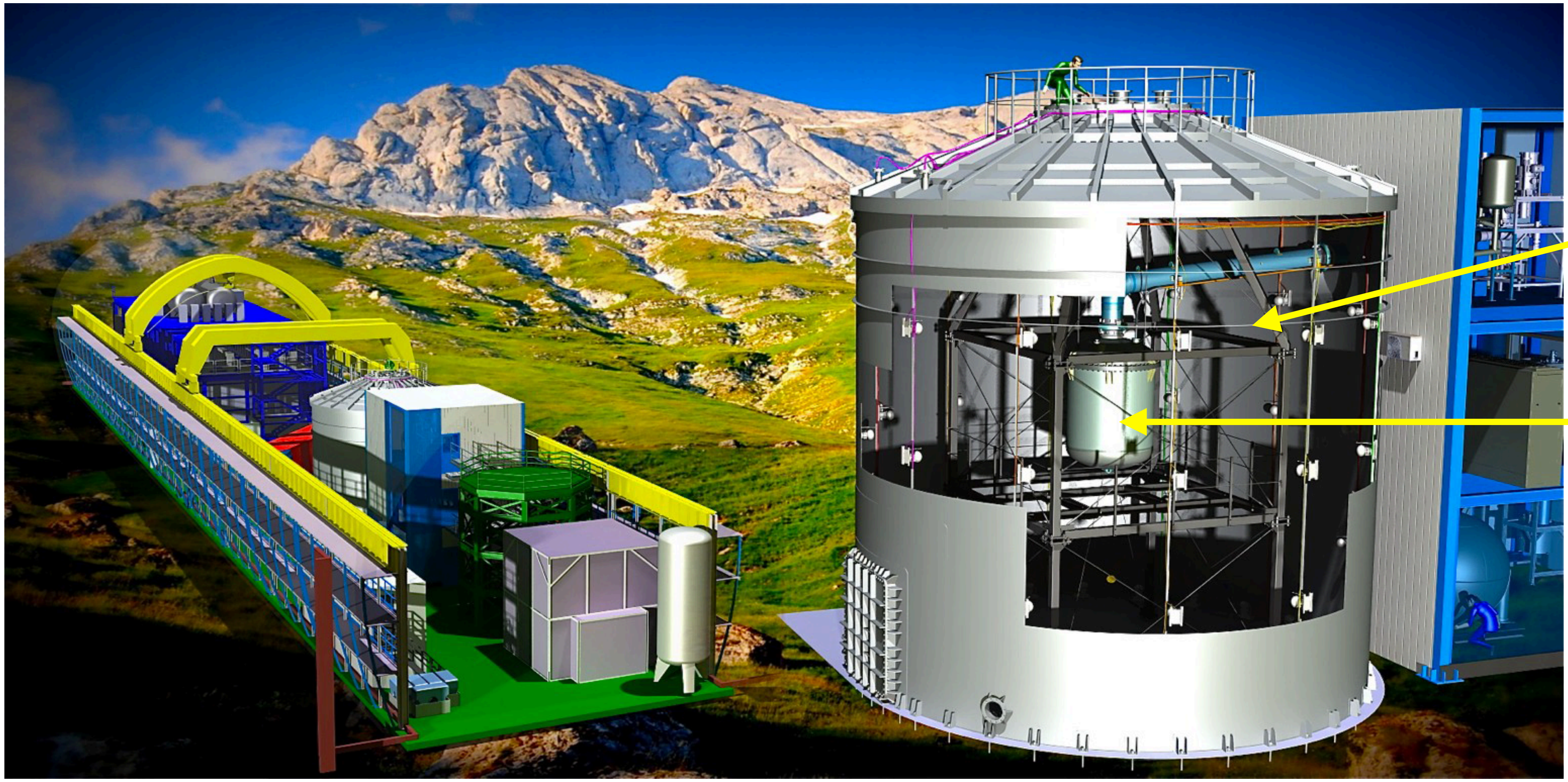
$(S2/S1)_{NR} < (S2/S1)_{ER}$



- S2/S1 ratio provides particle ID
- Top-array hit pattern provides the vertex position in the X-Y plane
- The time difference provides the depth

XENON1T at LNGS

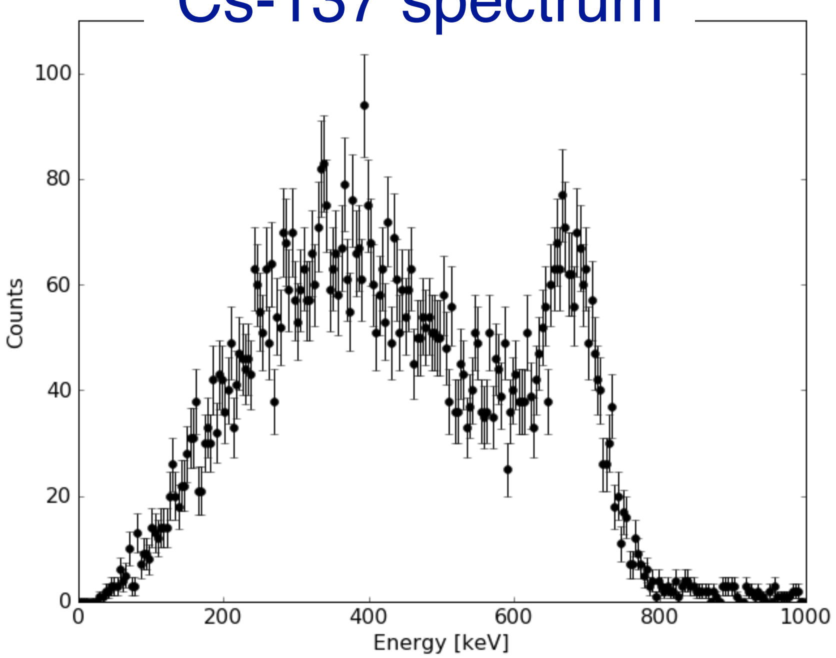
adapted from
Gianmarco Bruno

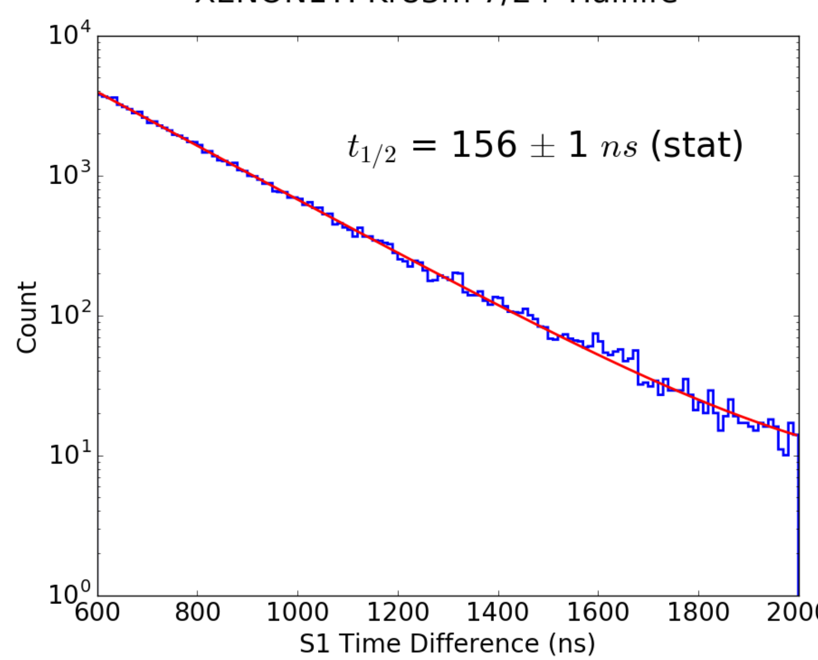


active water shield

TPC

Cs-137 spectrum





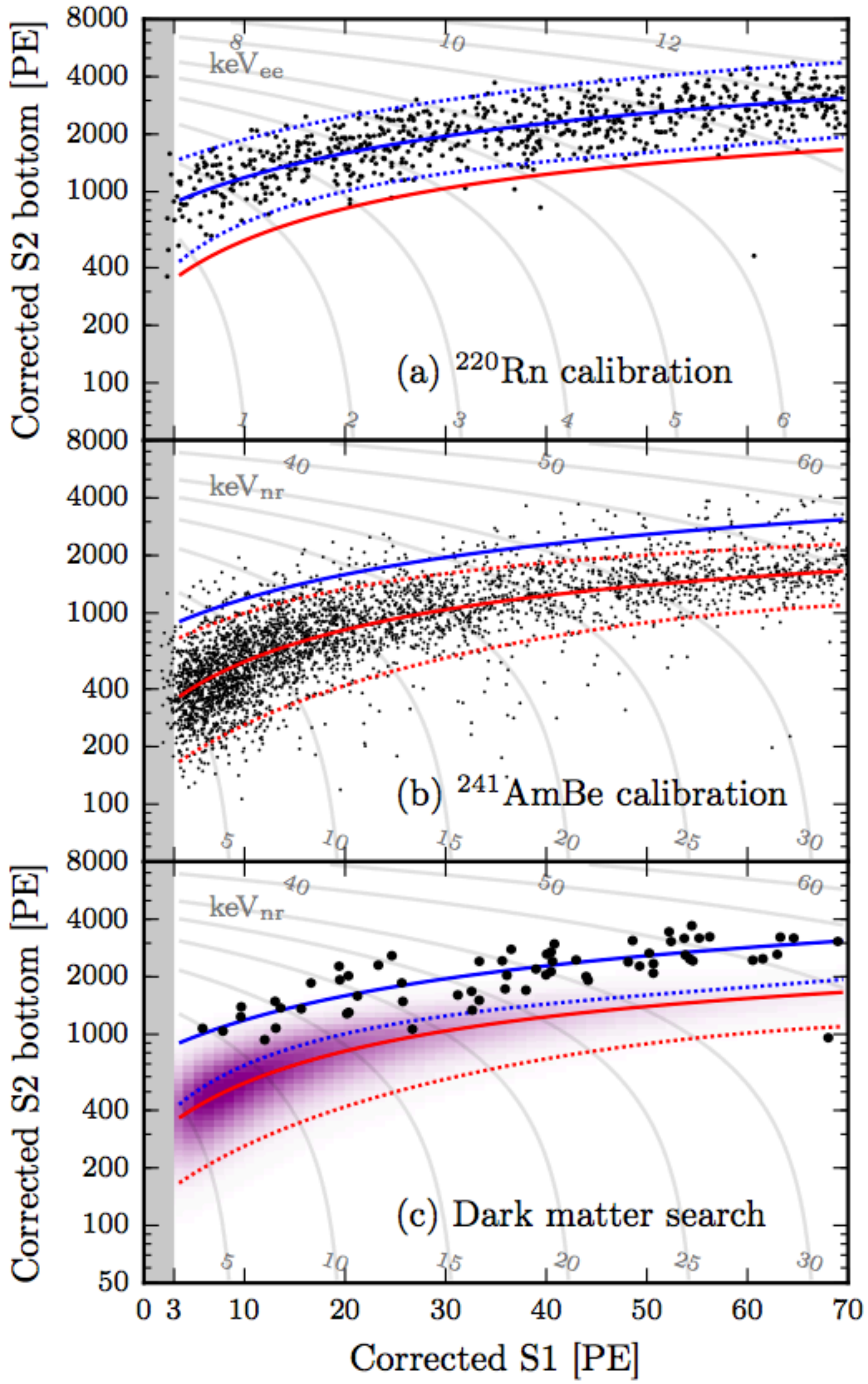
LY is x2 higher than XENON100

$$(1.93 \pm 0.25) \times 10^{-4}$$

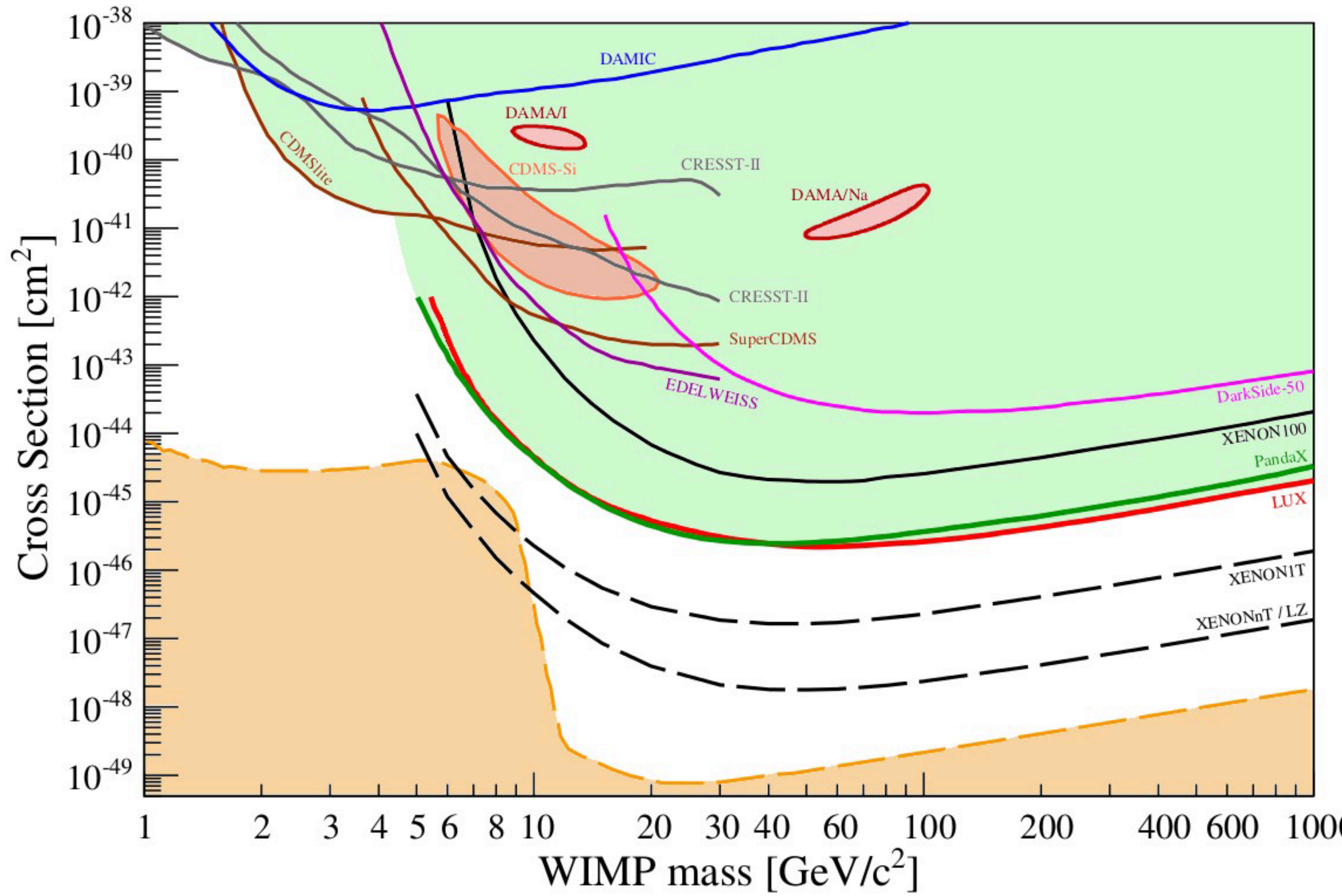
events/kg/d/keV$_{ee}$

XENON1T —> nT sensitivity projections

adapted from Gianmarco Bruno and Marc Schumann



Updated from: arXiv:1512.07501 JCAP04(2016)027

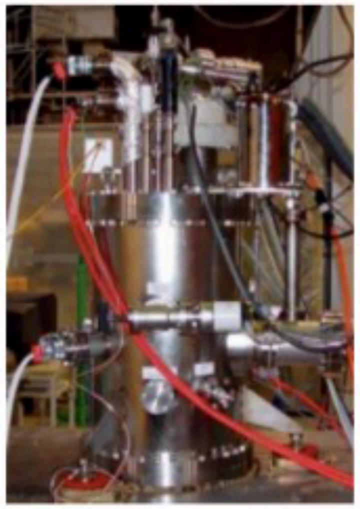


- 2 t·y exposure
- energy interval: 4-50 keV
- ER rejection: 99.5%
- NR acceptance: 50%
- 0.2 ppt ^{nat}Kr, 10 µBq/kg ^{222}Rn

The XENON detector genealogy

adapted from G. Bruno

(2007)



XENON10
Total Xe: 25 kg
Target: 14 kg
Fiducial: 5.4 kg
Limit: ~10^{-43}

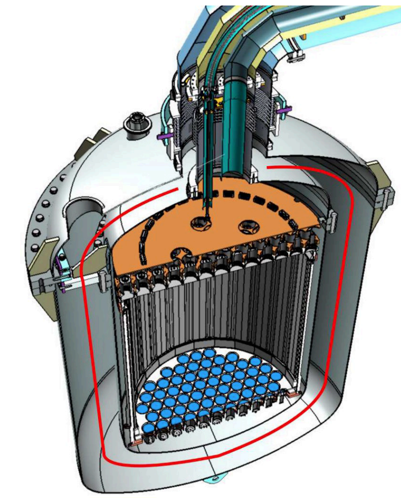
(2015)

XENON100
Total Xe: 162 kg
Target: 62 kg
Fiducial: 34/48 kg
Limit: ~10^{-45}

(2019)

XENON1T
Total Xe: 3.5 ton
Target: 2 ton
Fiducial: 1 ton
Limit: ~10^{-47}

(2022?)



XENONnT
Total Xe: 7.5 ton
Target: 6 ton
Fiducial: 4.5 ton
Limit: ~10^{-48}

(2028?)

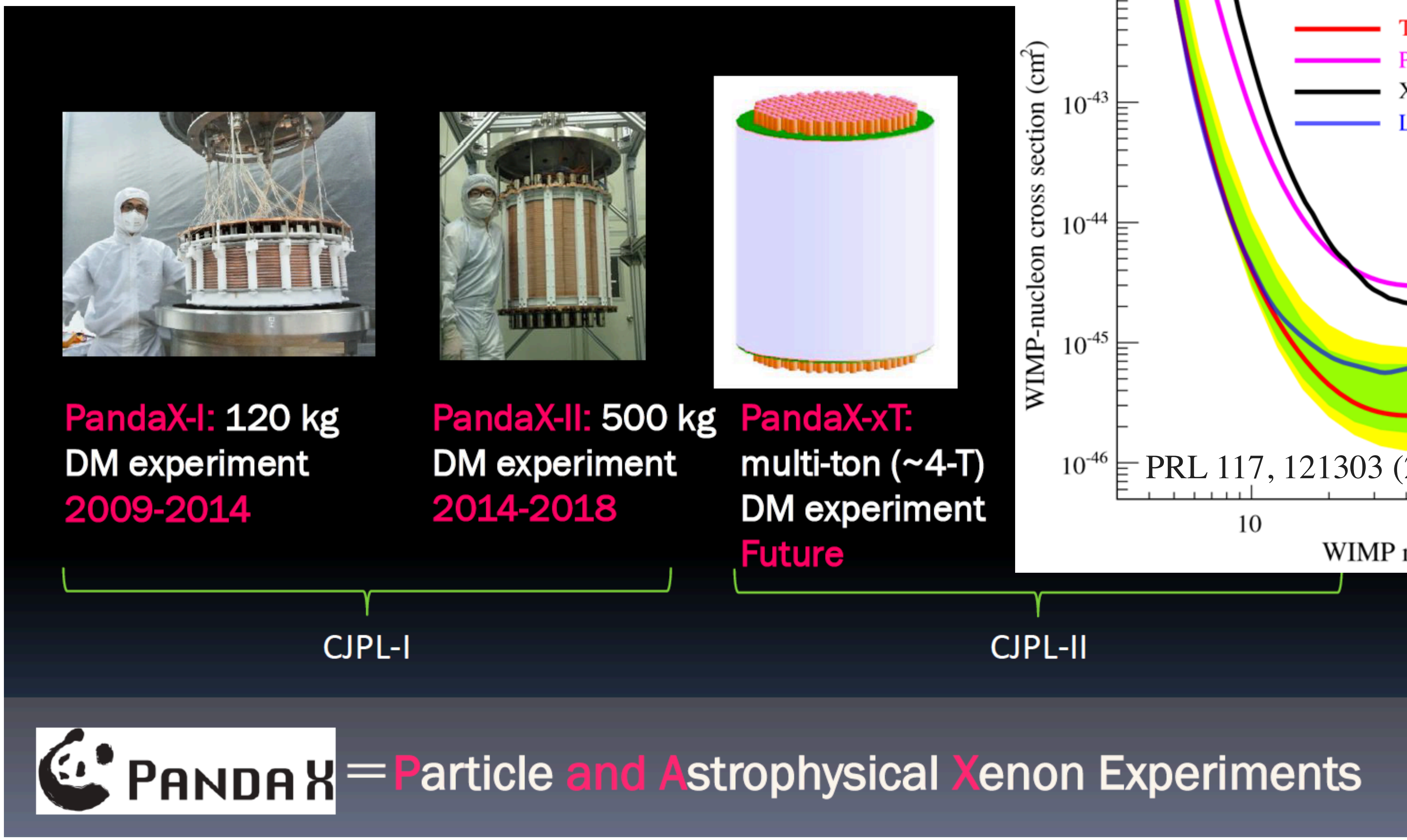
DARWIN
Total Xe: 50 ton
Target: 40 ton
Fiducial: 30 ton
Limit: ~10^{-49}

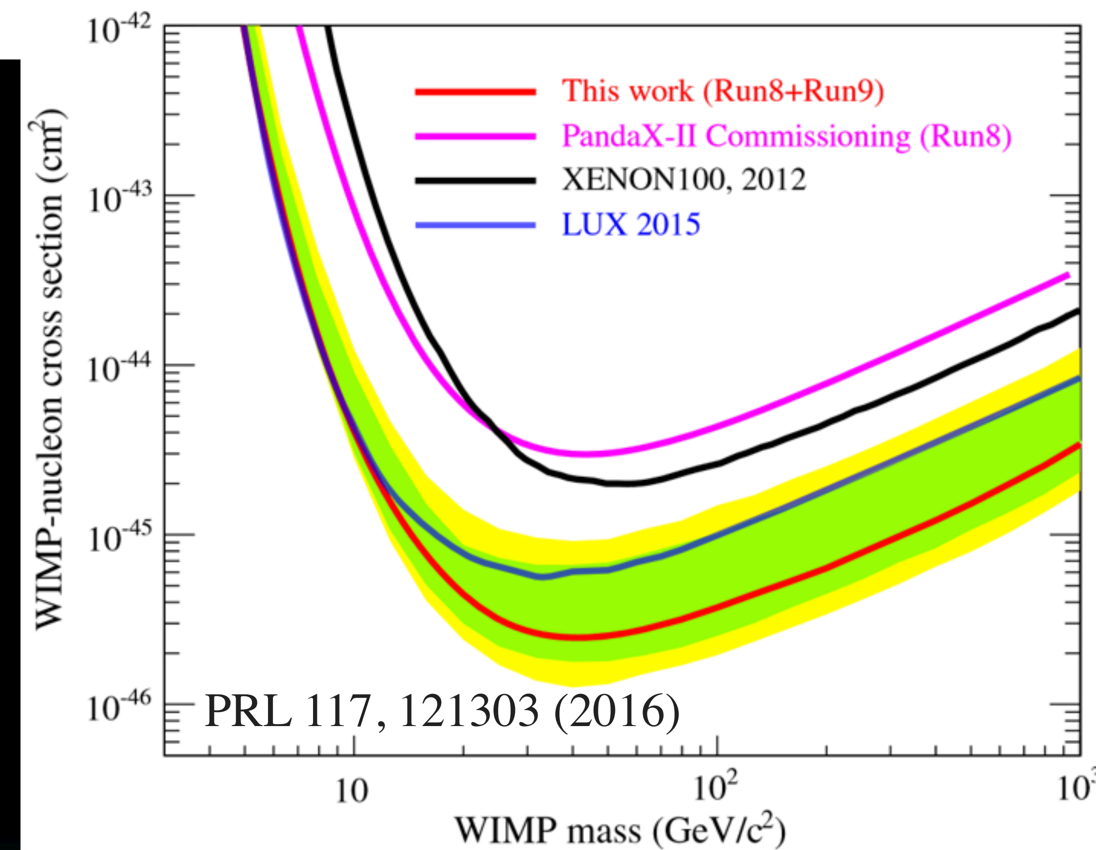
- Outer vessel sized for upgraded detector
- 200 more PMTs are needed
- Total Xe mass: 7.5 t
- Rn removal system
- Projected to start science in 2019

neutrino "floor"

PandaX program

adapted from Jianglai Liu, Pheno 2017



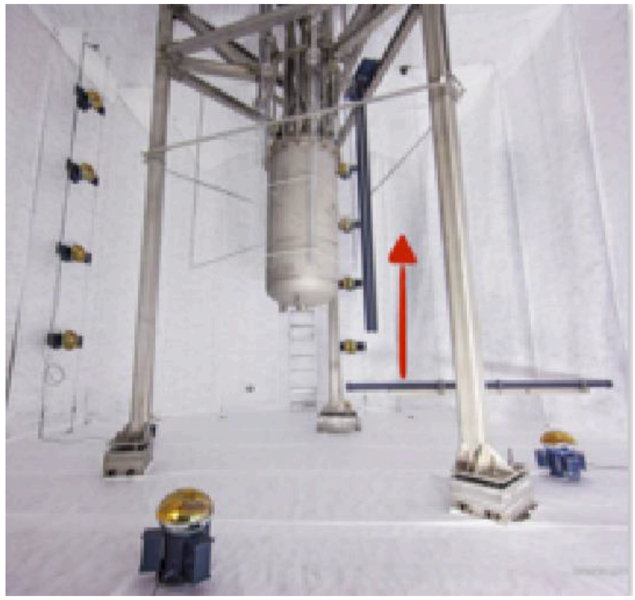


33 tonne-day exposure

- PandaX-II running after extended downtime
- Preparing hall at CJPL-2 for PandaX-4T with water tank ($\sim 10^{-47}$ cm^2, commissioning ca. 2020)
- Goal: 30T experiment —> neutrino floor

LUX —> LZ (LUX + Zeplin) program at Sanford Lab

adapted from Attila Dobi



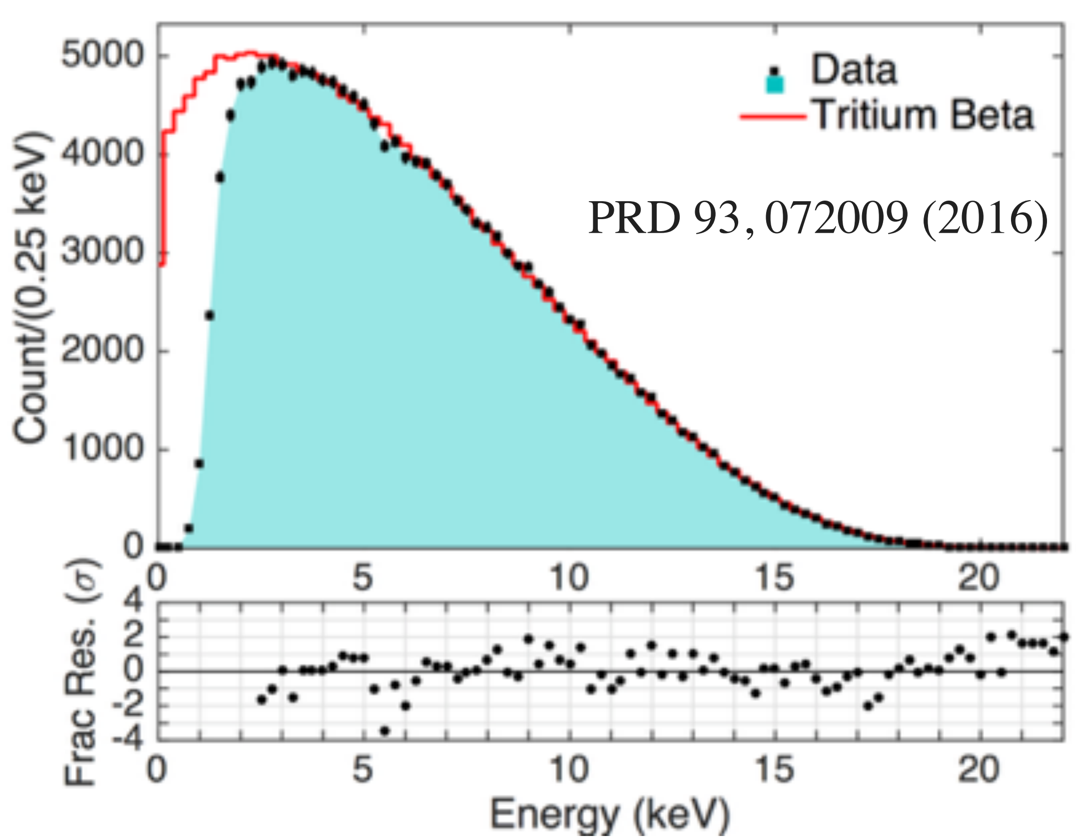
- LUX decommissioned in 2016 (~400 live days, 3.4×10^4 kg d exposure)
- 2nd best SI limits

PRL 118, 021303 (2016)

- innovative calibrations and Kr-85 bg reduction and control

- LUX —> LZ

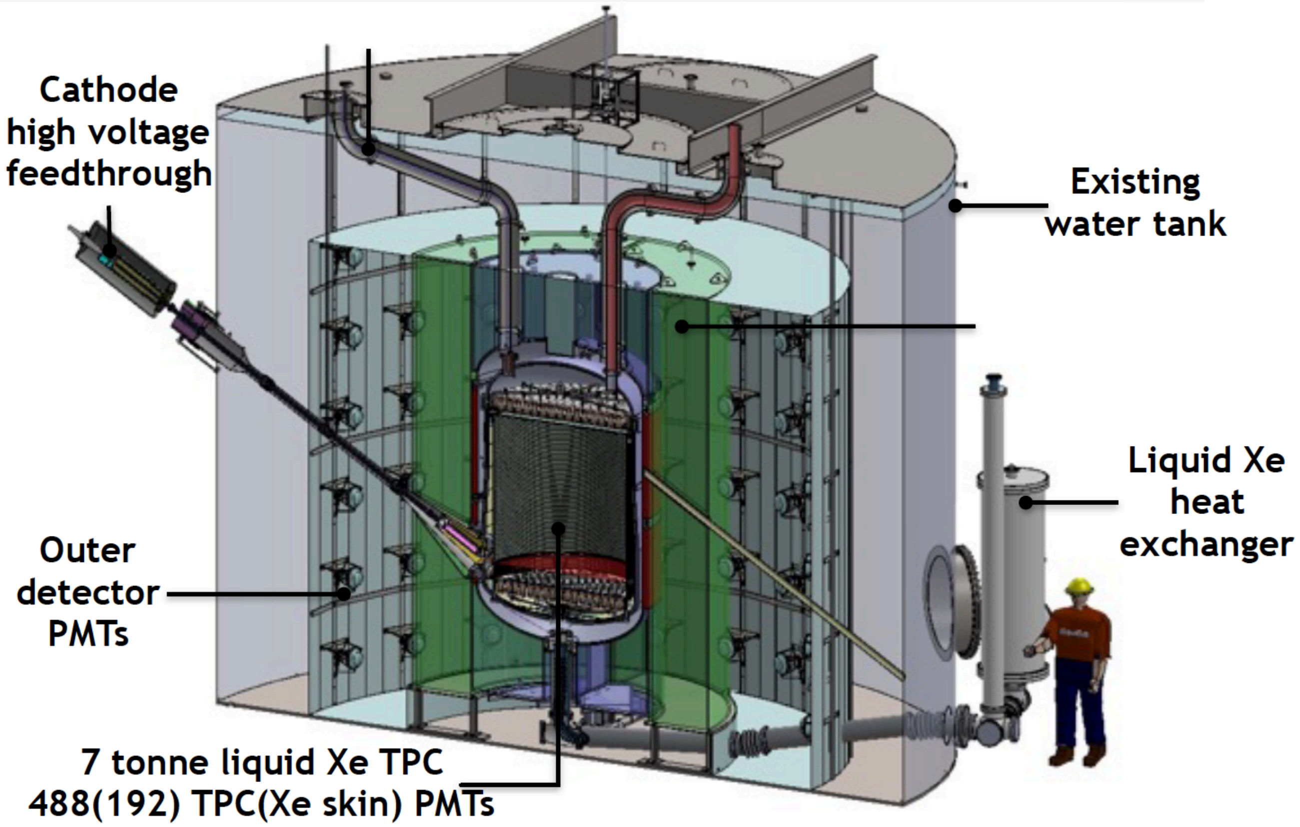
Tritium Beta Spectrum Measured in LUX



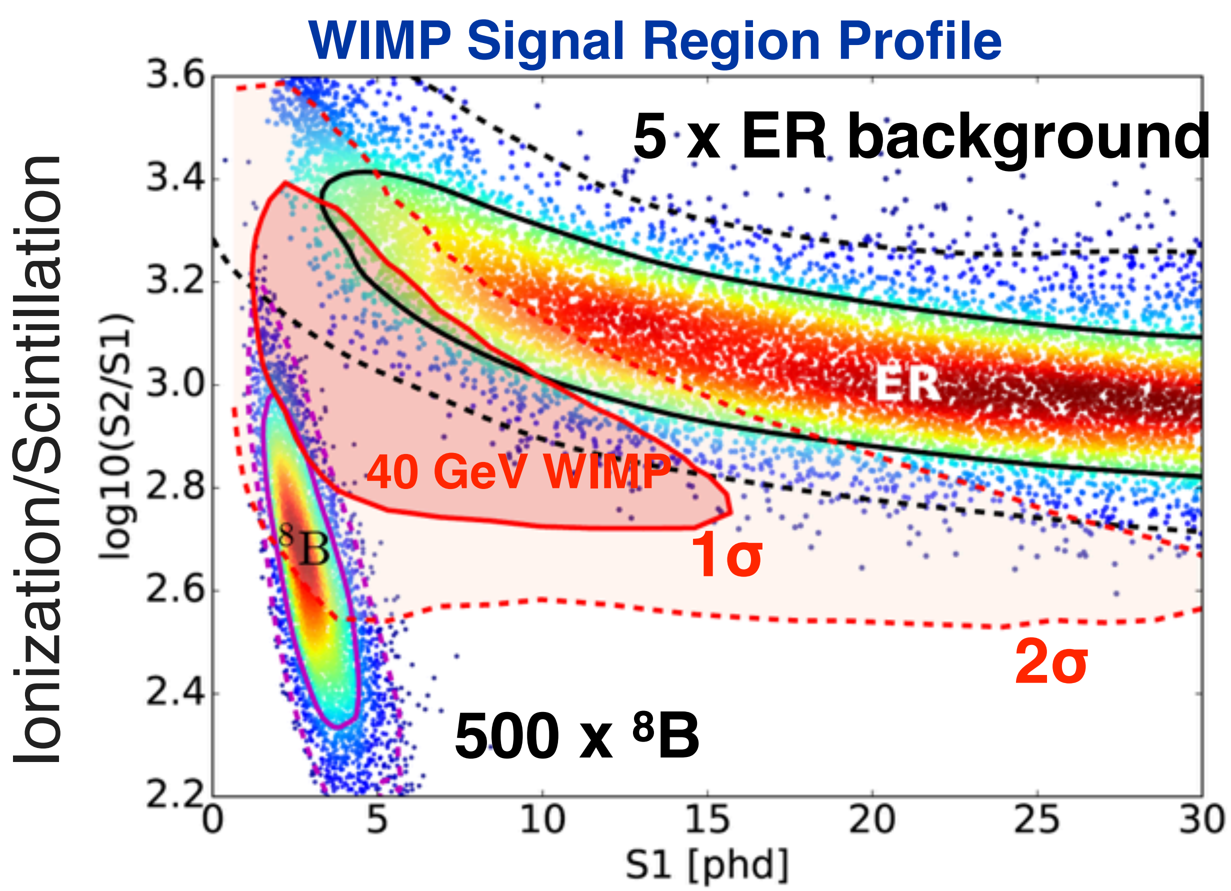
Kr-85: best LUX batch 200 ppq

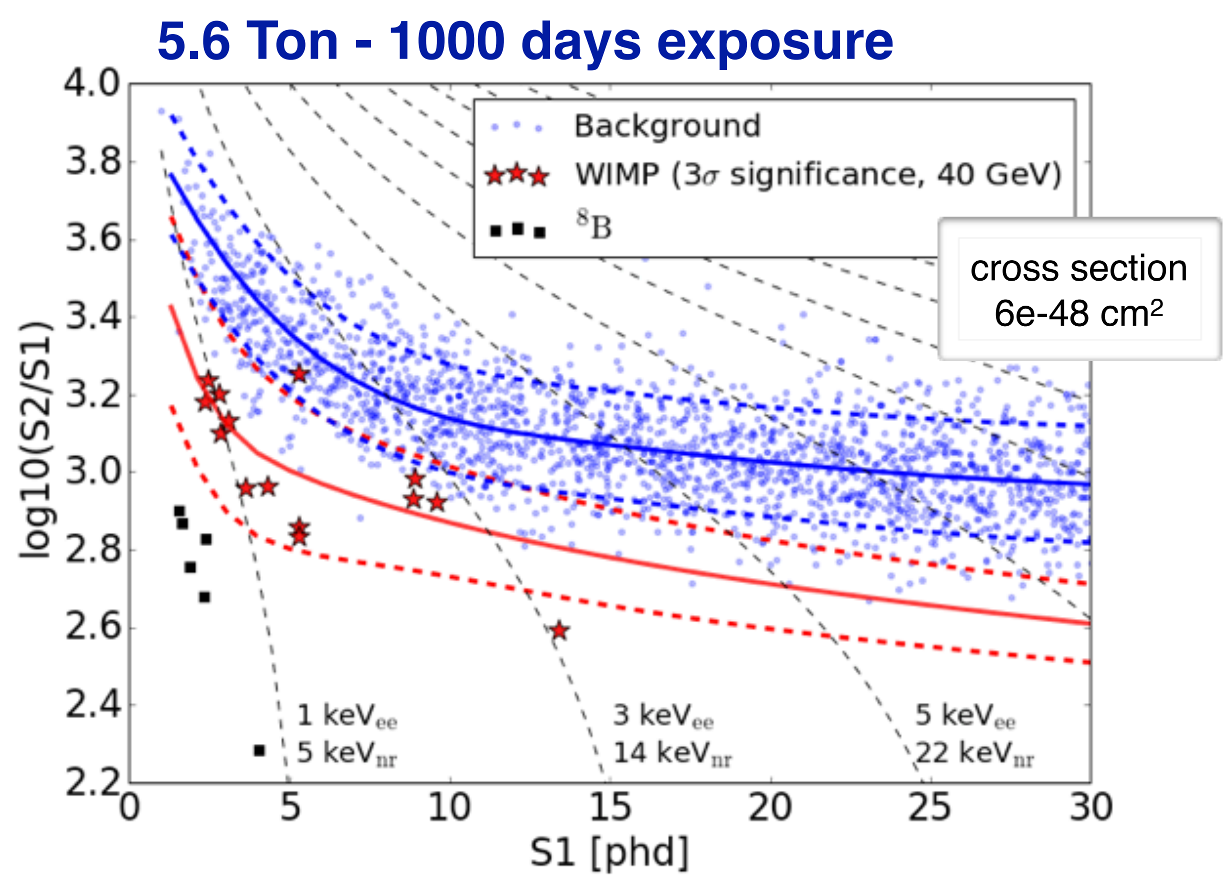
LZ at Sanford Lab

adapted from Attila Dobi

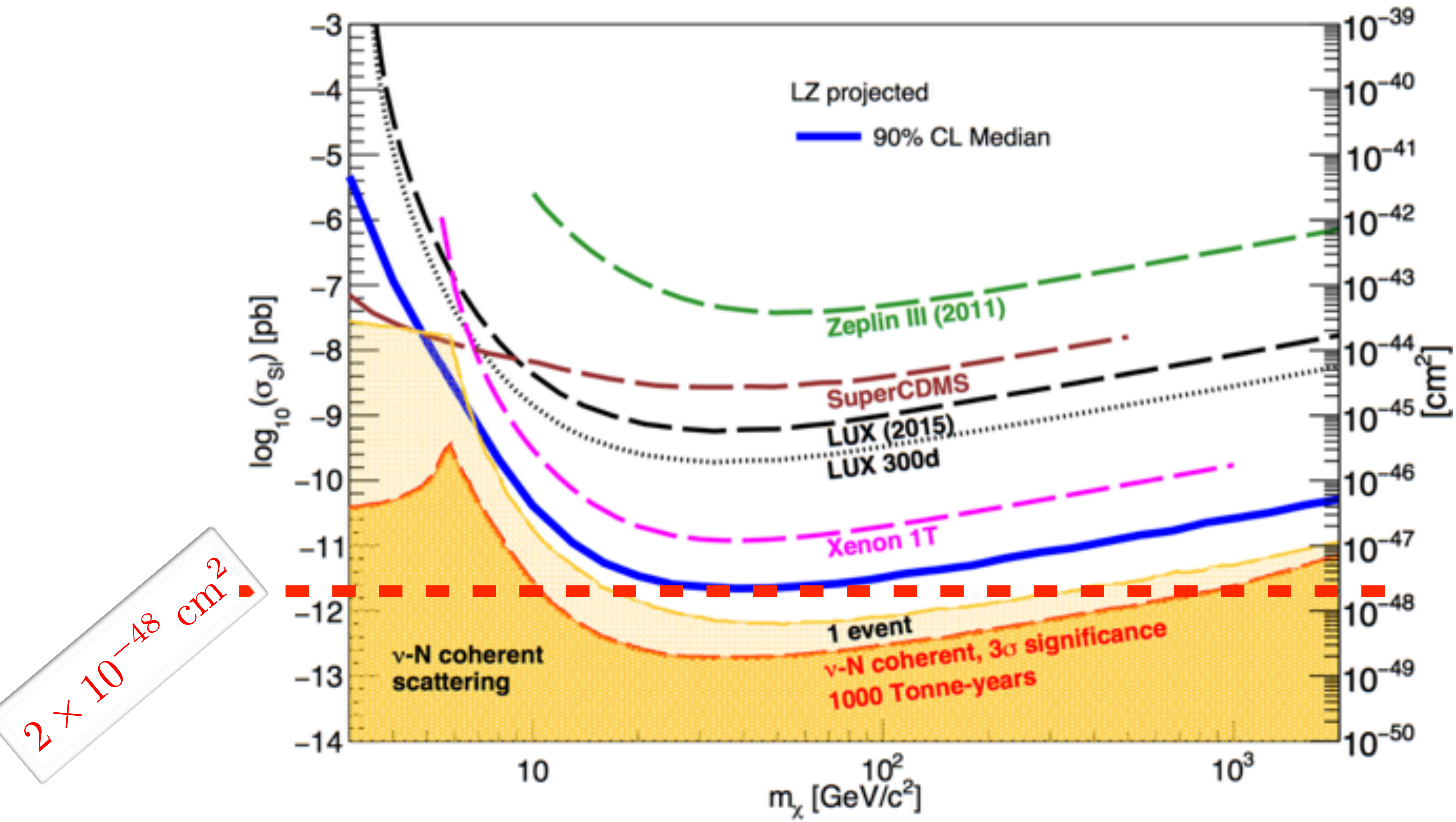


- 10 tons LXe / 7 active / 5.6 fiducial
- Triple veto system
- Gd-loaded scintillator n veto





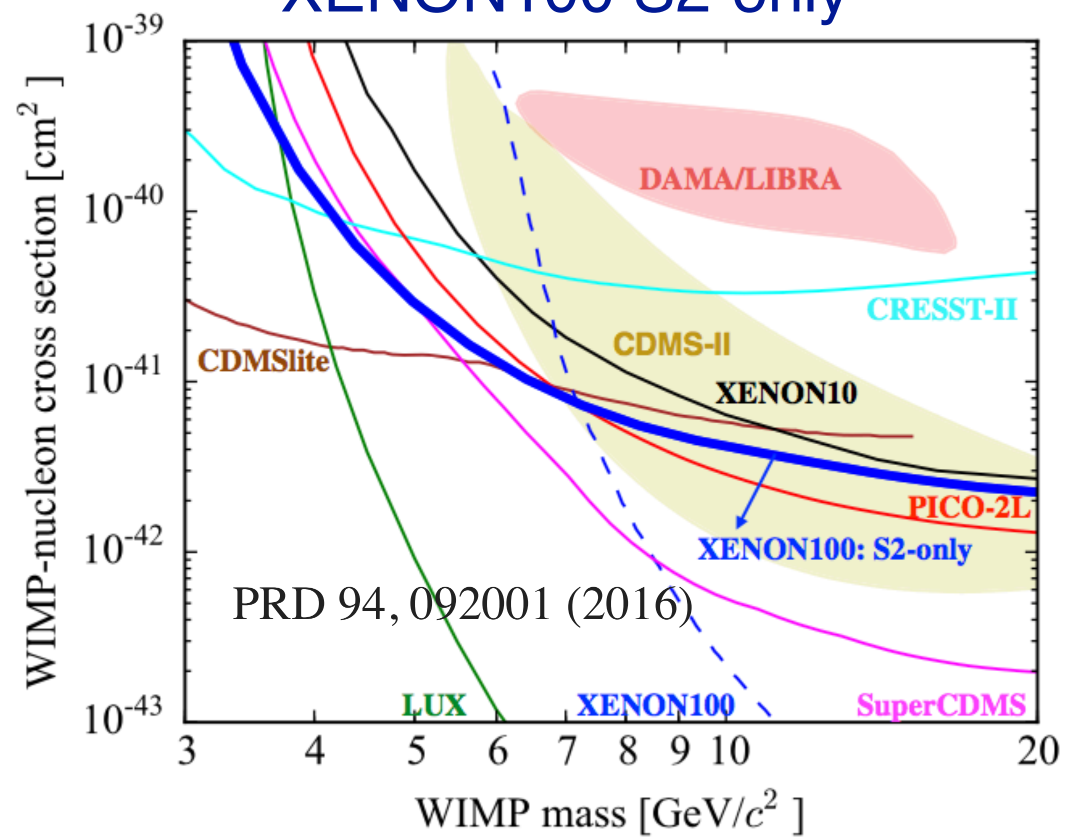
LZ projected sensitivity (SI, 5.6 Tonnes, 1000 live days)

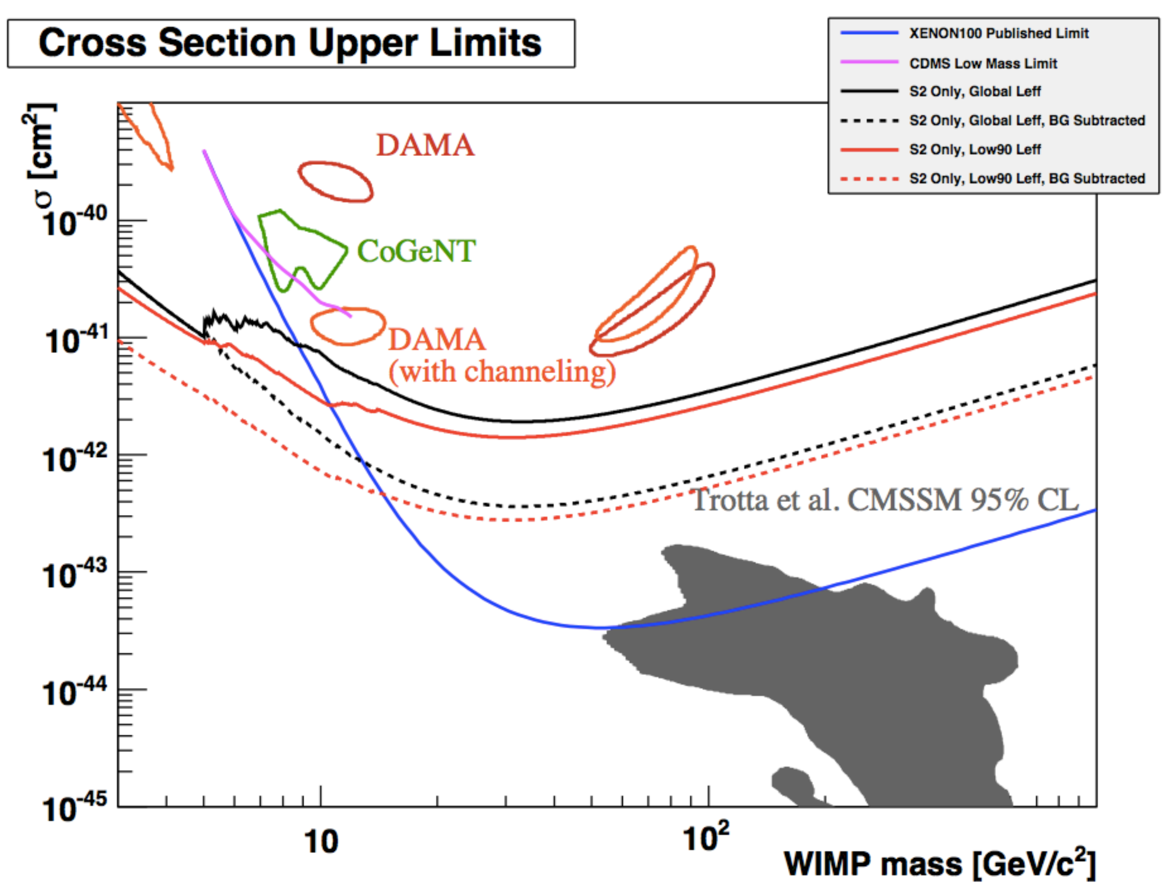


Low-mass WIMPs

	S1 + S2	S2 - only
Nuclear Recoils	• Vanilla WIMPs	• Light(er) WIMPs • Asymmetric Dark Matter
Electron Recoils	• ~keV axion-like particles	• subGeV hidden sector models

XENON100 S2-only



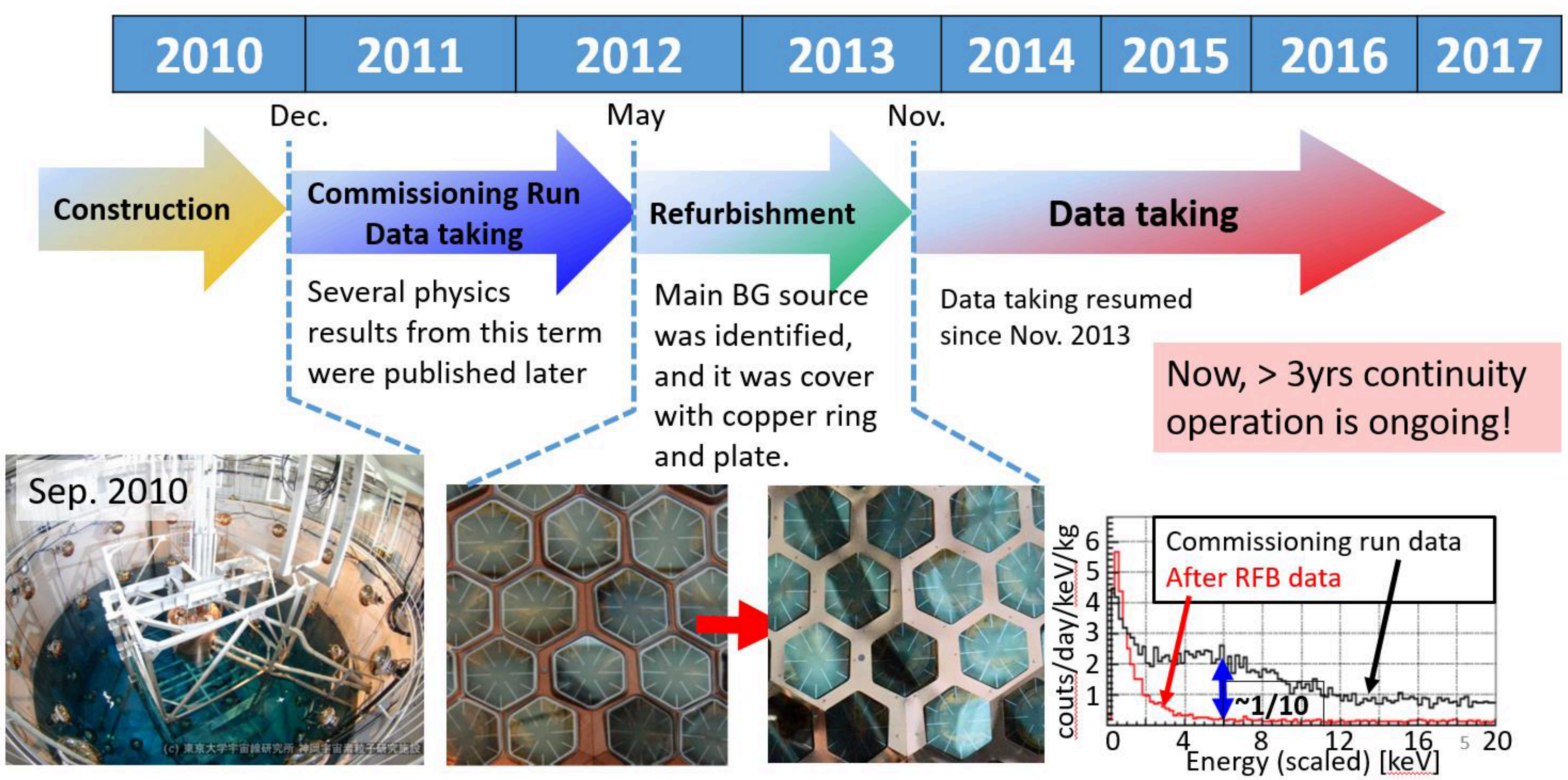


- no z-coordinate
- limited bg rejection
- very sensitive to impurities
- extraction efficiency
- single electron bg hard to model

Single phase LXe: XMASS at Kamioka

adapted from A. Takeda
XeSAT 2017

- 835 kg of LXe, 630 PMTs
- relative simplicity
- limited discrimination
- Key requirements:
  - low external background
  - low radon
  - fiducialization



- issues with PMT bg
- early attempt at PSD in small-scale setup
- annual modulation study

LXe —> LAr

- complementary searches at higher masses
- different systematic effects
- heading for the neutrino floor

➔ Argon is inexpensive and relatively "easy" to purify to levels required for DM searches - true for O_2, N_2, etc. and **also for radon**

➔ Singlet/triplet ratio and lifetimes in argon allow extremely good scintillation PSD (β/γ vs nuclear recoil rejection of 10^{10}) – low background single phase (scintillation-only) detector possible

➔ TPC also exploiting charge collection (S1/S2) increases background rejection (β/γ vs recoil + position reconstruction)

➔ ^{39}Ar – approx. 1 Bq of β decays per kg of argon – must be reduced or rejected in analysis

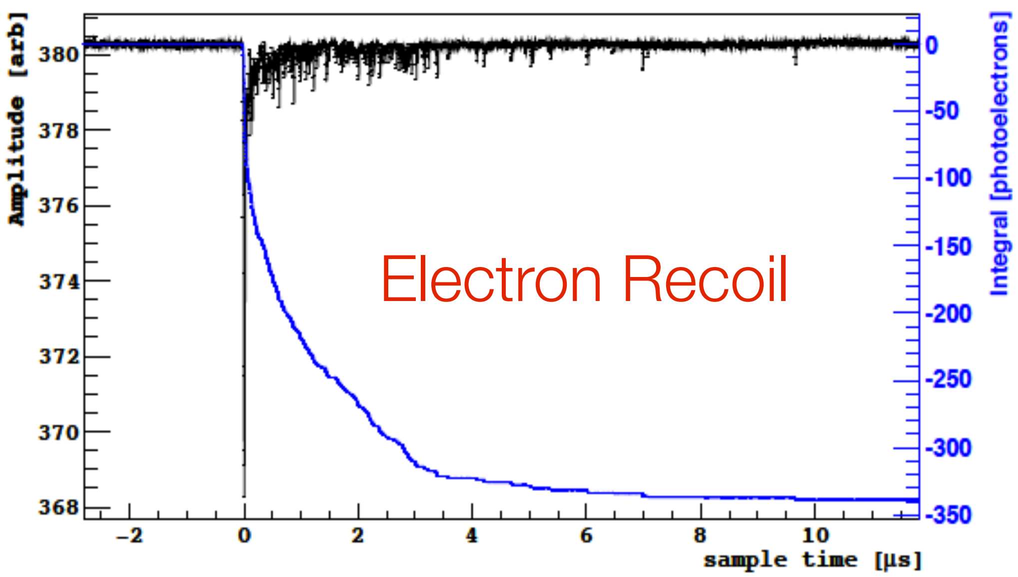
Pulse Shape Discrimination (S1) in LAr

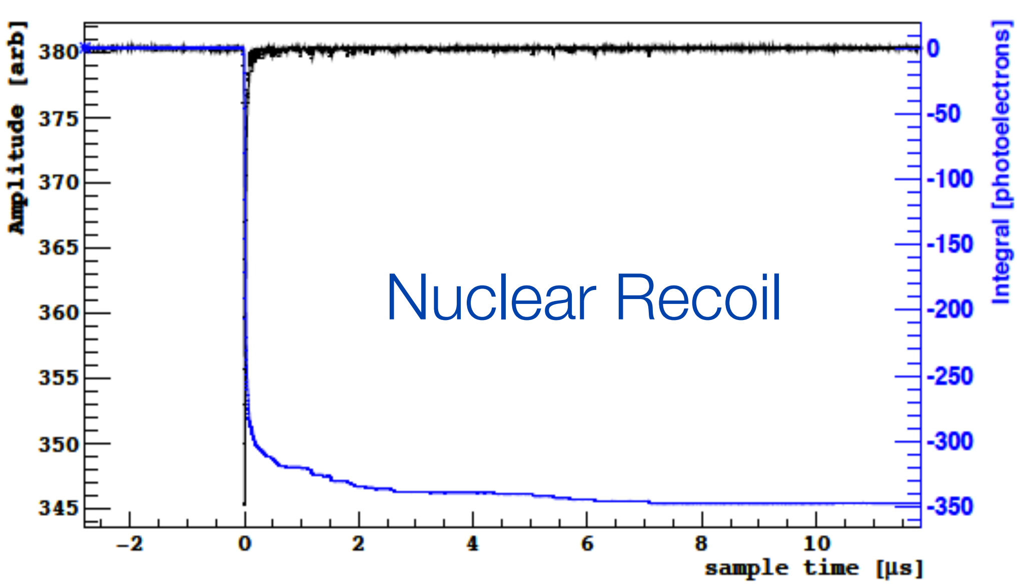
Boulay and Hime, Astropart. Phys. **25**, 179 (2006)

Electron and nuclear recoils produce different excitation densities in the argon, leading to different **ratios of singlet and triplet excitation states**

τ singlet ~ 7 ns

τ triplet ~ 1500 ns

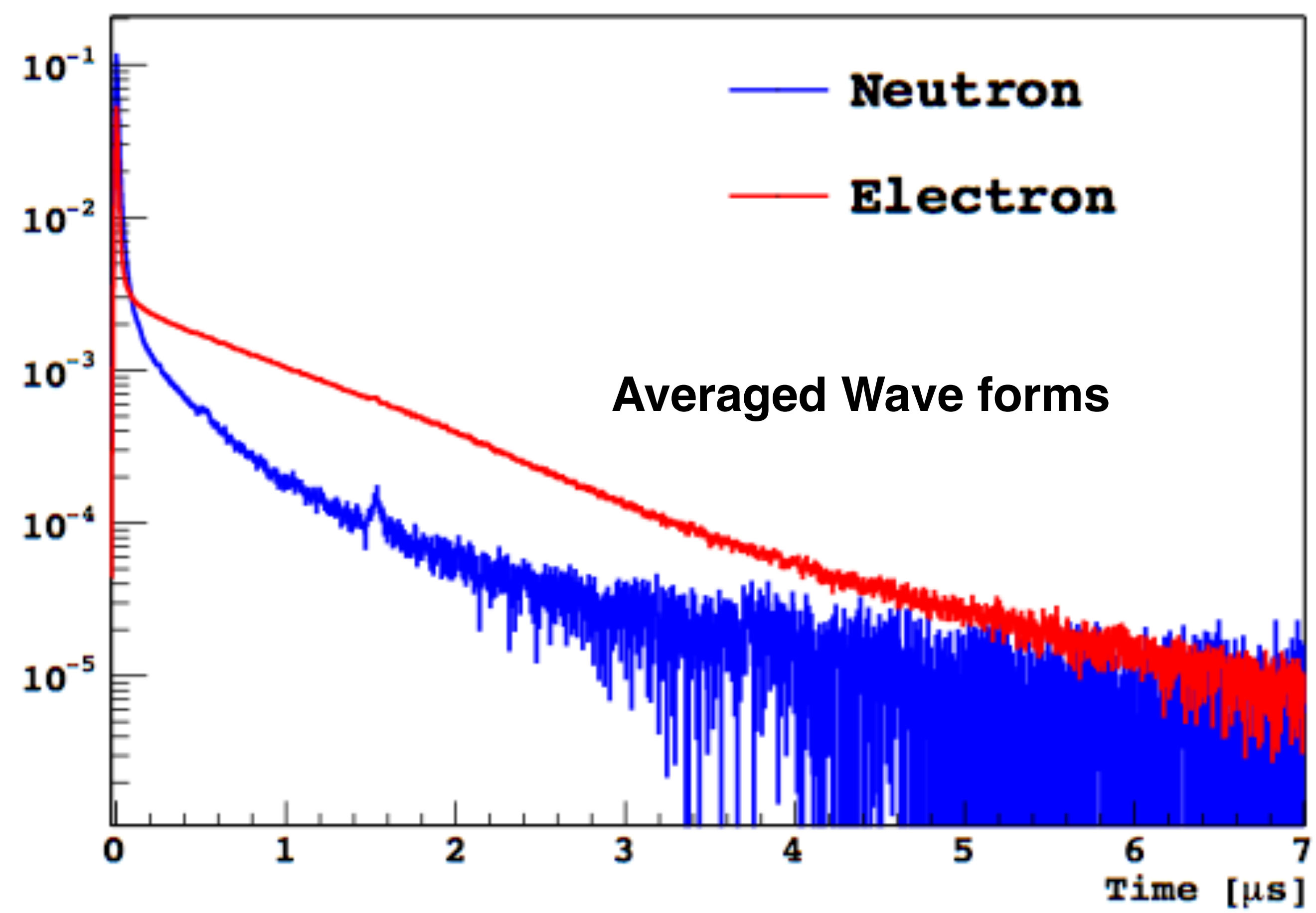




PSD parameter

F90: Ratio of detected light in the first 90 ns, compared to the total signal

~ Fraction of singlet states



World-wide LAr collaboration

Researchers from

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

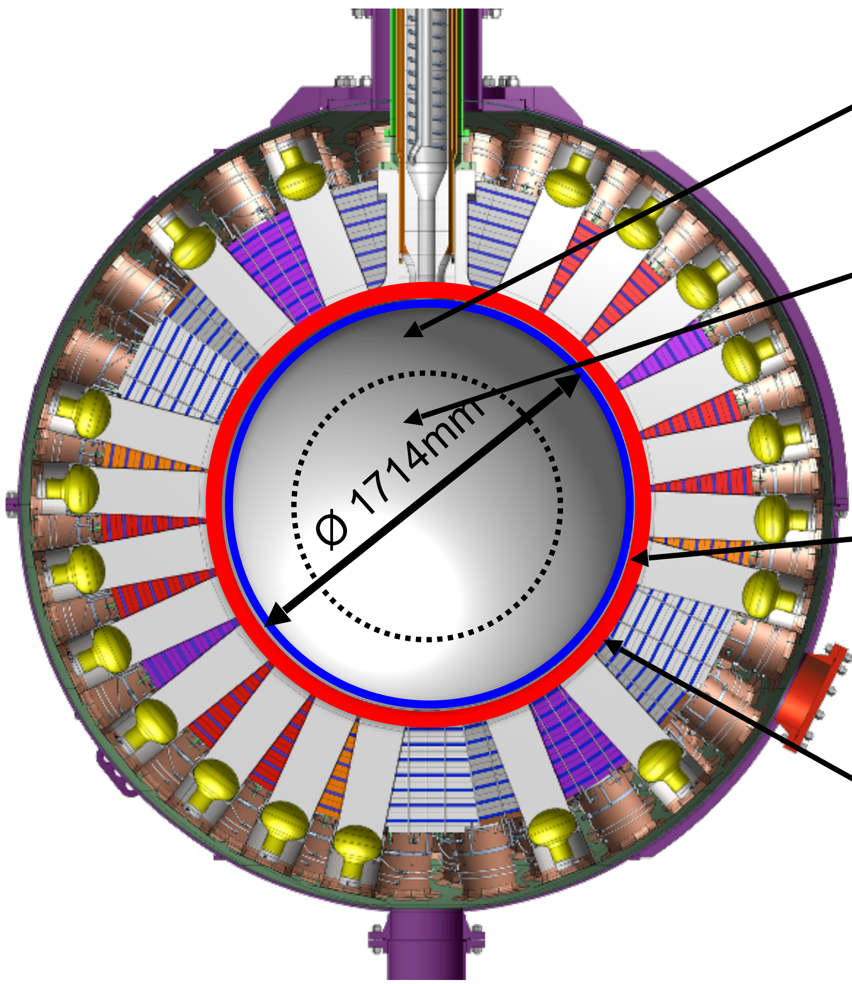
→ DS-20K → multi-100-T

planning to collaborate on future program:

- Completion of current science and R&D programs by each collaboration (DS-50, DEAP-3600, MiniCLEAN, ArDM)
- Joint collaboration on DS-20K at LNGS, including Low Radioactivity Argon (operation starting 2021) and SiPM photodetectors
- Joint collaboration on future multi-hundred-tonne LAr detector, site TBD (mid-2020's)

Single phase LAr: DEAP-3600

adapted from Fabrice Retière

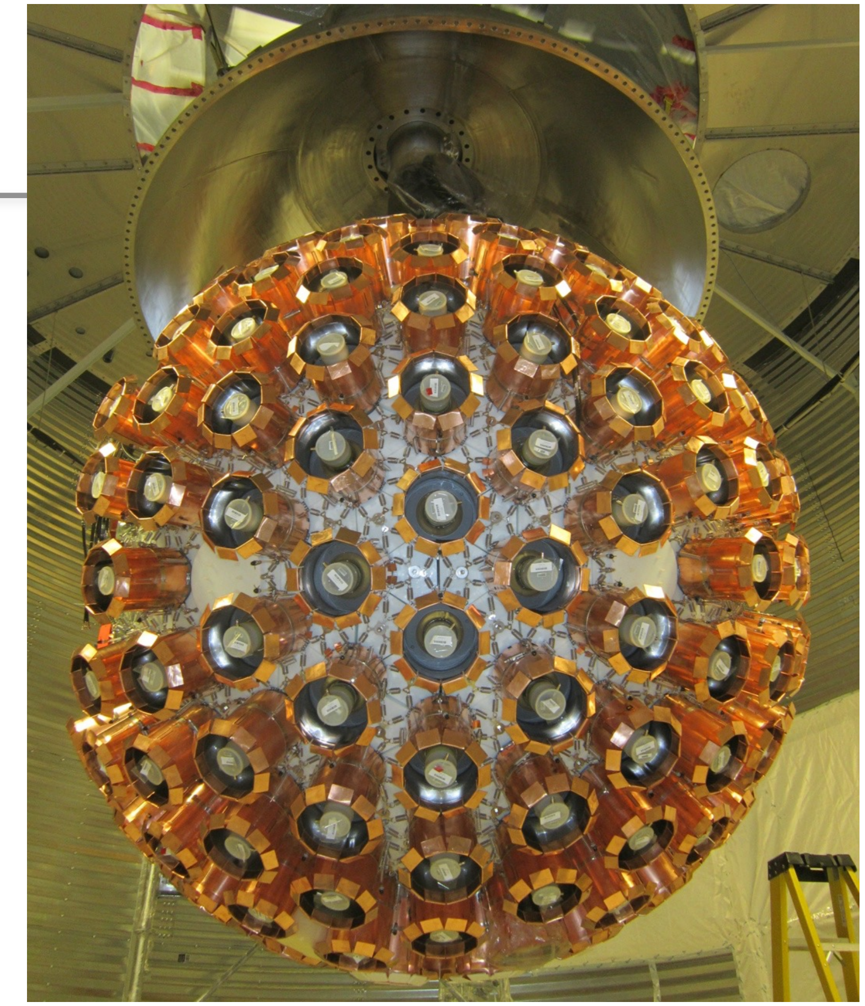


3600 kg of Liquid Argon

1000 kg Fiducial mass

Wavelength shifter
(distilled TPB)

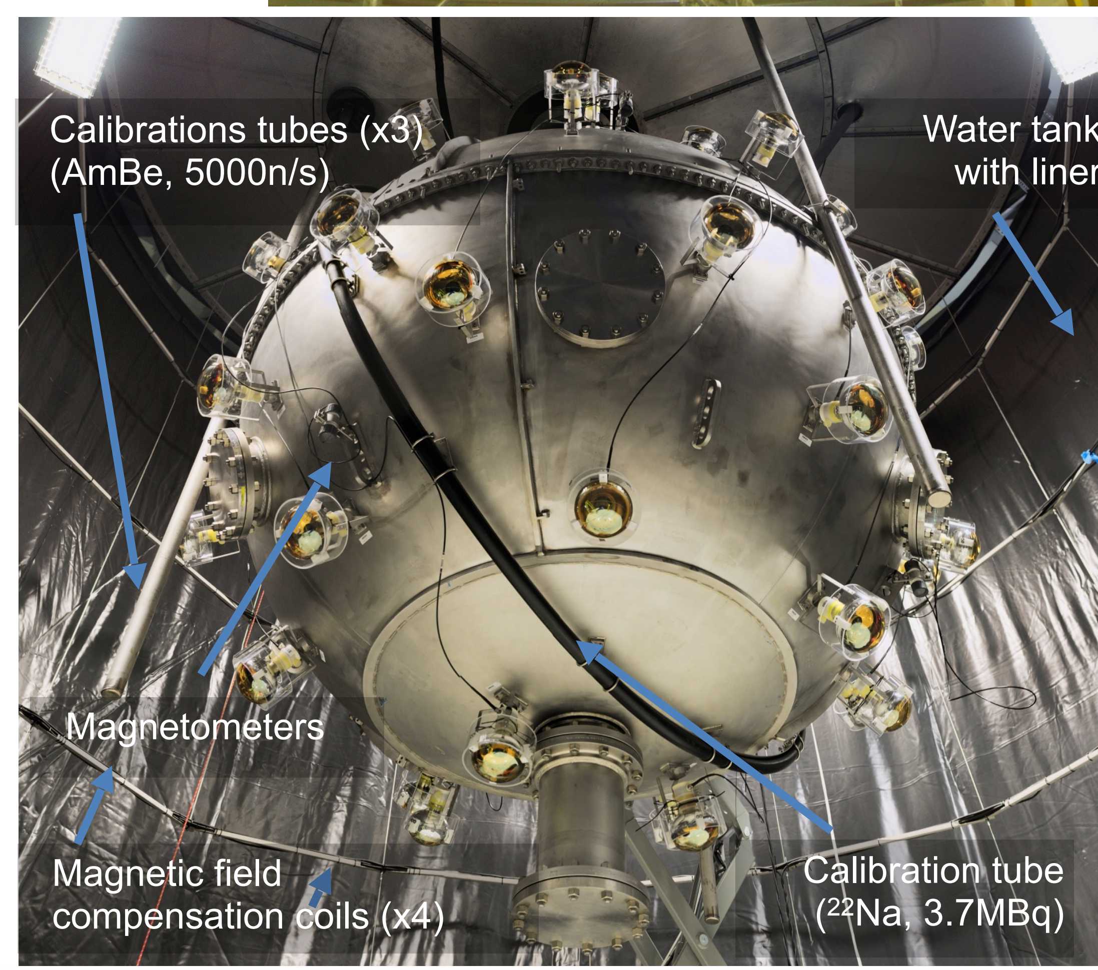
Vessel



WIMP search

Distinguish nuclear from electron recoils by Pulse Shape Discrimination (PSD) of the scintillation signal

(very powerful in Argon)



DEAP-3600

- Room-temperature PMTs
- Ultra-low bg acrylic
- Exposure in line with XENON1T
- Very high statistics PSD

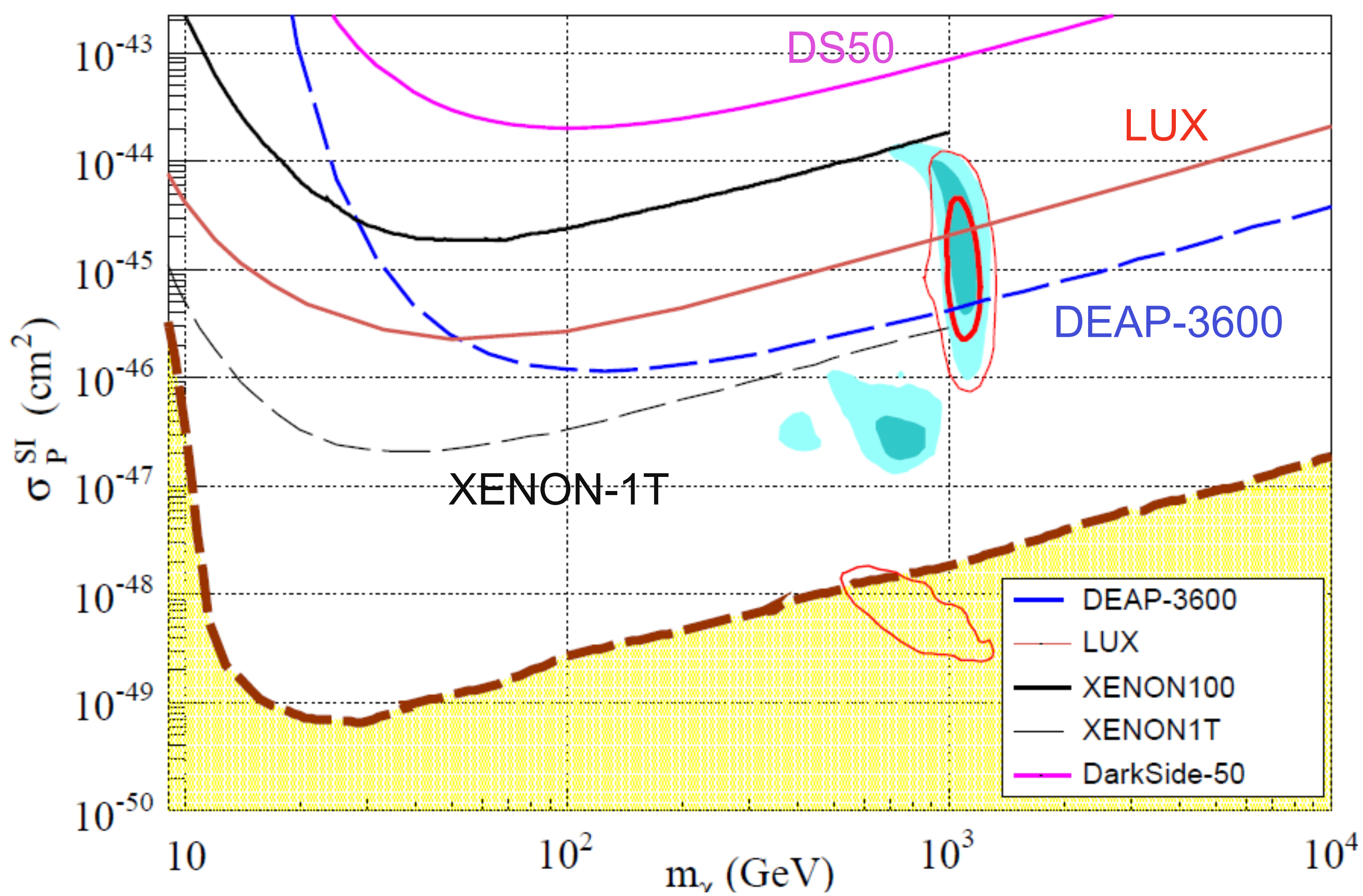
Background	**Fiducial No. Events in Energy ROI – 3 live years**
Neutrons	<0.2
Surface α's	<0.2
^{39}Ar β's (natural argon)	<0.2

designed for
1-tonne fiducial mass
3 live years

DEAP-3600 status

adapted from Mark Boulay

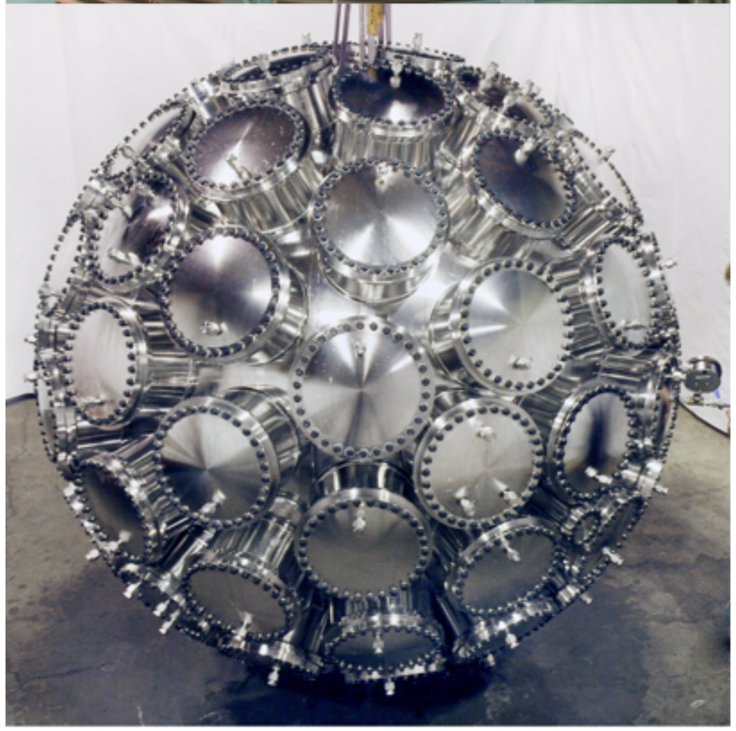
- Detector filled since Nov 1, 2016
- Collecting DM search data so far > 0.5E6 kg-days raw exposure
- So far stable performance good light yield
- Taking physics and calibration data
- plan: continue data collection for ~4 years
- Analysis from the 1st fill data ongoing physics publication expected this year



Single-phase LAr: MiniCLEAN at SNOLAB

adapted from David Asner

- Current Project Status
  - Exceptional purity: Gas triplet time constant >3.6 μs
  - Detector atmospheric liquid argon fill underway
- Run plan (2017/18)
  - 3 months - fill and final commissioning
  - 3 months - baseline technical demonstration
    - light yield, background levels, position reconstruction,…
  - 6 months - ^{39}Ar spiked data
    - Pulse Shape Discrimination R&D at 10^{-10} level
- Lead by Pacific Northwest National Lab since 2014
  - Completion of detector construction (2015)
  - Cool down and commissioning (2016)
  - Favorable Operations Readiness Review (2016/17)
  - Leads project management, operations, data analysis & ^{39}Ar spike program
- Informs technology choices for 100+ ton experiment



ArDM — a ton-scale LAr TPC for DM research

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

ETH Institute for Particle Physics

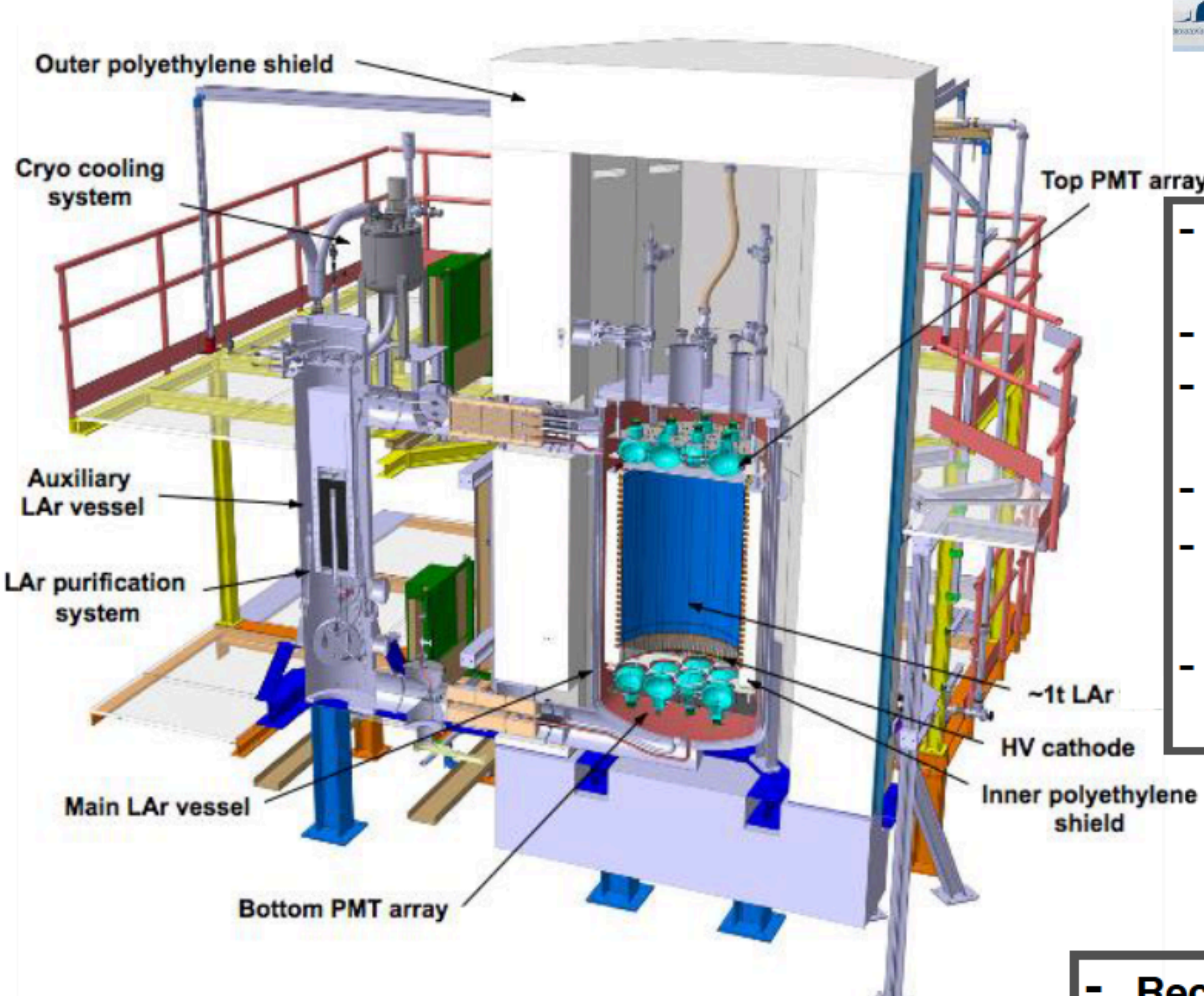
Ciemat

CERN

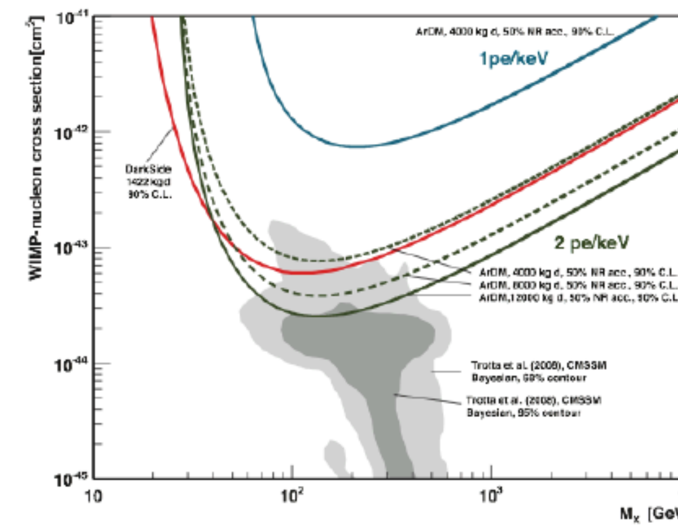
LSC

ETHZ led collaboration with CIEMAT, LSC, CERN ….

- **Contribution to searches of higher mass WIMPs!**
- **Design parameters / developments for future LAr facilities!**

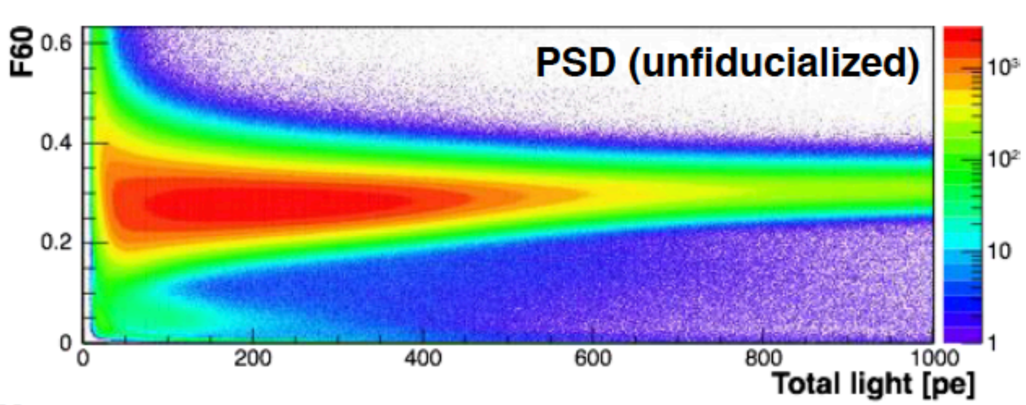


- **Experiment commissioned in single phase in 2015**
- **$3{\times}10^9$ triggers recorded**
- **Low background goal confirmed**
- **Detector upgraded in 2016**
- **Double phase run planned for 2017**
- **Main tasks: Verification of sensitivity and neutron IA**



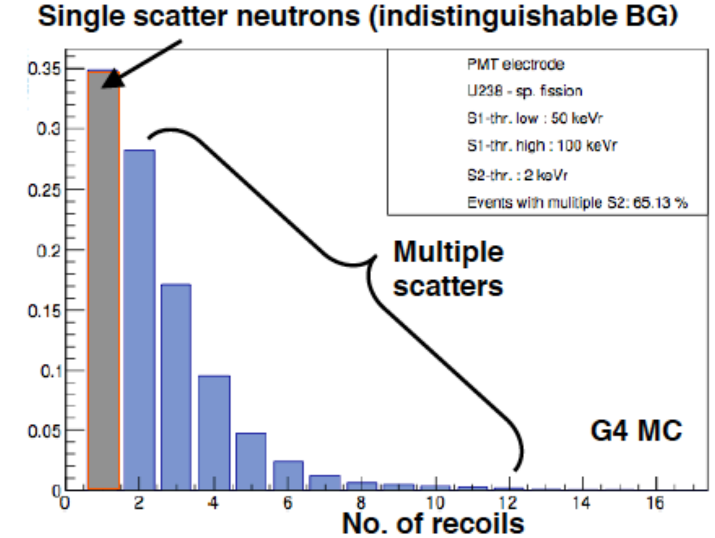
1 neutron event per ~20d expected

Commissioning of the ArDM experiment… JCAP, 03, 003 (2017)



- **Recent integration of ArDM in the DS project**
- **Combining efforts towards future G2 and G3 facilities**

Single scatter neutrons (indistinguishable BG)



^{39}Ar depleted argon research planned for 2018 and beyond

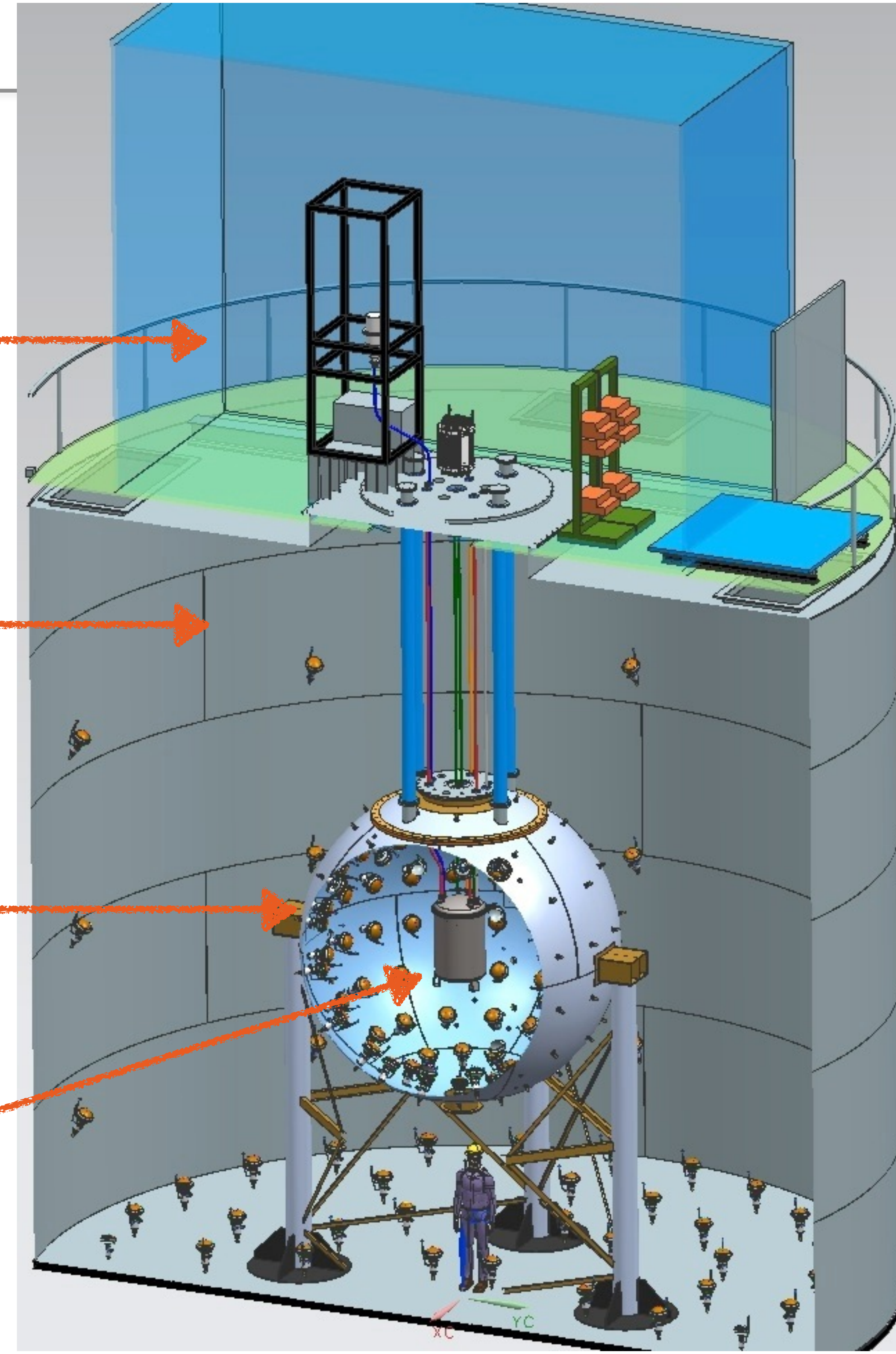
DarkSide 50 at LNGS

Radon-free **Clean Room**
(Rn levels < 10 mBq/m^3)

1,000-tonne Water-based Cherenkov
Cosmic Ray Veto

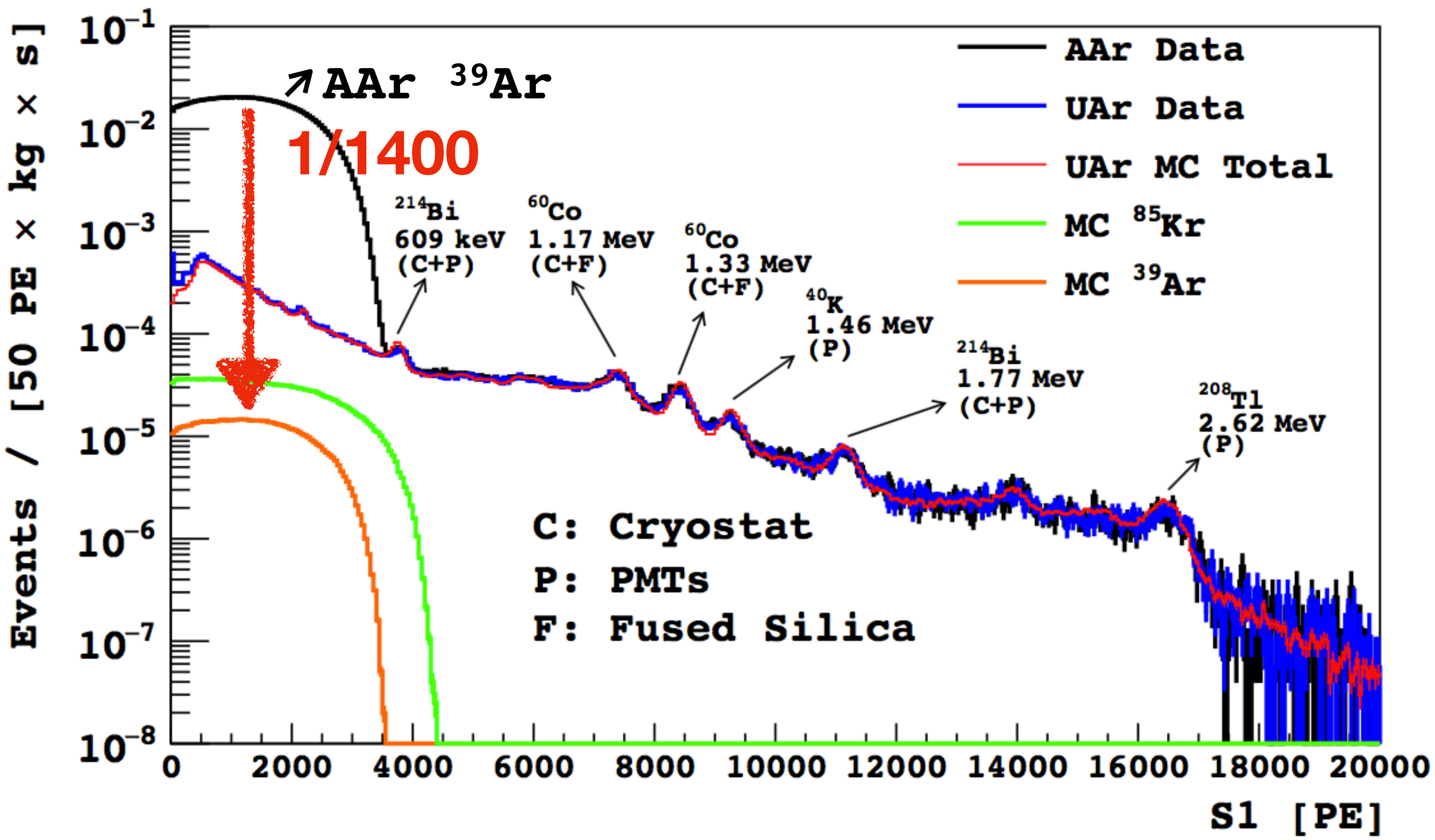
30-tonne Liquid Scintillator
Neutron and γ's Veto

Inner detector **TPC**



DarkSide-50

AAr vs UAr. Live-time-normalized S1 pulse integral spectra at **Zero** field. **^{39}Ar reduction factor of ~1400**

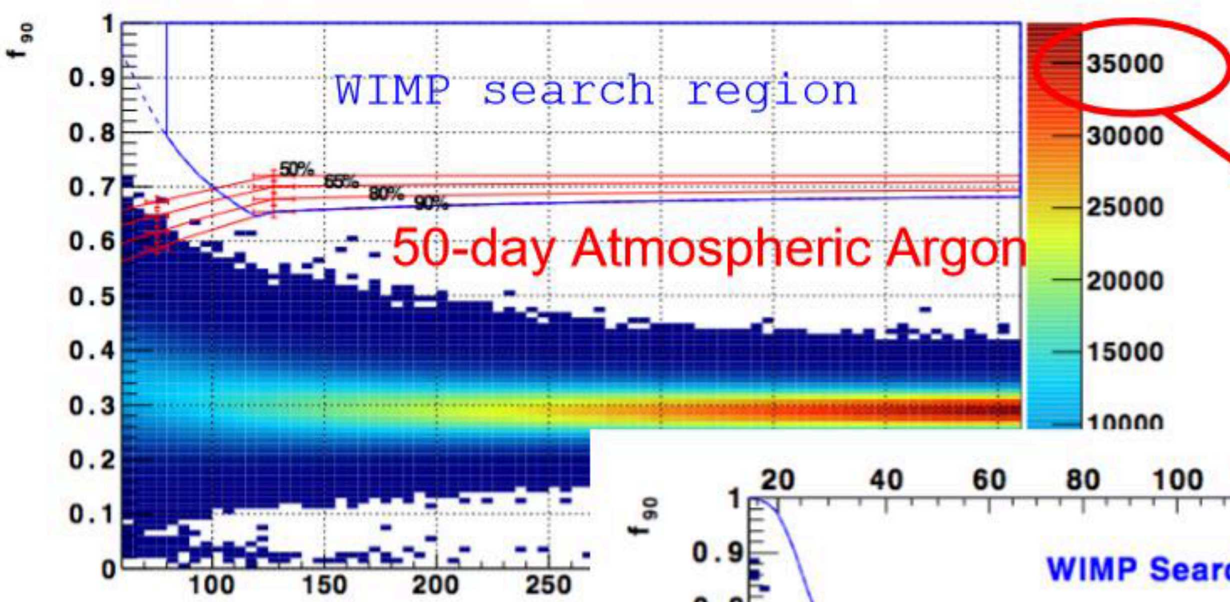


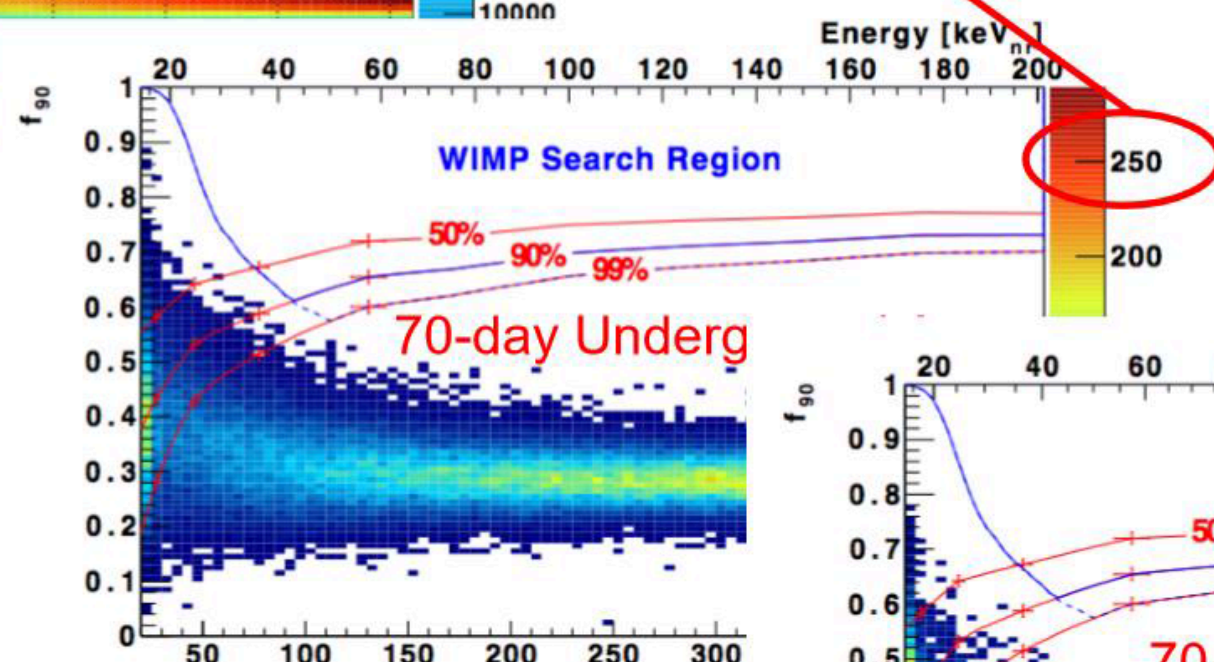
- pioneered the use of low radioactivity argon from underground sources
- introduced the use of an active neutron veto design
- low bg operation of a LAr TPC
- high light yield ~8 p.e./keV$_{ee}$

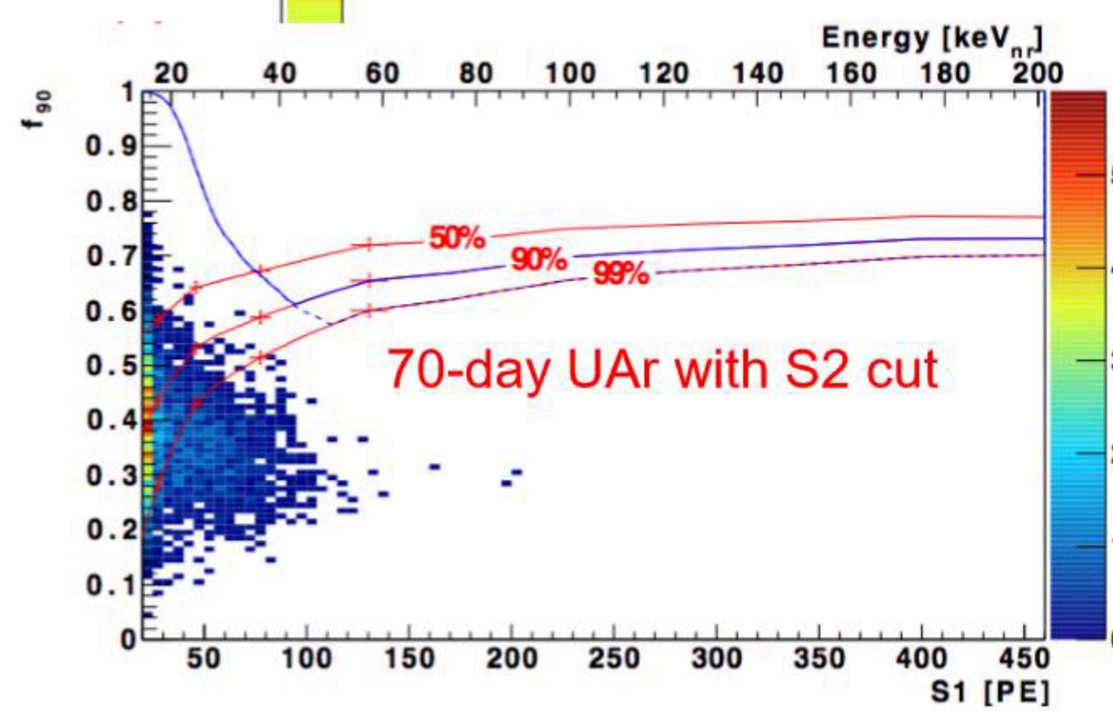
Low level of ^{39}Ar allows extension of DarkSide program to ton-scale detector.

DarkSide-50

- collected large statistics with AAr equivalent to few tonne-yr of UAr

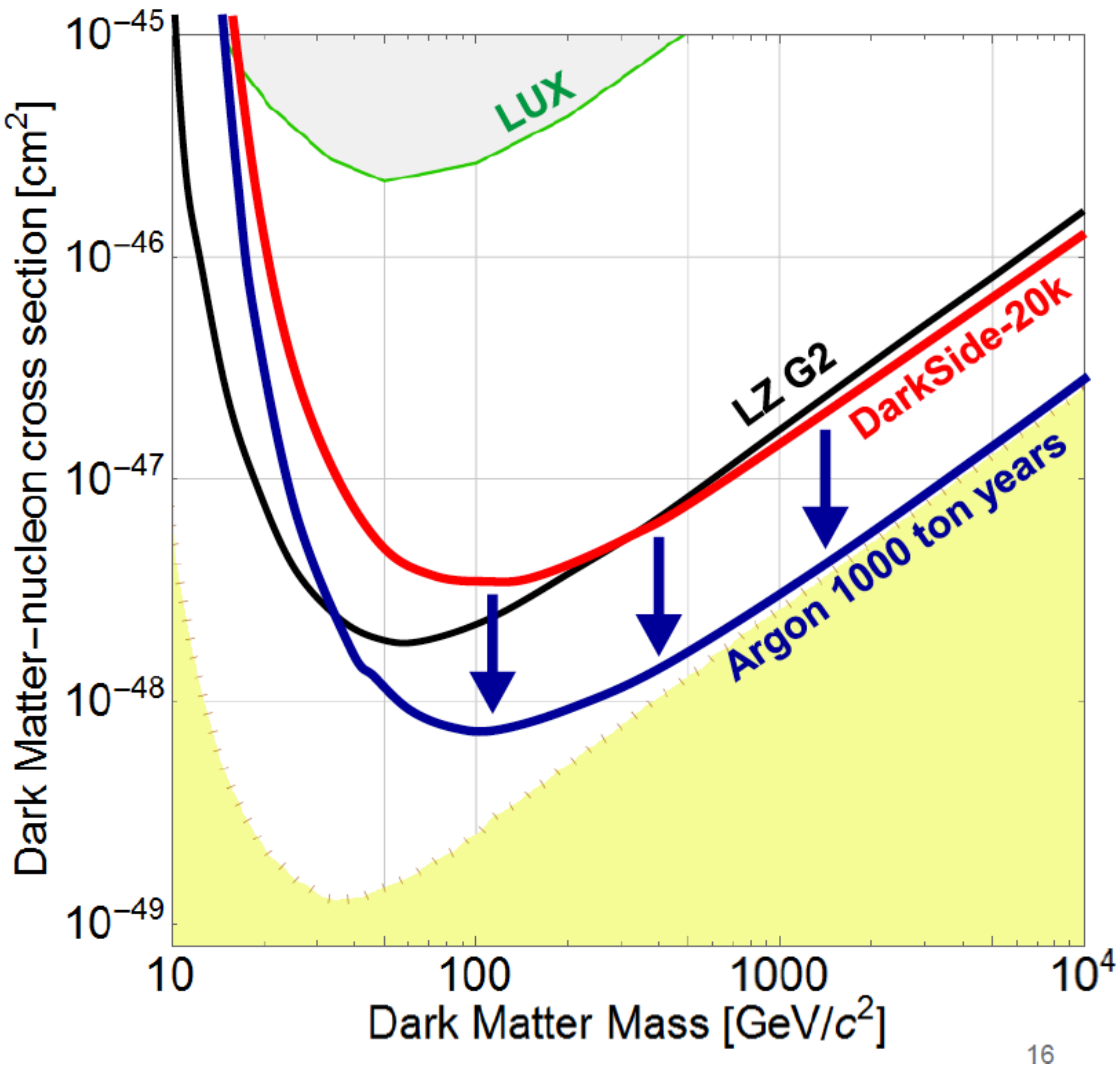






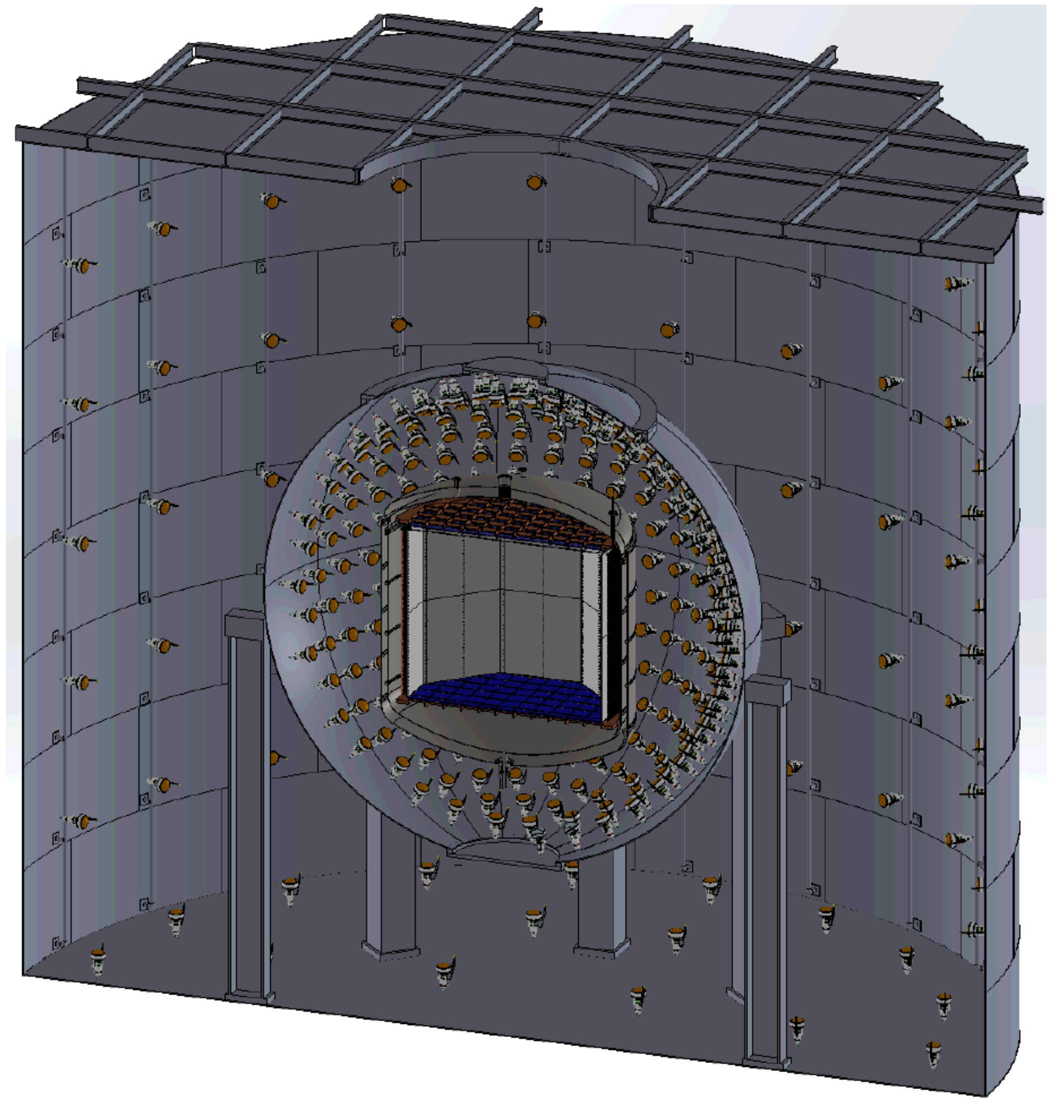
Demonstrates that v. large low-background argon using UAr TPC is feasible

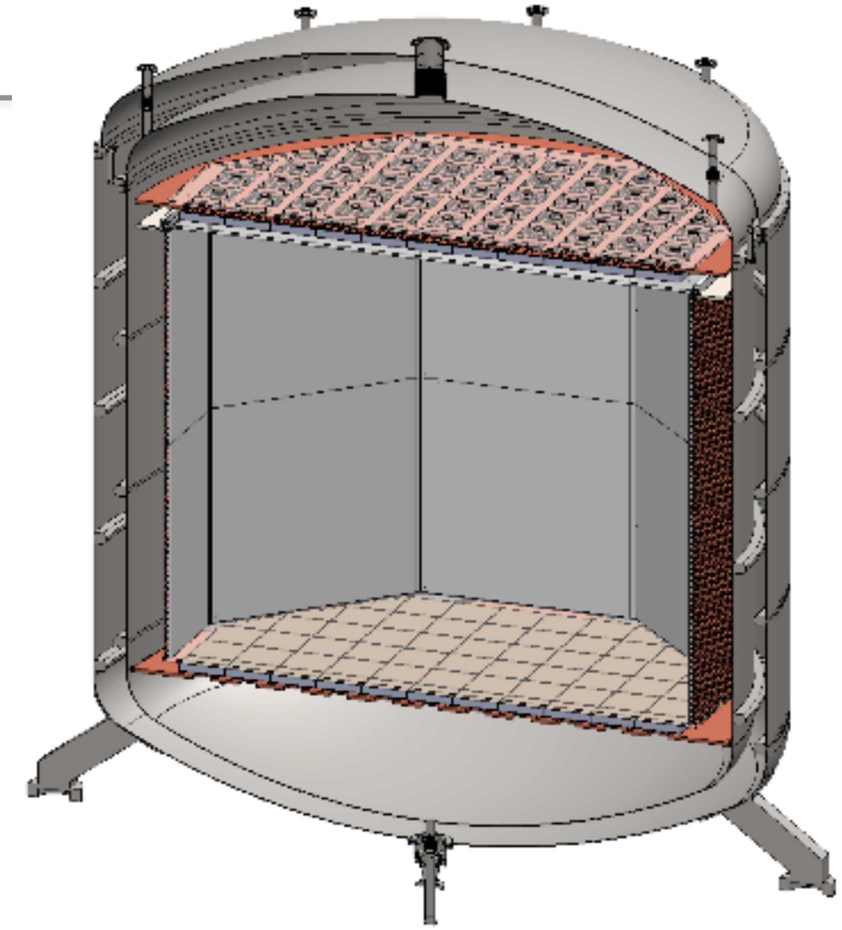
DS-20k and beyond — zoom in on heavy WIMPs



- Argon has good sensitivity in high-mass region
- DS-20K (20 tonnes UAr) competitive with LZ — start operation 2021
- 1000-tonne years (future detector) reaches down to neutrino floor
- Complimentary to xenon — only other target allowing such large exposure
- β/γ discrimination:
  solar pp neutrino ES background not a concern — in X1T, LZ expected dominant bkg at ~0.5 event per tonne-year after recoil discrimination

DS-20k at LNGS





- 20 tonnes low radioactivity Ar
- Scale-up from DS-50
- Global LAr community
- Advanced design (Yellow Book)

- background-free, 100 tonnes-yr exposure
- SiPMs replace cryogenic PMTs (single-p.e. 5x5 cm^2 tile demonstrated in March 2017)
- complementary to LHC searches

More UAr, less ^{39}Ar

Urania (Underground Argon):

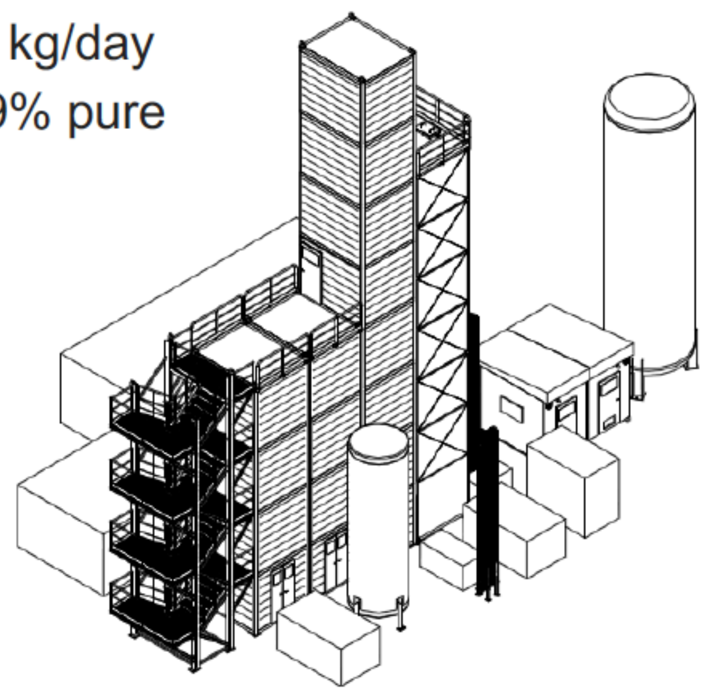
- Expansion of the argon extraction plant in Cortez, CO, to reach capacity of ~**150 kg/day** of Underground Argon

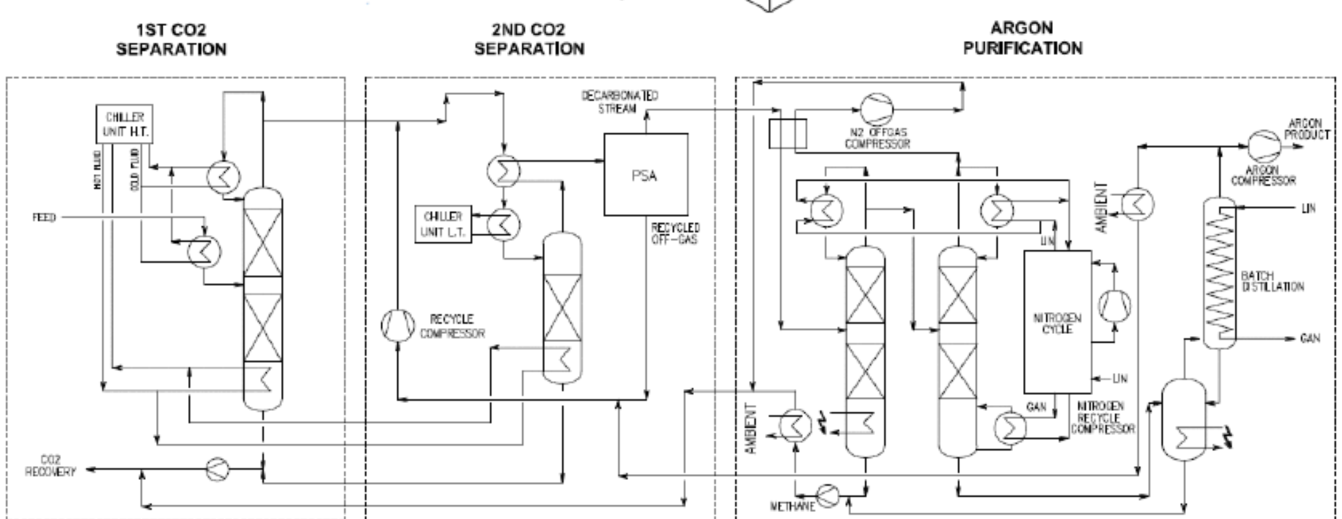
Aria (UAr Purification):

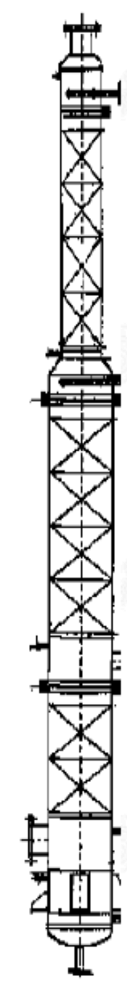
- Very tall column in the Seruci mine in Sardinia, Italy, for high-volume chemical and isotopic purification of Underground Argon

Urania and ARIA

- **Urania** *(planned)*
  - Extracts argon from CO2
  - Same source as DarkSide-50 target
  - Production:
    - 100 kg/day
    - 99.9% pure
- **Aria** *(under construction)*
  - Final argon purification
  - Capable of isotope separation (^{39}Ar depletion)
  - Located in the Seruci mine in Sardinia, Italy







Beyond DS-20k — few hundred tonne LAr detector

- 1000 tonne-yr, background-free exposure reaching the neutrino floor
- Sensitivity to WIMPs > few tens of GeV/c^2
- mid 2020's

- Large collaboration will pursue an integrated program
- Single/dual-phase design under consideration

- Physics program largely complementary with the LHC and to the expanding effort in searching low-mass WIMPs
- Solar neutrino program possible

Conclusions

stay hungry, my friend

- LXe and LAr detectors are leading players in the search for WIMP dark matter heavier than a few GeV
- The tonne-scale dark matter search is under way with XENON1T and DEAP-3600 — more to follow in the next few years
- LXe 2-phase TPCs allow for single electron sensitivity for low-mass WIMPs (~GeV/c^2 scale)
- Future detectors with target mass of tens —> hundreds of tonnes are planned to search for WIMPs down to the neutrino floor
- Compelling, complementary physics program to the LHC (and searches for light dark matter)

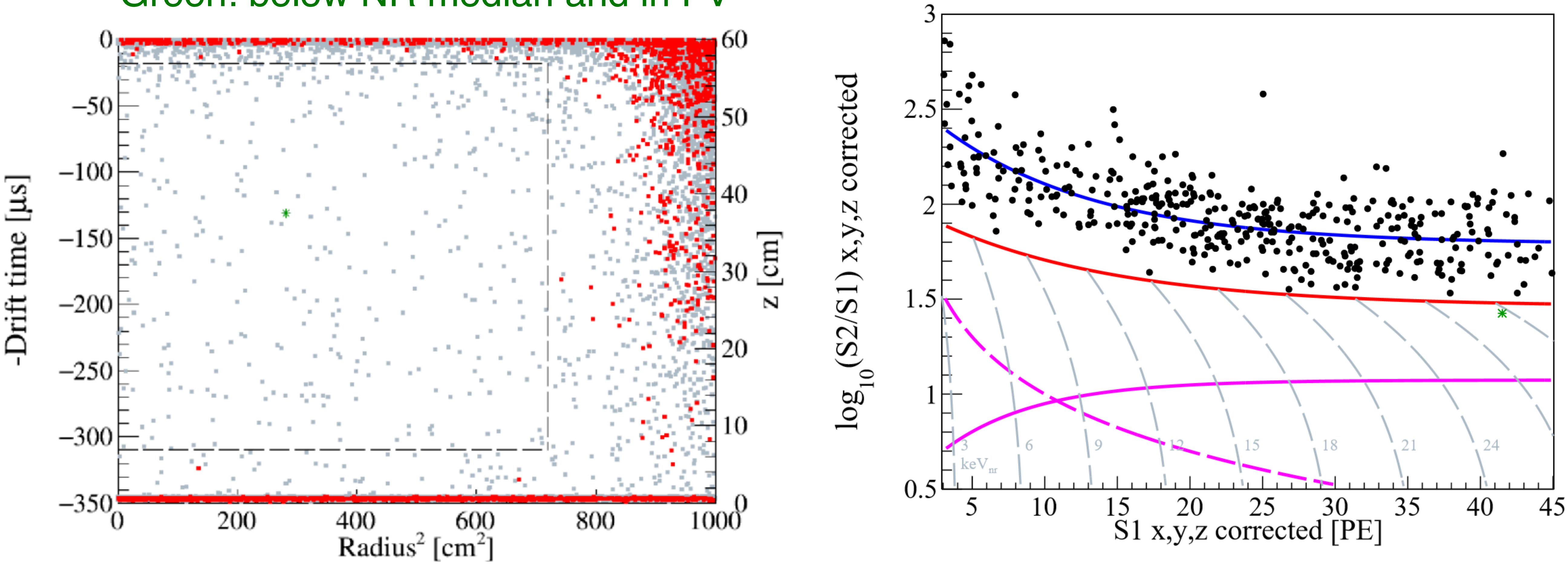
PandaX-II data

adapted from Jianglai Liu, Pheno 2017

Gray: all

Red: below NR median

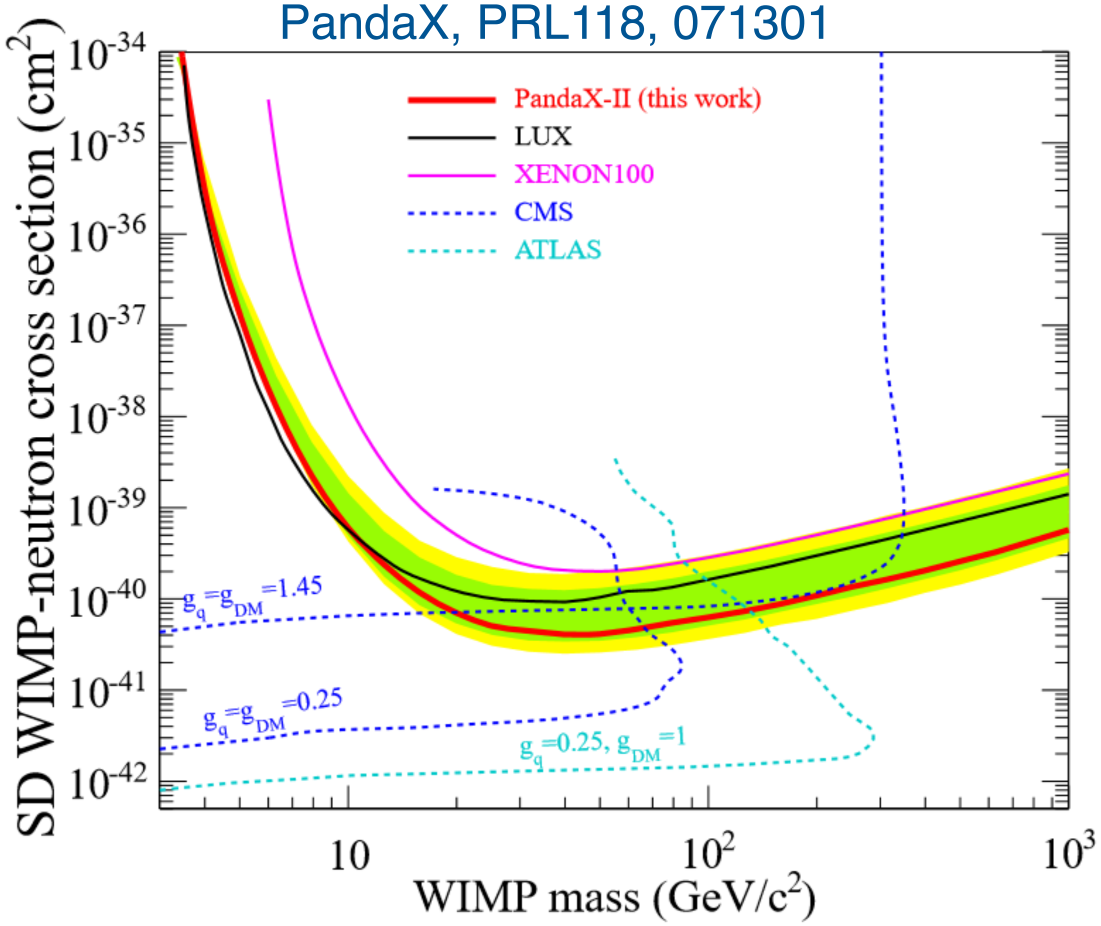
Green: below NR median and in FV



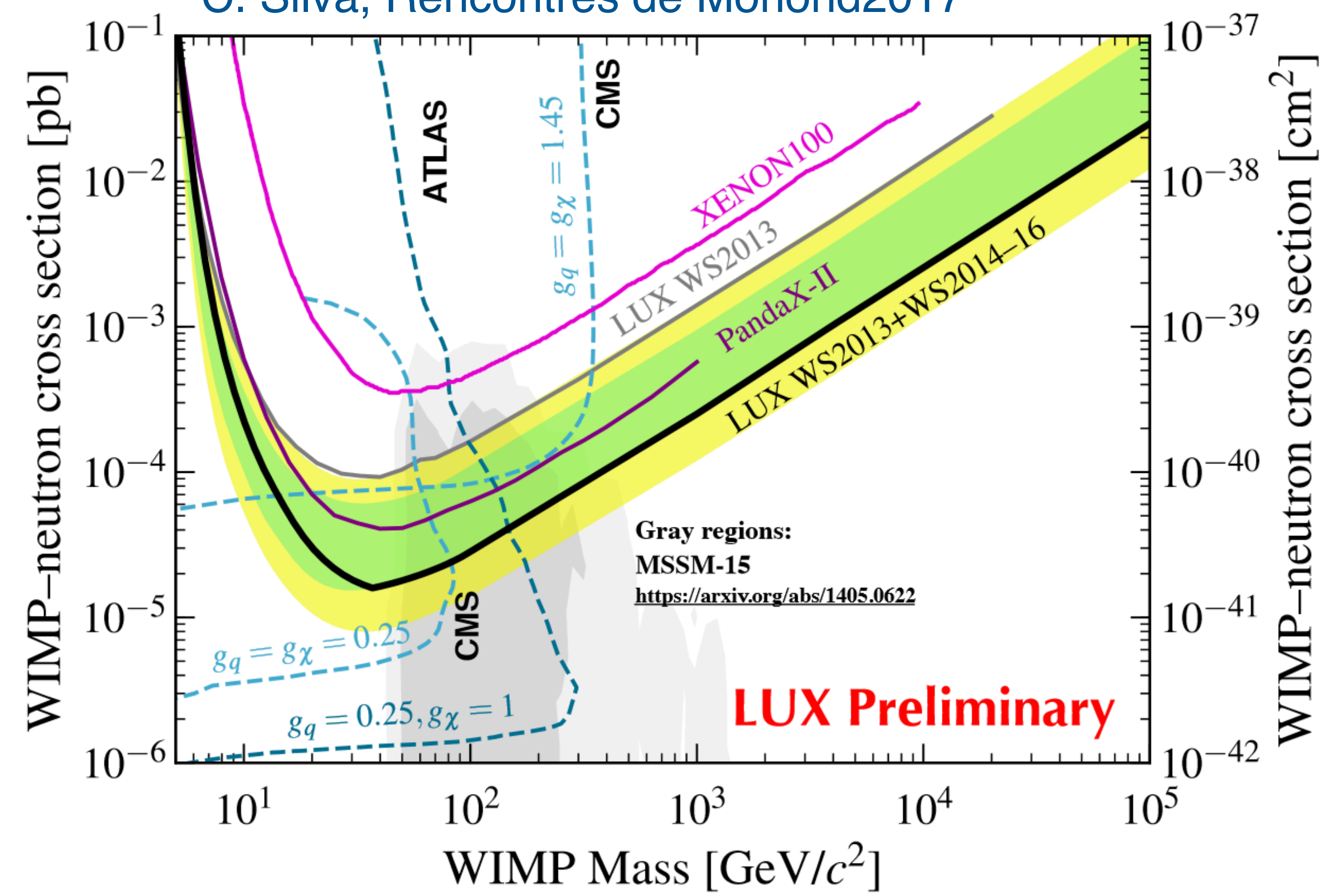
Spin-Dependent WIMP interactions

adapted from Jianglai Liu, Pheno 2017

PandaX, PRL118, 071301



C. Silva, Rencontres de Moriond2017



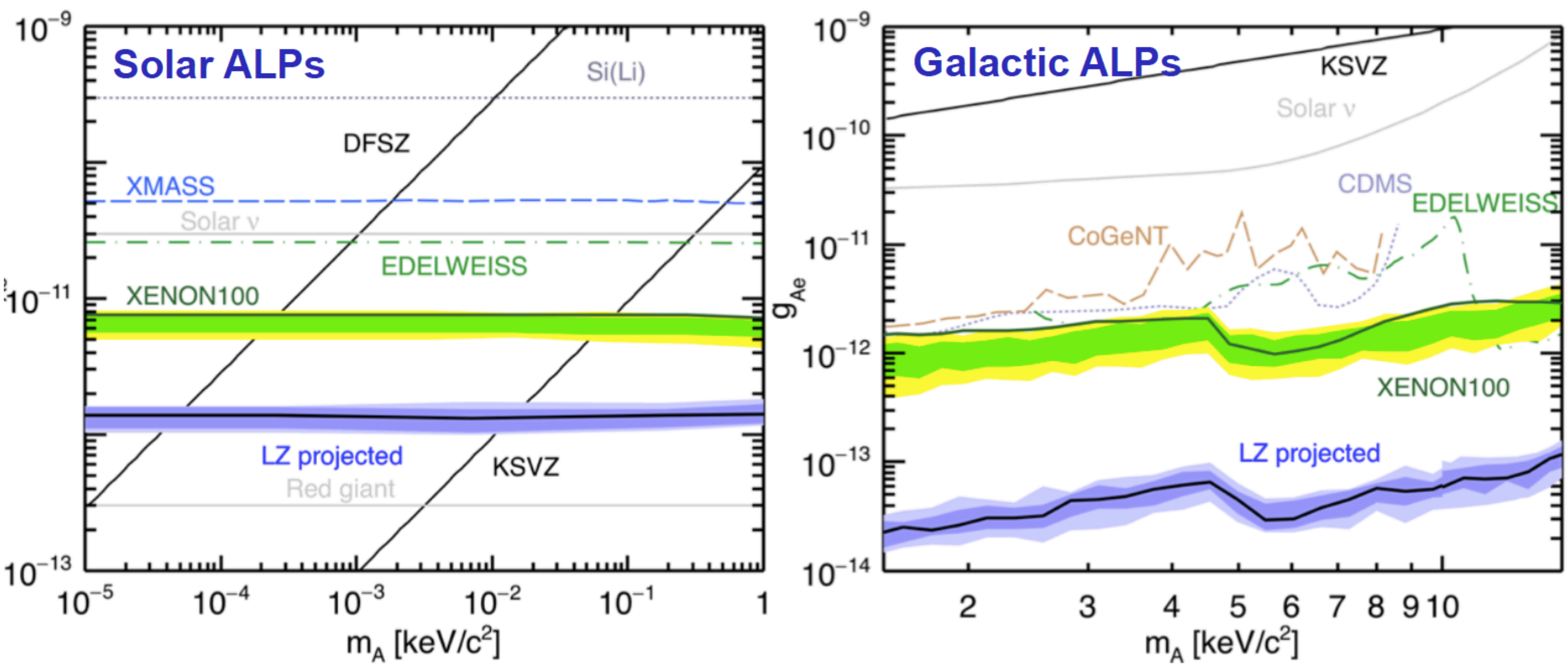
- Spin-dependent WIMP-neutron cross-section on ^{129}Xe and ^{131}Xe
- complementary to collider searches at lower masses

LXe TPCs: sensitivity to axion-like particles (ALPs)

Axion-Like Particles (ALP)

- **Sensitivity to axions and ALPs via the axioelectric effect:**
  - **Nonrelativistic galactic ALPs (DM candidates)**
  - **ALPs emitted by bremss/Compton in the Sun**
- **Technique pioneered in Xenon100 (see arXiv:1404.1455)**

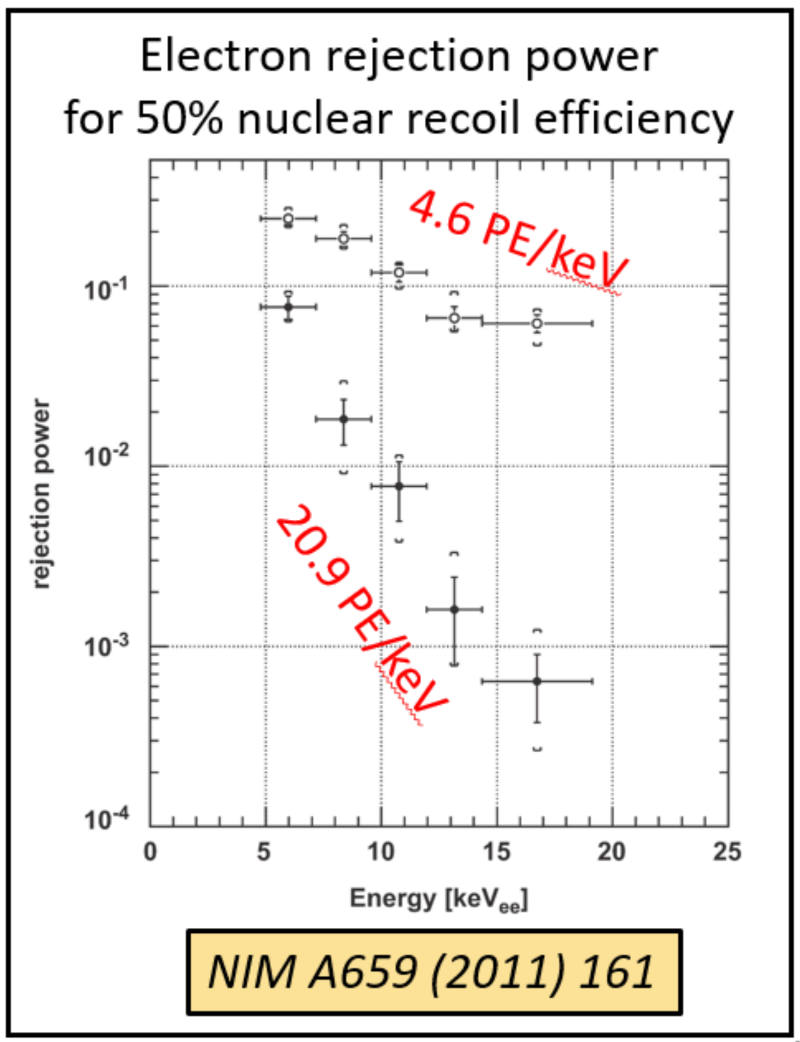
adapted from
Maria Elena Monzani

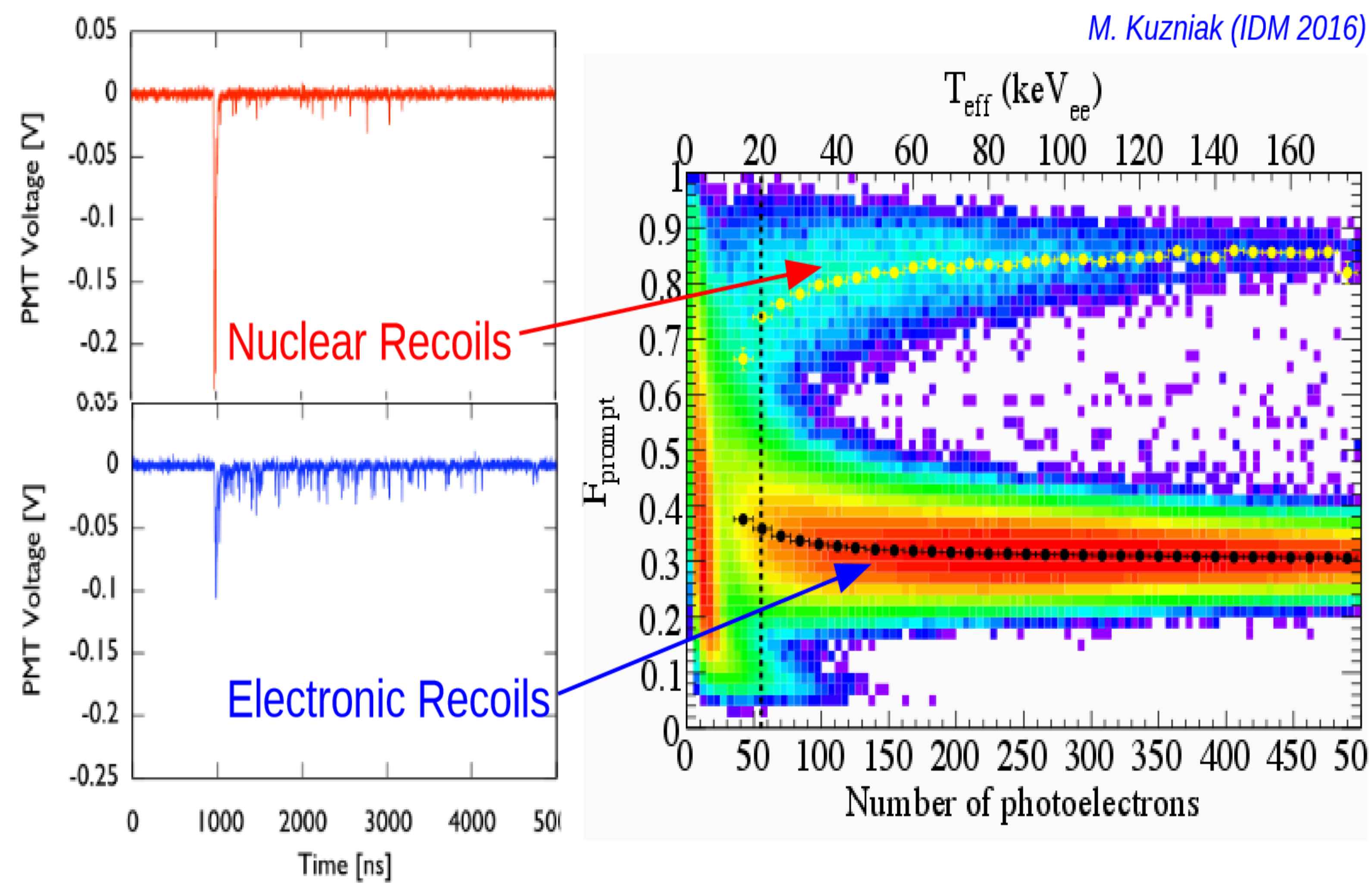


LZ TDR, in preparation

PSD in LXe (XMASS R&D)

PSD study with a small setup





XMASS: annual modulation results

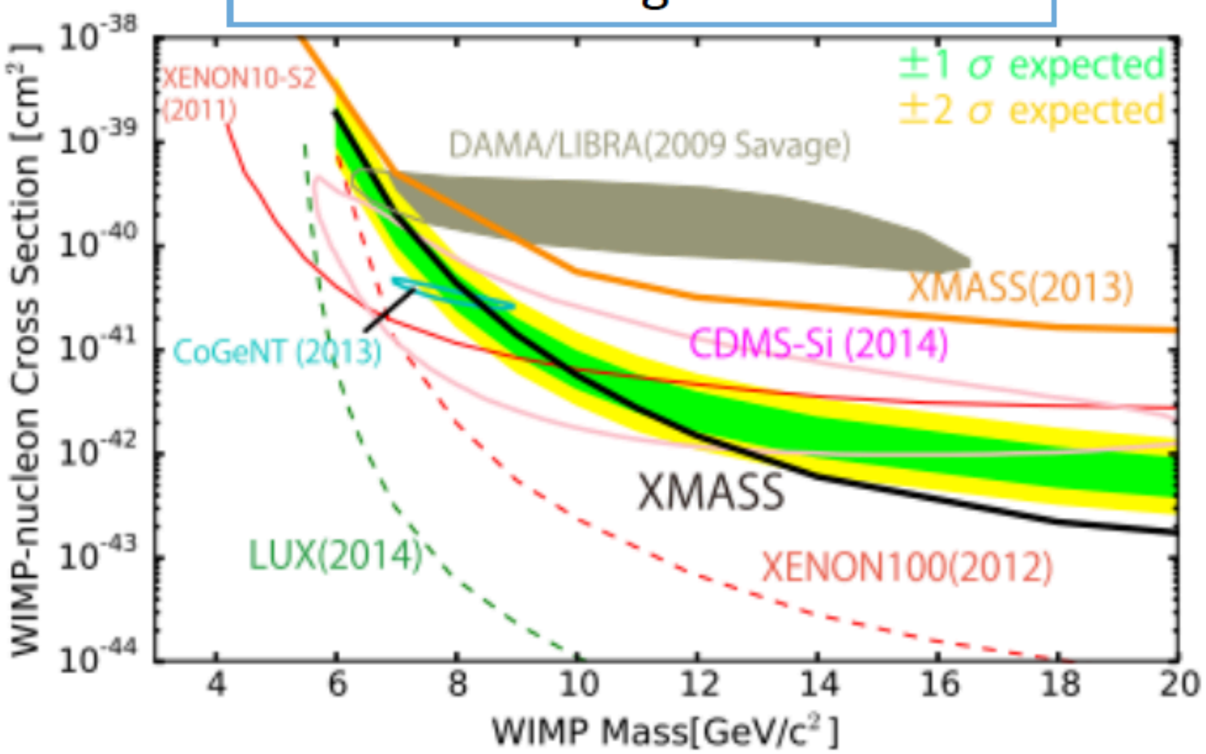
adapted from Shigetaka Moriyama

- DAMA/LIBRA (14 cycles)
  ~250 kg NaI(Tl): **1.33 ton×yr, no PID**
- XMASS-I (1.5 cycle)
  - ~800kg LXe: **0.82 ton×yr, no PID**

  Phys. Lett. B 759 (2016) 272

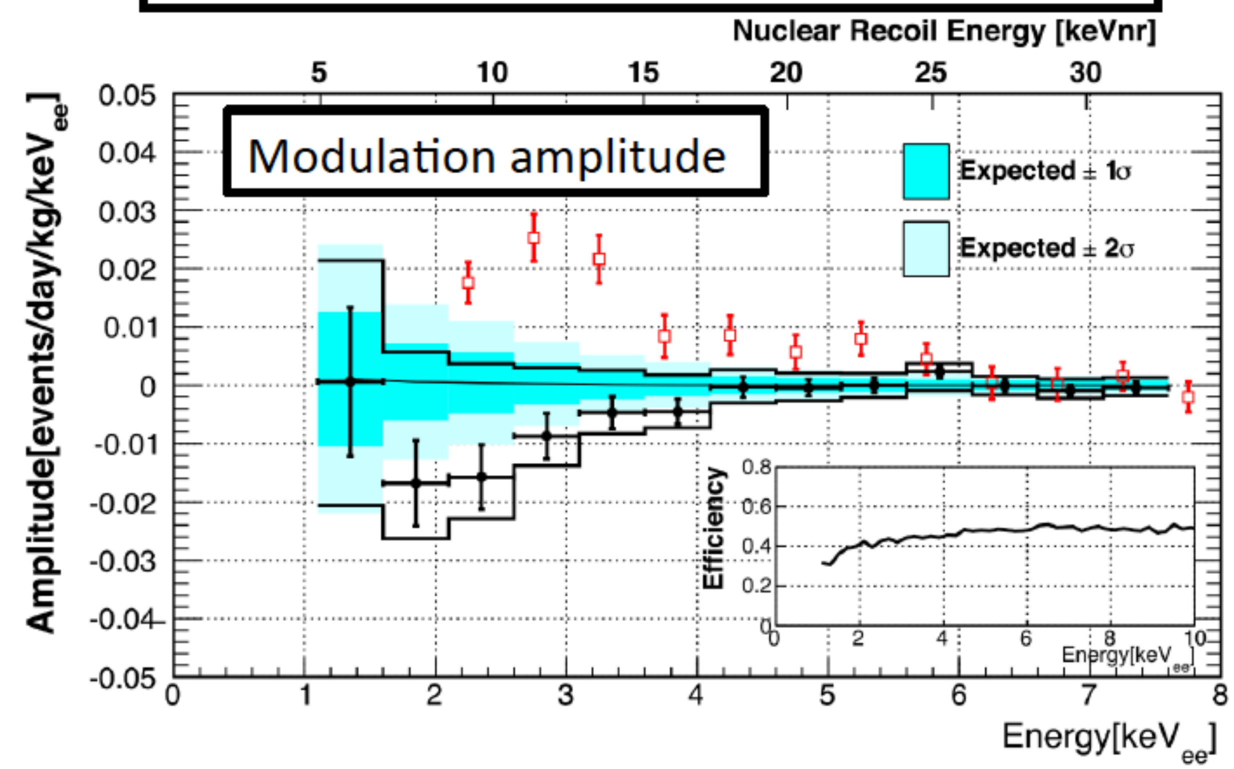
First extensive annual modulation search proving this region with an exposure comparable to DAMA/LIBRA.

Result assuming WIMP model



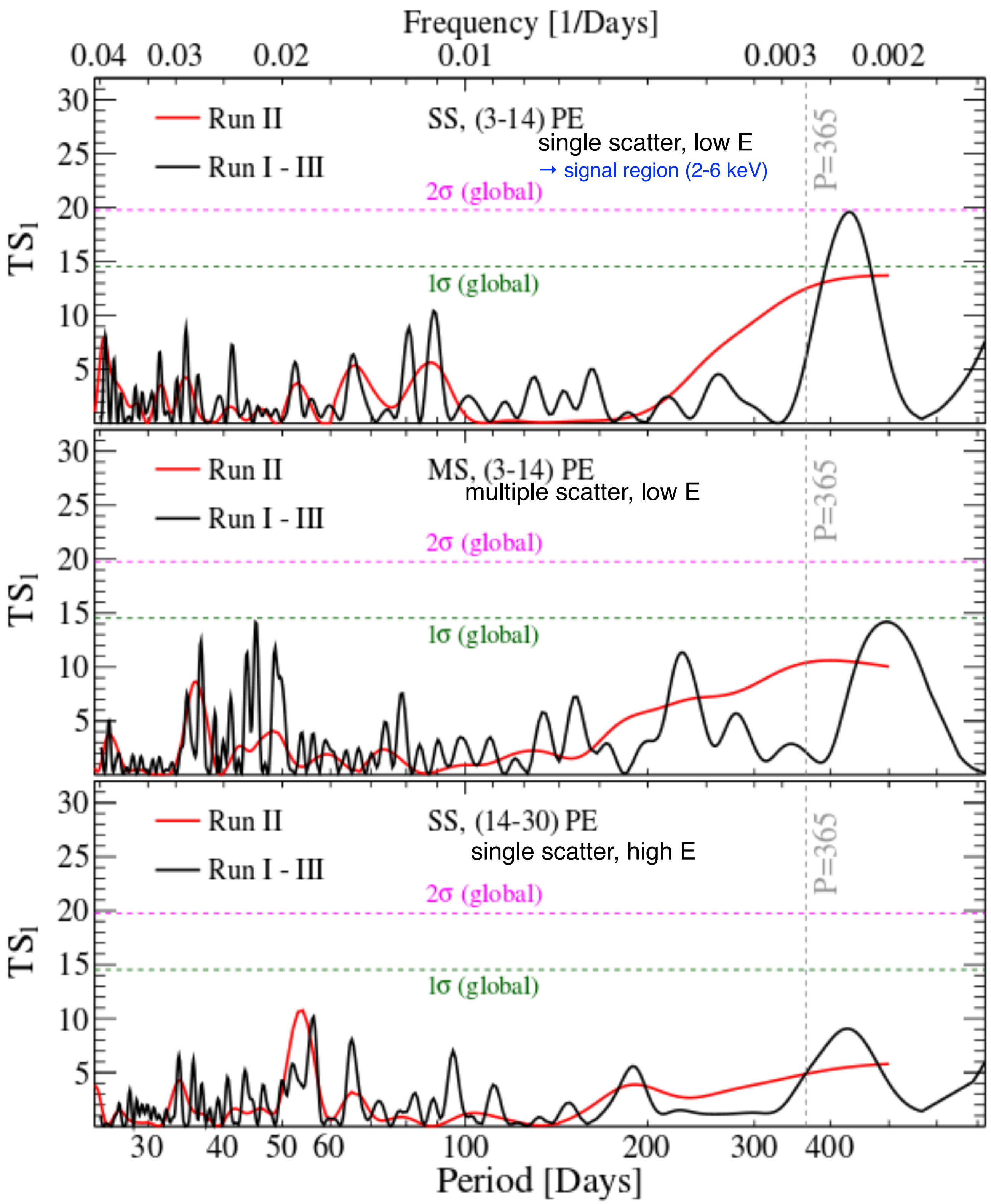
Results on individual energy bin

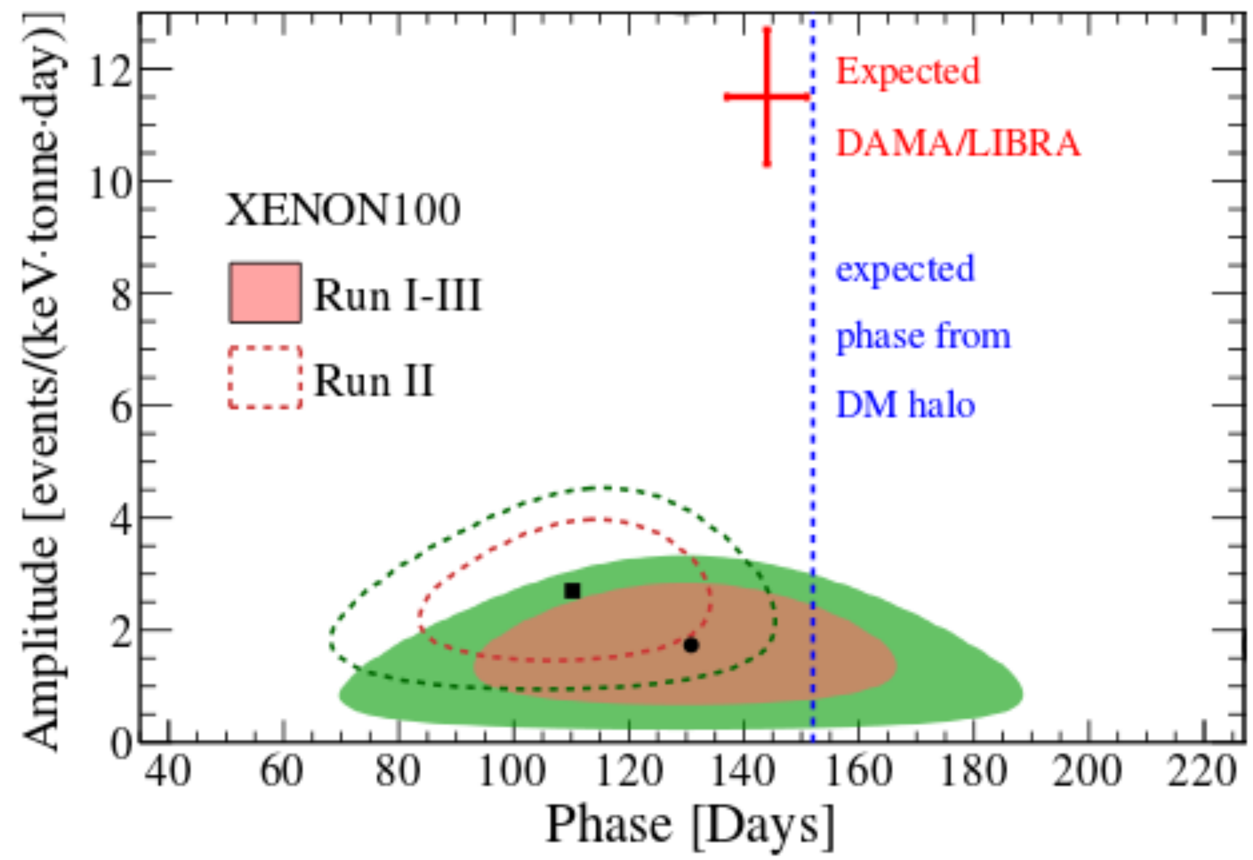
XMASS
90% C.L. positive and negative upper limits
DAMA/LIBRA



XENON100 — 4-year annual modulation

adapted from Marc Schumann

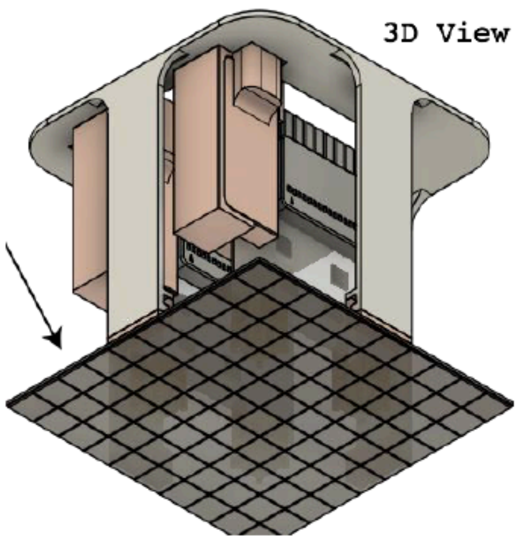




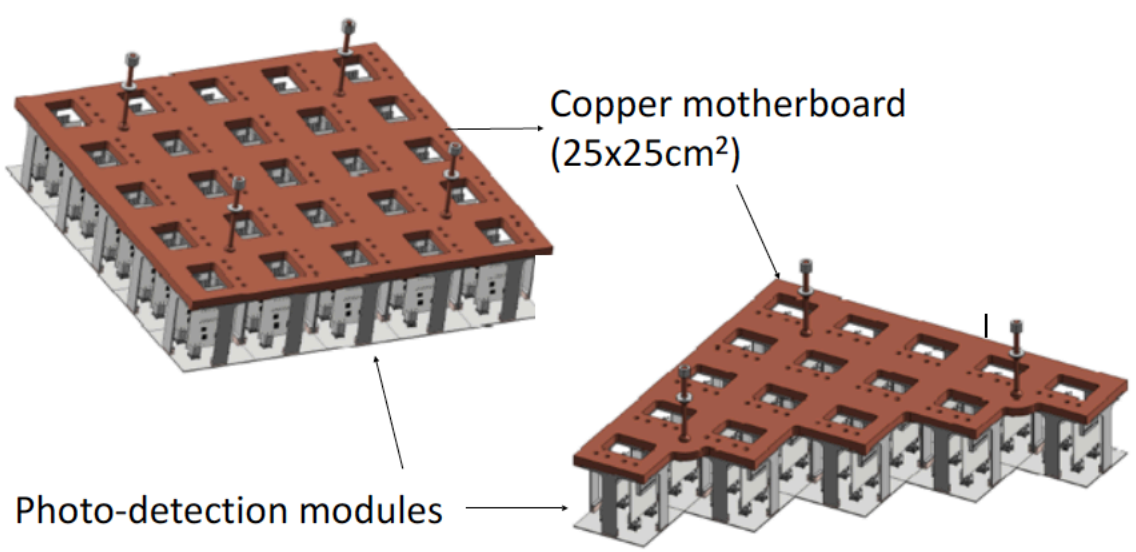
- improves upon previous analysis PRL 115, 091302 (2015)
- no significant modulation observed
- Dark matter explanation of DAMA/ LIBRA
- signal excluded @ 5.7σ

DS-20k SiPMs

- Photon Detection Efficiency (PDE): 45% requirement met and surpassed
- Dark Count Rate (DCR): 0.1 Hz/mm^2 requirement met and surpassed
- Challenge in tiling due to 50 pf/mm^2 capacity. Signal-to-Noise Ratio (SNR) rapidly decreases with increasing surface. The steps:
    - 2×2 cm^2 tile: fully demonstrated September 2016
    - **5×5 cm^2 tile: fully demonstrated March 2017**



DS-20K SiPM tile



ARIA: isotopic purification via cryogenic distillation

Prototype column allows 10 kg/day purification

Full column: 100 kg/day x10 reduction per pass