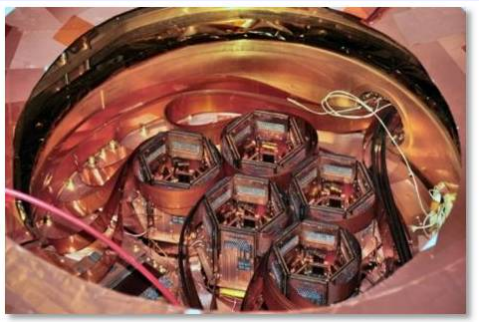
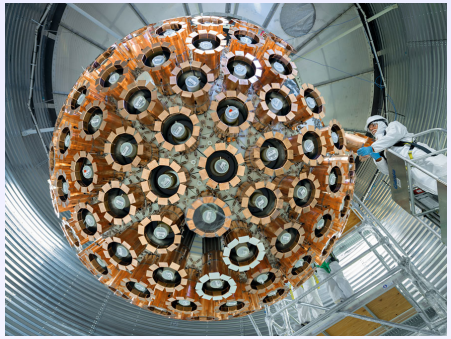
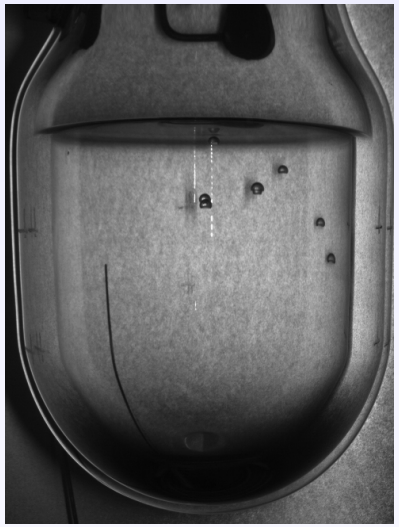
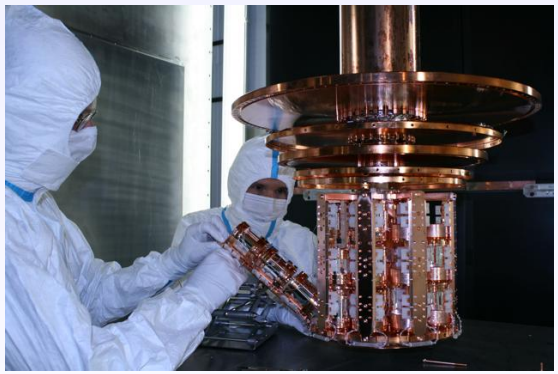
Rensselaer

Status of Dark Matter Direct Detection









Ethan Brown
Rensselaer Polytechnic Institute

RPI Colloquium – Feb 4th, 2015

Outline

- Introduction
- High Mass WIMPs
  - Liquid Noble Detectors
    - Single Phase Ar
    - Dual Phase Ar and Xe
- Low Mass WIMPs
  - Cryogenic Crystals
    - CRESST, SuperCSMS
- Spin Dependent Sector
  - Bubble Chambers
    - PICO
  - Liquid Nobles Again
    - XENON / LUX

A Busy Business

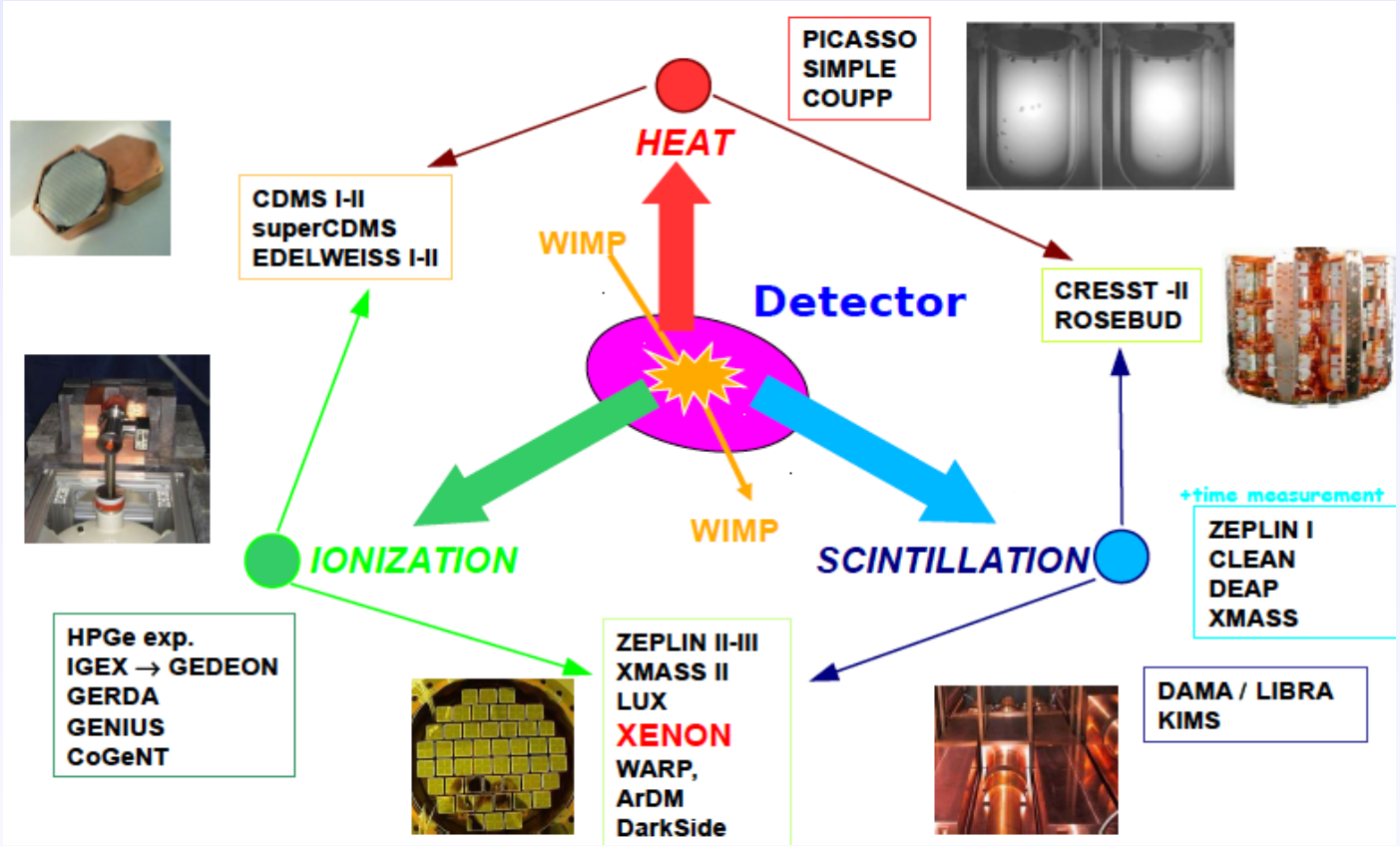
LUX/LZ
XENON100, 1T, nT
CRESST
PICO
XMASS
DEAP-3600
NEWAGE
DMTPC
DAMA/NaI
DAMA/LIBRA
NEWS-SNO
SuperCDMS-Soudan
SuperCDMS-SNOLAB
DAMIC
CDEX

KIMS-NaI
PandaX-II
DarkSide-50, 20k, ARGO
SABRE (N&S)
MiniCLEAN
CoGeNT
DRIFT
DARWIN
Edelweiss
DM-Ice
COSINE
KIMS
ANAIS
TREX-DM
NEWS

Plenty of players in the game!

Direct Detection Experiments

- Look for evidence of nuclear recoils in target material
- Low rate (few events per year)
- Small recoil energy (few keV)



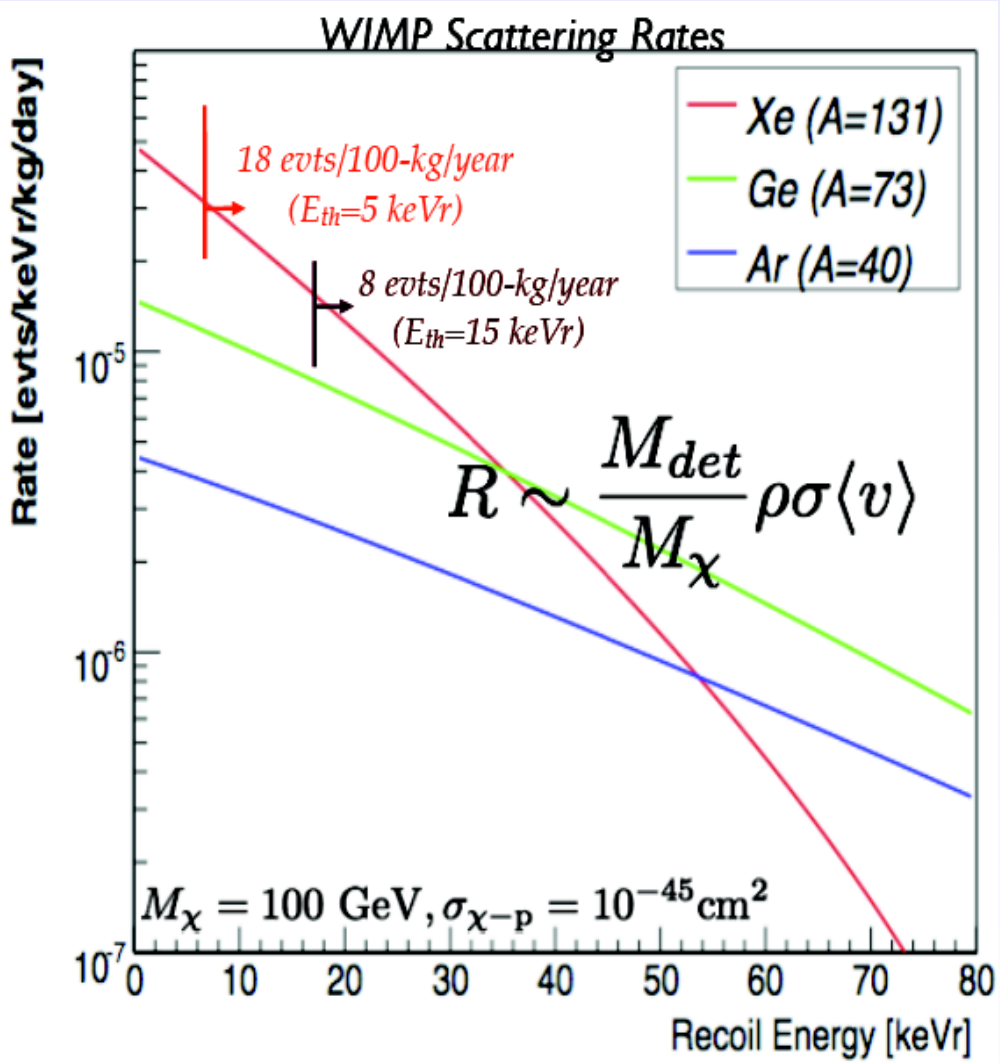
- Measure recoil energy via:
  - Light : scintillation photons
  - Charge: ionization electrons
  - Heat: phonons or bubbles
- Using multiple channels allow recoil discrimination

Target Materials

- Rate scales with A^2
  - Heavy targets favored
    - Xe, Ge, I, W
- Form factor suppression at higher recoil E
  - High threshold experiments
  - Can win with lighter mass

- Large target mass needed
- Liquid nobles popular
  - Easily scalable
  - Liquid Xe and Ar

But, at low WIMP mass
- Very low recoil energies
- Lower target mass favors higher recoil E
- Need extremely low threshold
- Cryogenic crystals most competitive

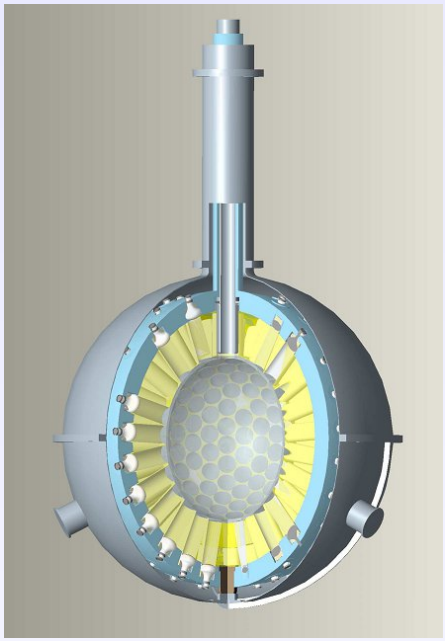


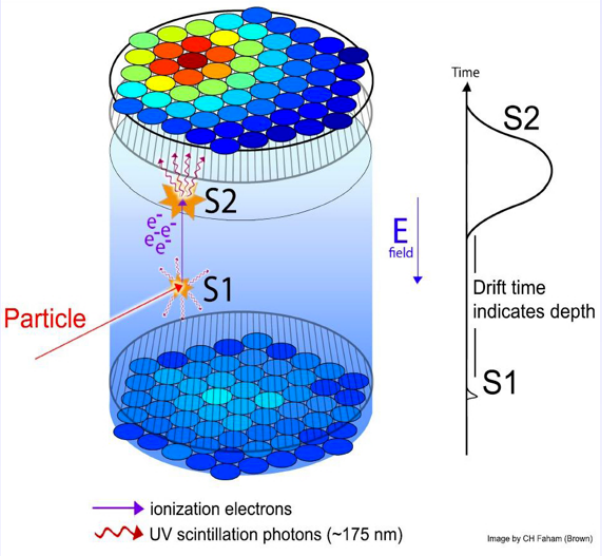
Liquid Noble Detectors

Use liquid noble gas as target
Monitor with PMTs

Single phase
XMASS, DEAP3600
Detect only scintillation light

Dual phase TPC
XENON, LUX, PandaX, DarkSide
Detect scintillation and ionization





<u>Xenon detectors</u>
- Directly detect photons (178 nm)
- Need two phase for recoil discrimination (S2/S1)
- Intrinsically radiopure
  - ^{85}Kr (removed via filter)
  - ^{222}Rn (control emanation, filter)

<u>Argon detectors</u>
- Wavelength shifter required
  - 120 → 400 nm
- Recoil discrimination with single phase
- Pulse shape discrimination
- Must remove ^{39}Ar
  - Depleted Ar from underground mines

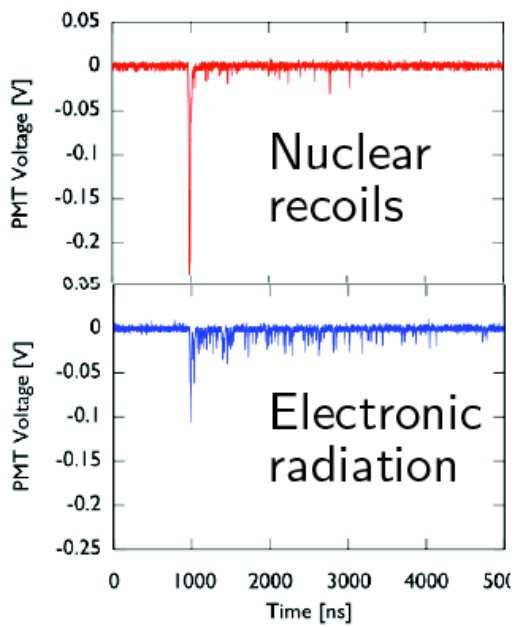
Pulse Shape Discrimination

$$\frac{dE}{dx} \longrightarrow \text{LAr dimers} \longrightarrow \text{UV light}$$

Singlet $\tau_1 = 6\text{ns}$ Triplet $\tau_3 = 1.5\mu\text{s}$

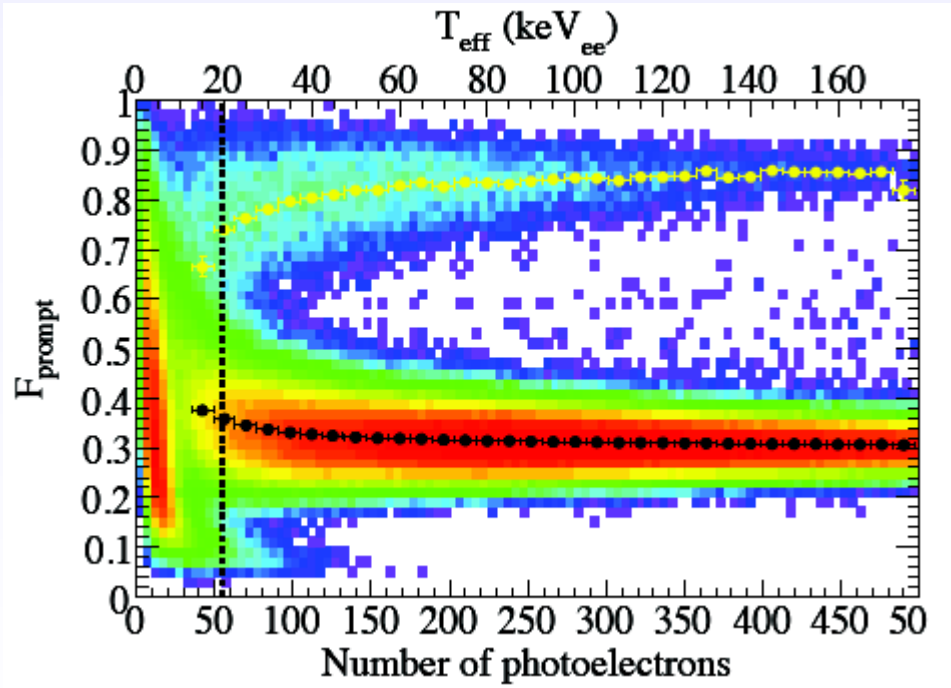
LAr allows for excellent pulse shape discrimination (PSD)

$$\text{Fprompt} = \frac{\text{Prompt Light}}{\text{Total Light}}$$



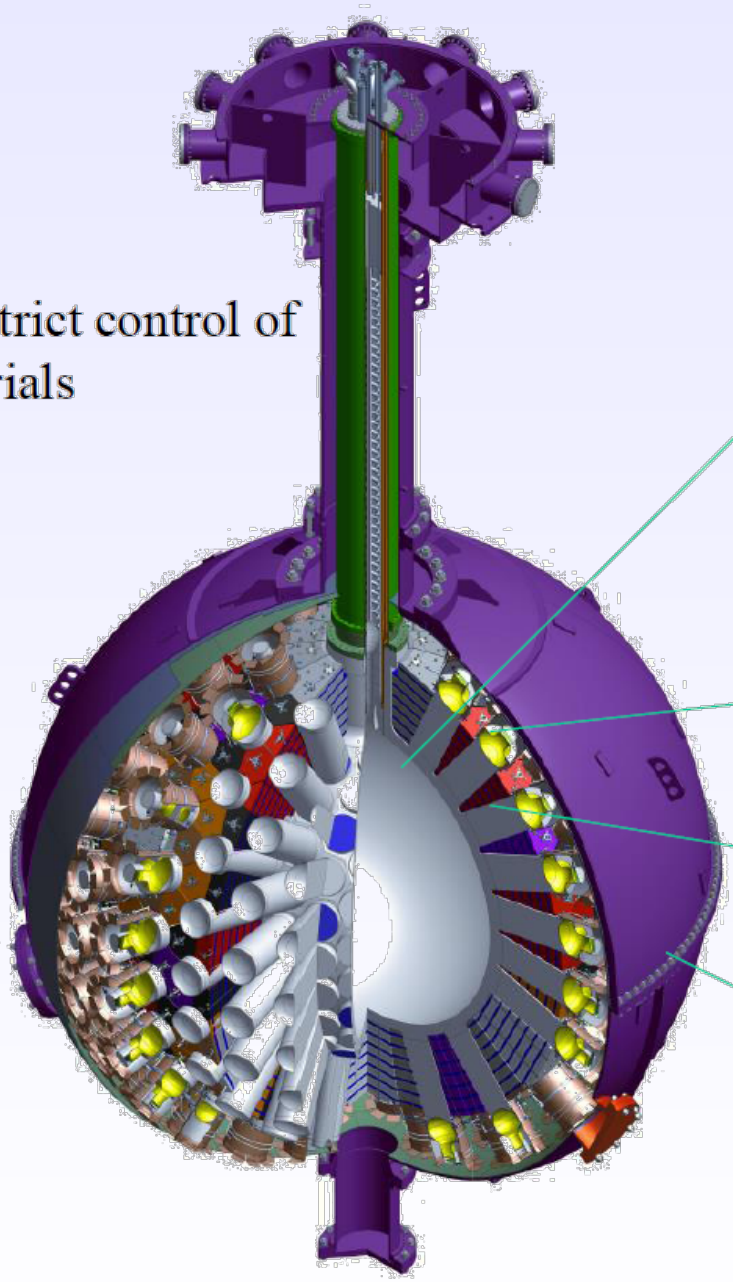
$$\frac{\text{Singlets}}{\text{Triplets}} = 3$$

$$\frac{\text{Singlets}}{\text{Triplets}} = 0.3$$



DEAP 3600

DEAP-3600 Detector



very strict control of materials

3.5 meters

3600 kg argon in sealed ultraclean Acrylic Vessel (1.7 m ID)

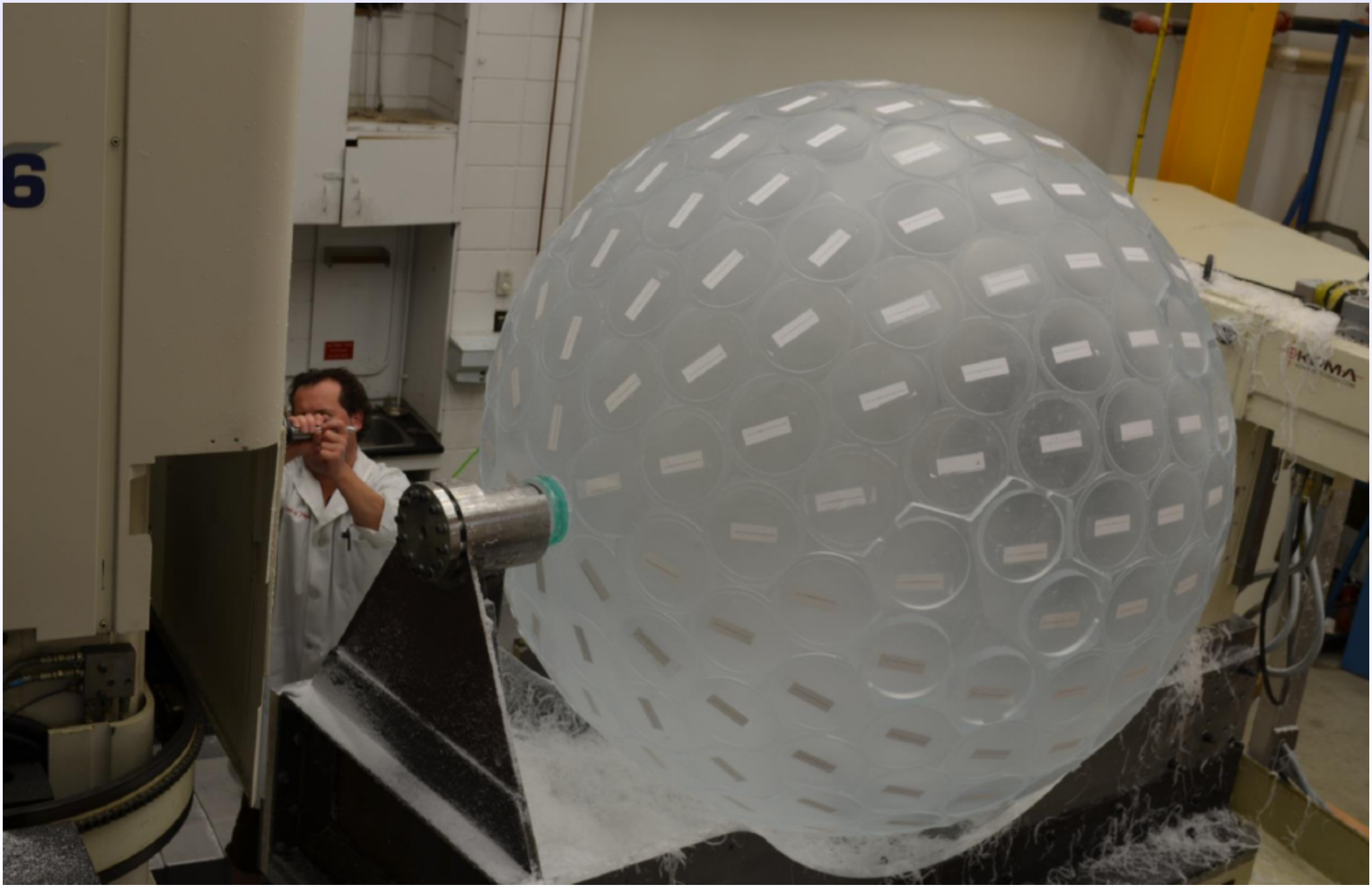
Vessel is "resurfaced" in-situ to remove deposited Rn daughters after construction

255 Hamamatsu R5912 HQE PMTs 8-inch (Light Sensors)

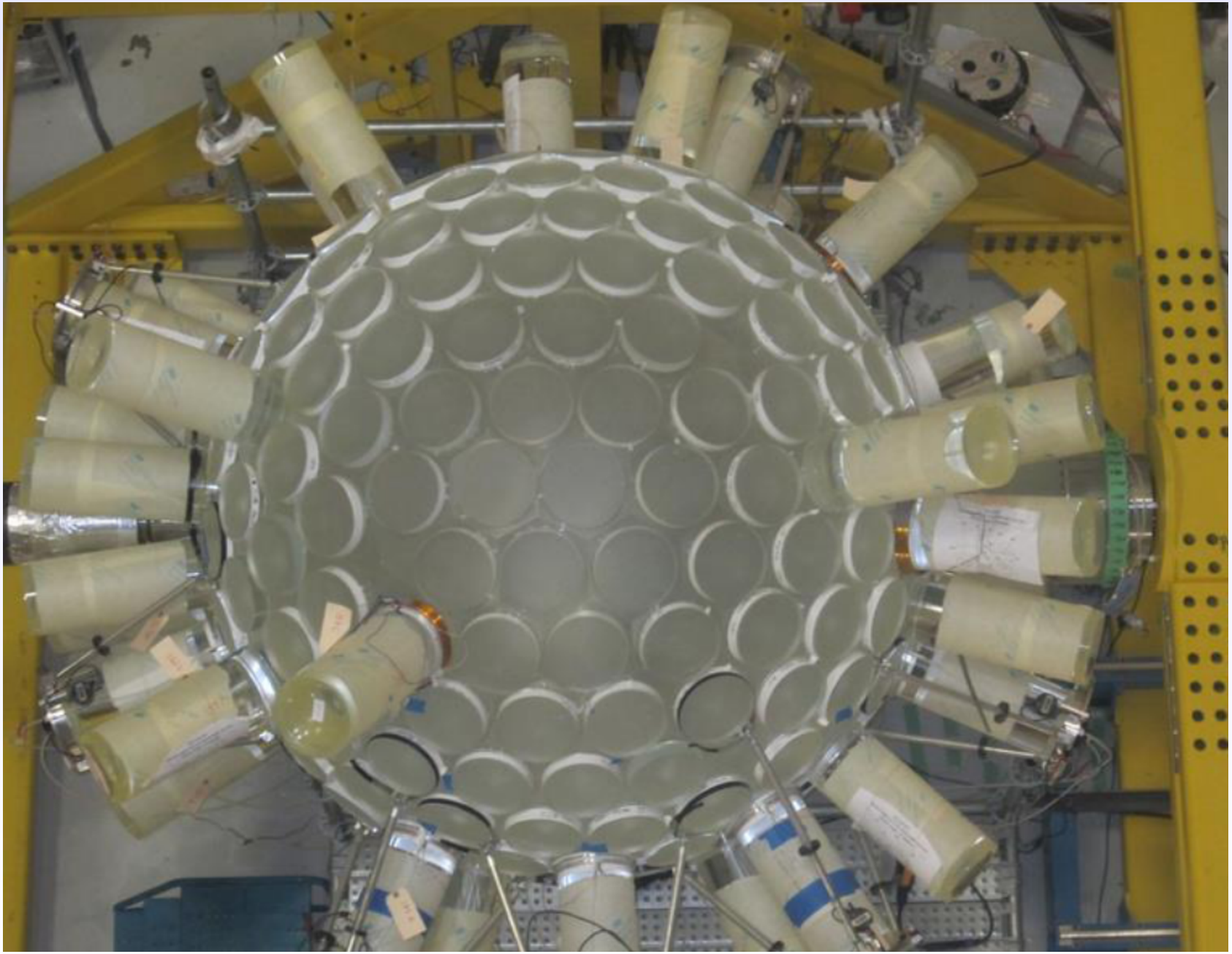
50 cm light guides + PE shielding provide neutron moderation

Scintillation light only – PSD for background discrimination

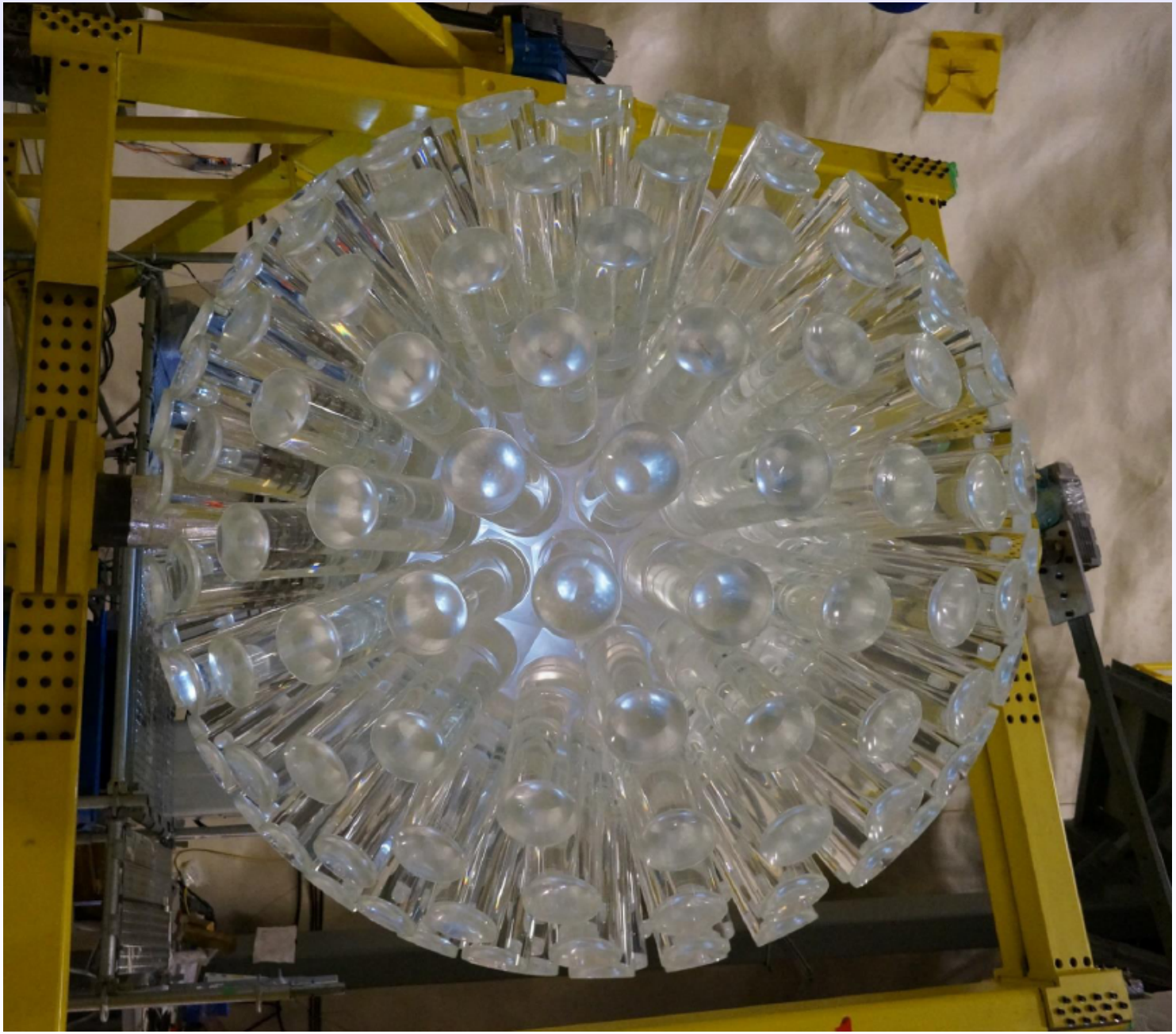
Acrylic Vessel



Bonding Light Guides



Completed Vessel



Physics Reach of DEAP 3600

Background budget for 3 live years data

Background	Raw No. Events in energy ROI	Fiducial No. Events in energy ROI
Neutrons	30	< 0.2
Surface α	150	< 0.2
^{39}Ar β (natural argon)	1.6×10^9	< 0.2

- 1000 kg fiducial volume
- 3 years live time
- 3000 t-yr exposure
- < 0.6 total background events
- Sensitivity: 10^{-46} cm^2 @ 100 GeV

Neutrons
- Dominated by PMTs, alpha-n, and rock
- Shielded by light guides, filler blocks, and water

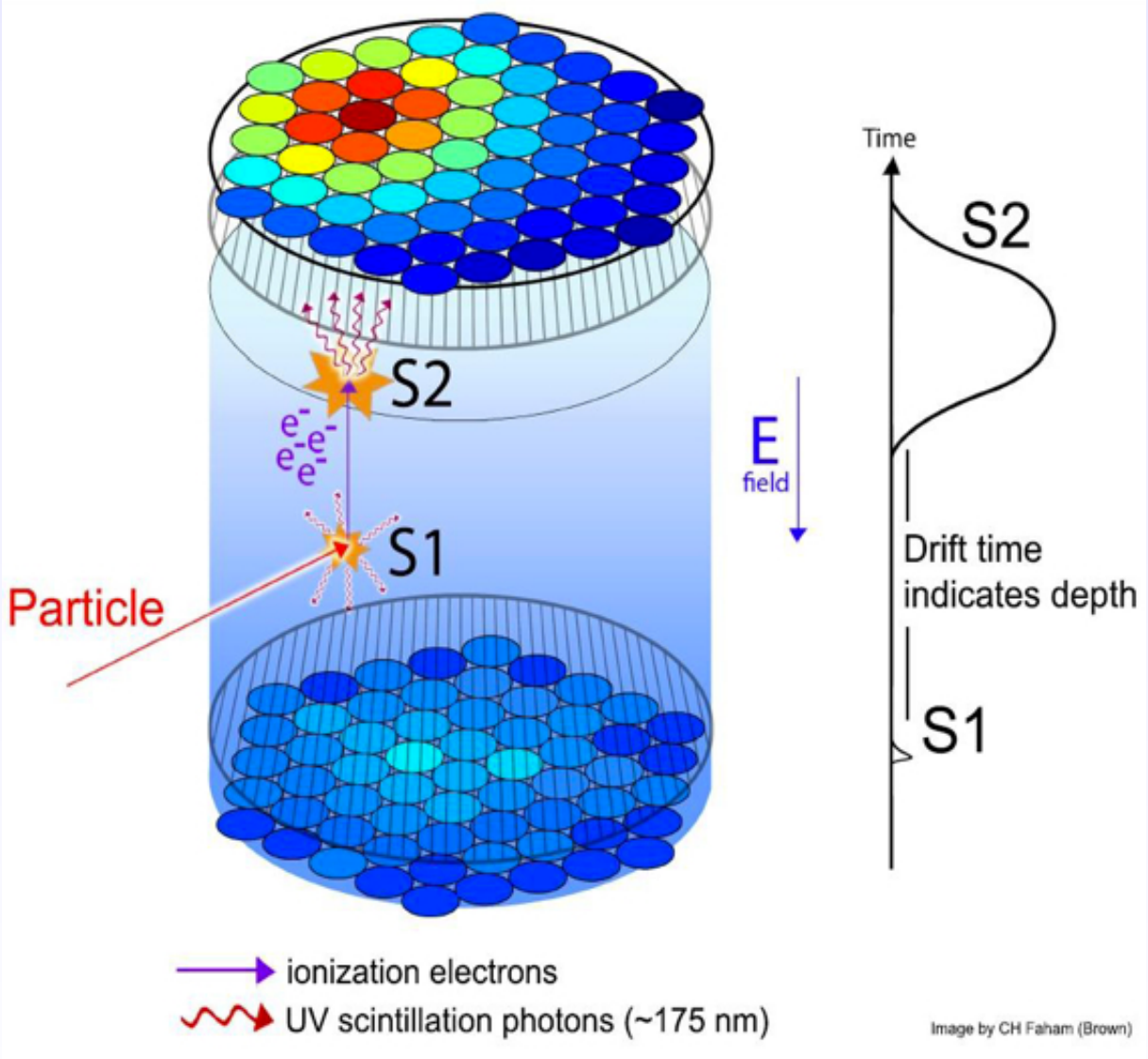
Surface
- Very clean acrylic assessed to have ^{210}Pb < 10^{-19} g/g
- Inner surface sanded and kept in Rn free environment

^{39}Ar
- Pulse shape descrimination

Dual Phase TPC

- Liquid phase target
- Gas phase on top
- Prompt scintillation measured with PMTs (S1)
- Ionization drifted to the top, extracted into gas
- Accelerated in high field to produce electroluminescence
  - Also detected by PMTs (S2)

- Time difference gives depth
- Localized hit pattern of S2 gives x, y
- Ratio of charge to light (S2/S1) gives recoil discrimination

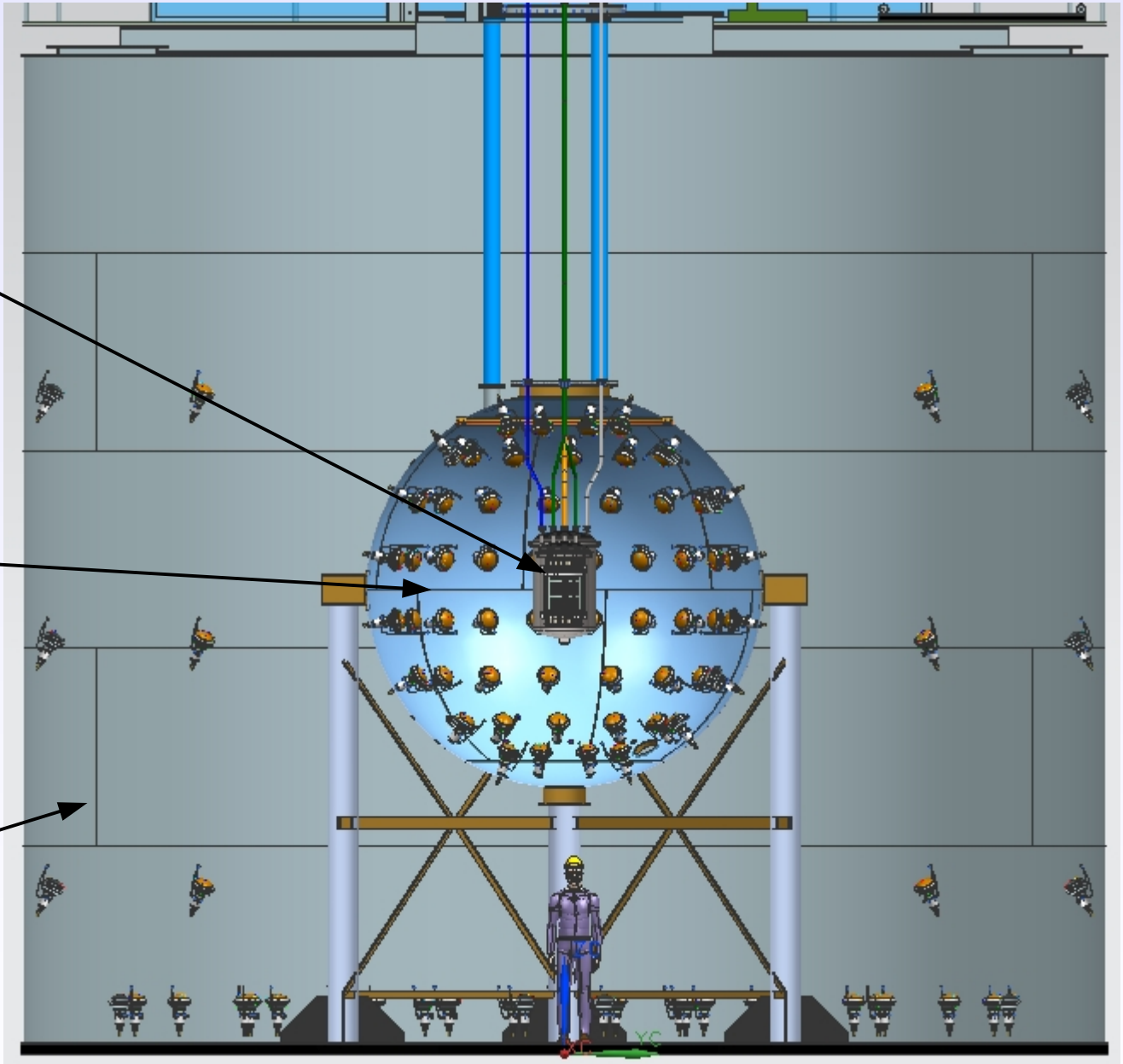


DarkSide-50

- Liquid Ar TPC
- 153 kg ^{39}Ar-depleted
- Underground Ar target
- Dual phase TPC

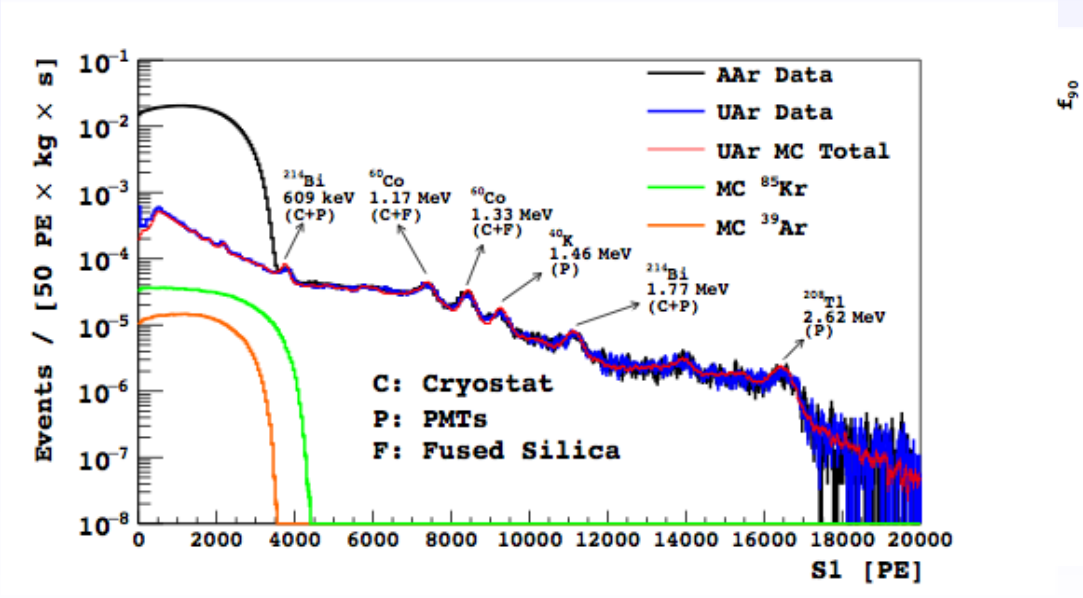
- 4m diameter
- 30 T liquid scintillator
- Neutron veto

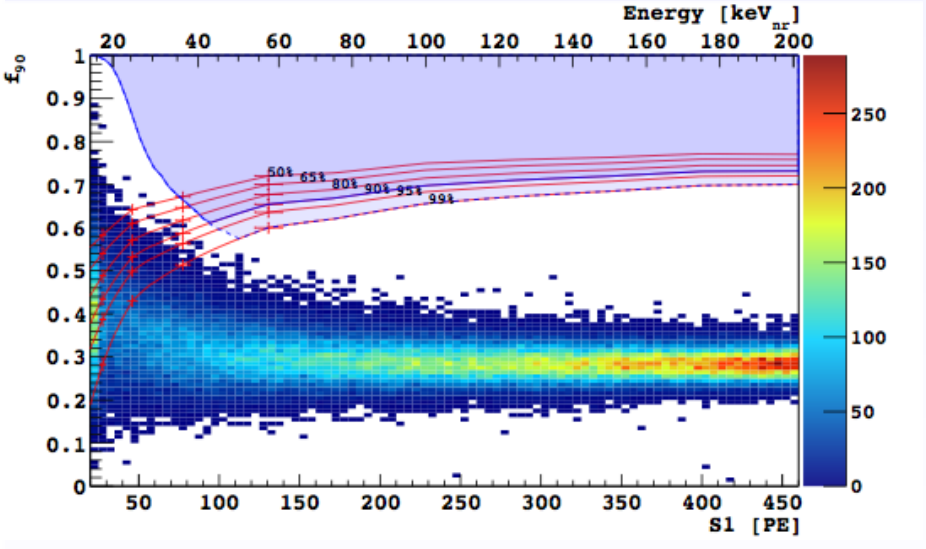
- 1000 T Water Cherenkov muon veto
- 10m high
- 11m diameter



DarkSide-50 Milestones

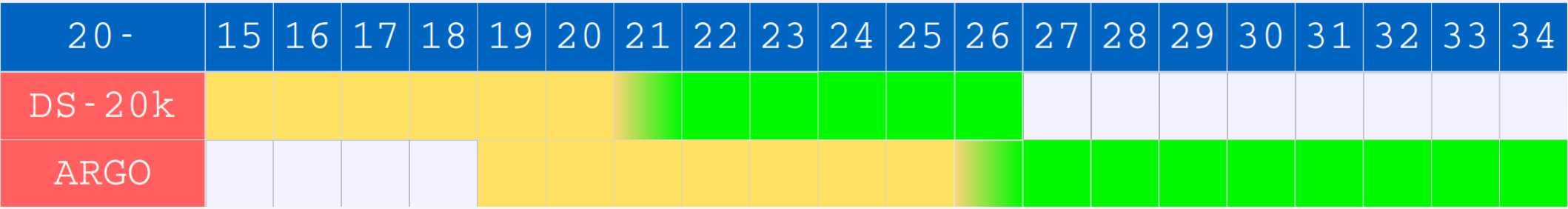
- Oct 2013: three detectors commissioned, cryostat filled with Aar
- Oct 2014: WIMP search results with 1422 kg d AAr exposure
- Fall 2014: Calibration campaign
- Winter 2014: Refurbishment of LSV, ^{14}C rate from 150 kHz to 0.3 kHz
- Apr 2015: Cryostat drained and filled with 153 kg of Uar
- Oct 2015: WIMP search results with 2616 kg d UAr exposure





DarkSide 20k and ARGO

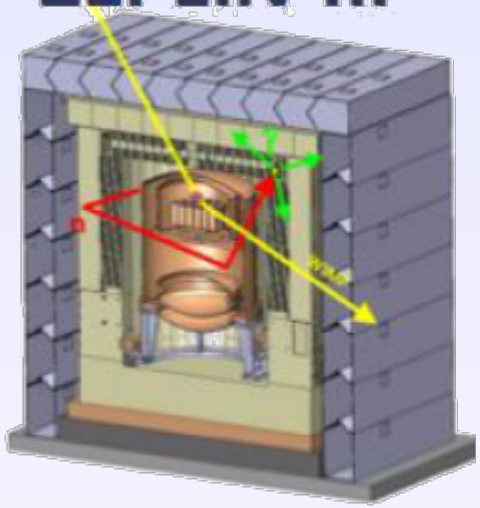
DarkSide-20k
- 20 ton fiducial dark matter detector
- Start of operations at LNGS by 2021
- 100 t-year background-free search for dark matter



ARGO
- 300 ton depleted argon detector
- Start of operations at LNGS by 2026
- 1000 t-year background free search for dark matter
- Precision measurement of solar neutrinos

LUX / LZ

ZEPLIN-III

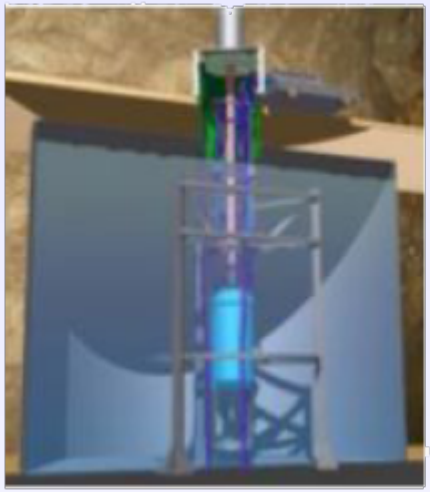


6 kg LXe fid

ZEPLIN pioneered WIMP-search with 2-phase Xe 3.9×10^3 pb/n

+

LUX

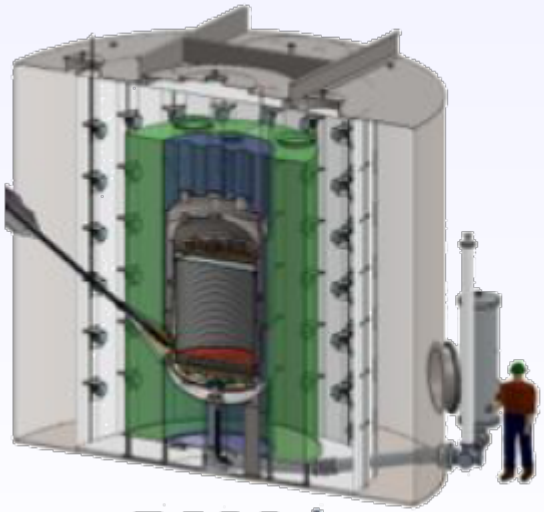


100 kg

Current world leader: $\sim 6 \times 10^{-10}$ pb/n and counting

→

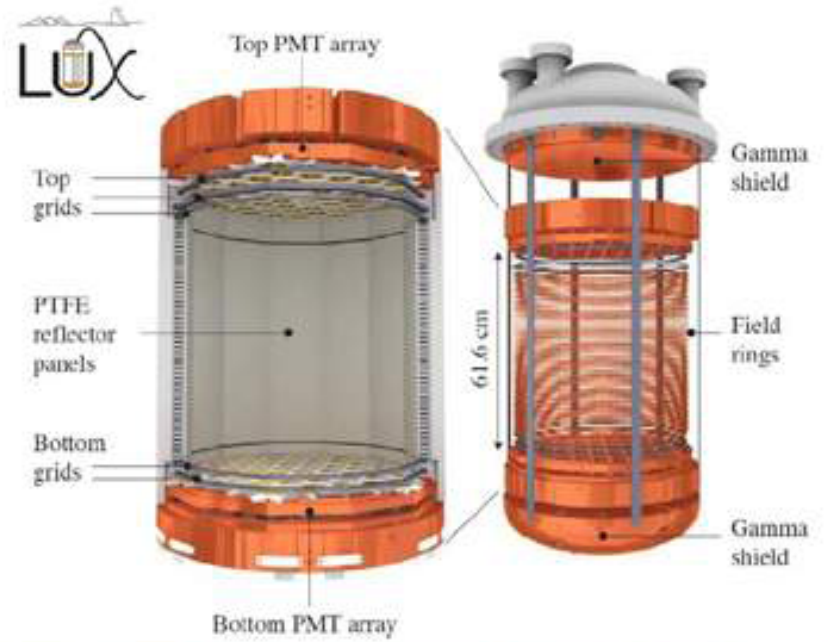
LZ

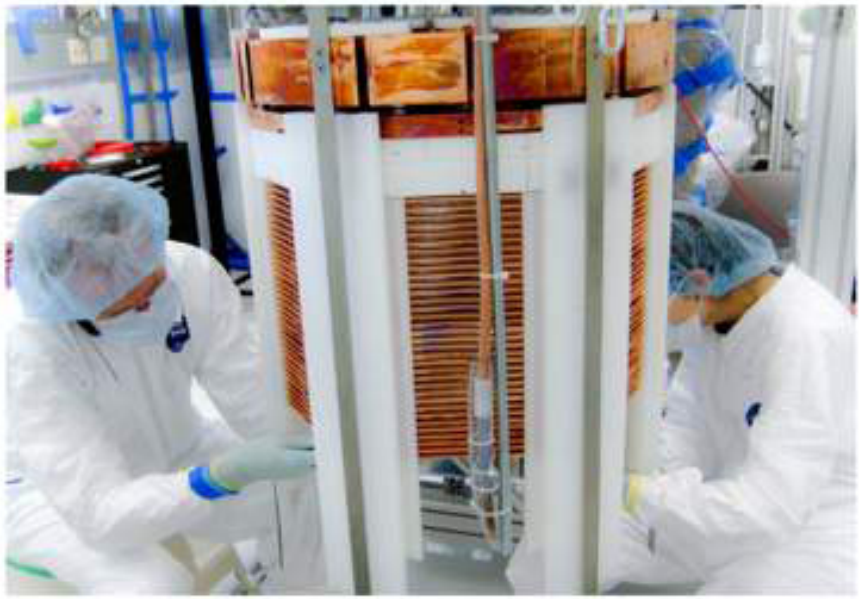


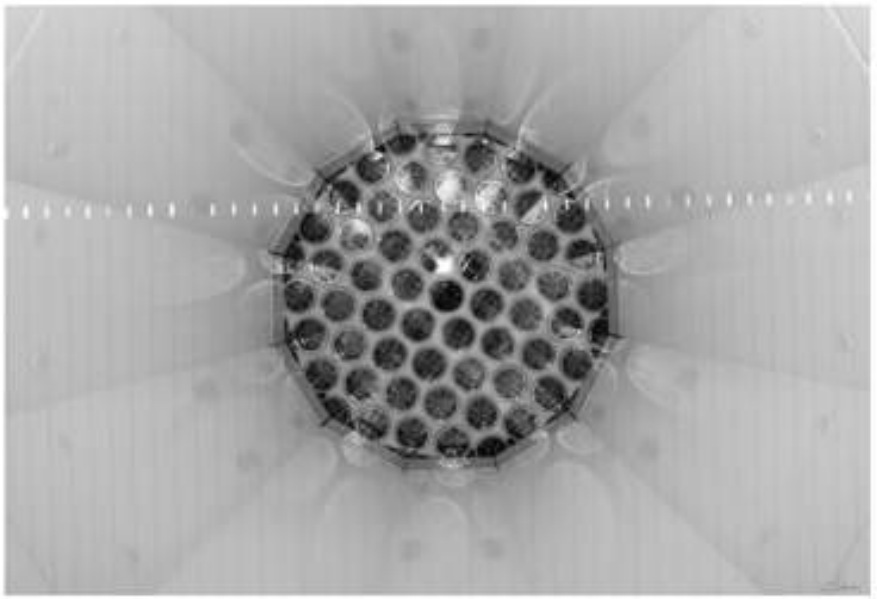
5600 kg

Scale-up using demonstrated technology and experience for low-risk but aggressive program

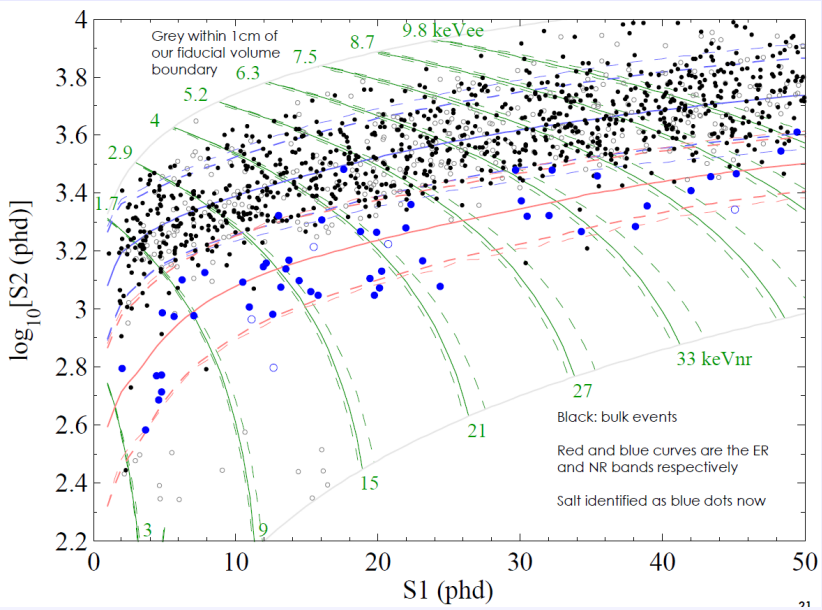
LUX Detector

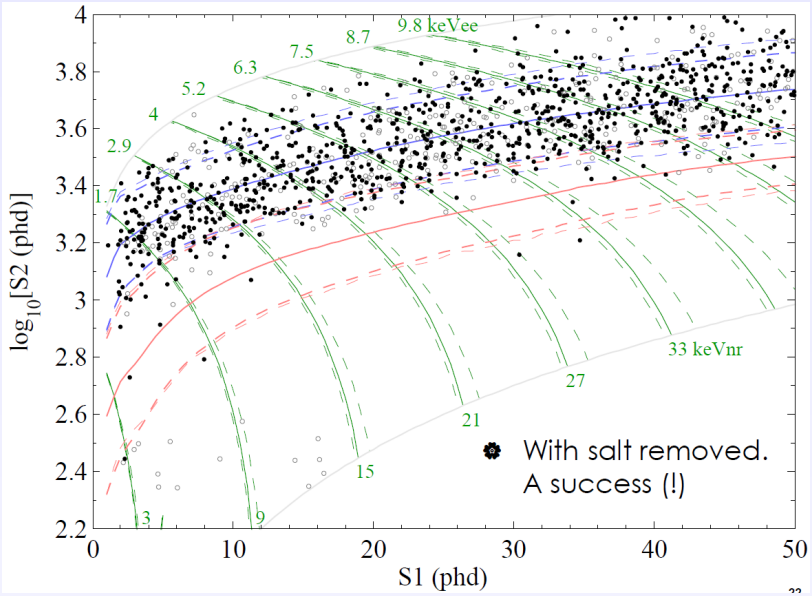






LUX Results

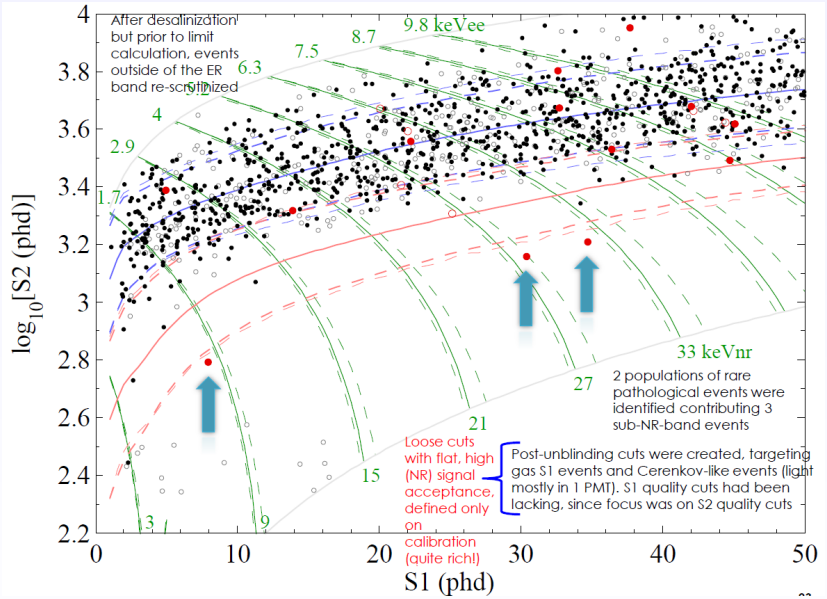




Salted DM search

- Added unknown # of fake DM events (salt)
- Injected at raw waveform level
- Built from calibration data
- Mitigates bias while allowing scrutiny of individual events

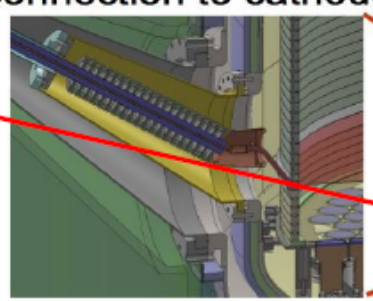
- 3 Events remain after desalination
- Very unlikely hit patterns
- Removed by post-analysis
- Limit: 2.2 X 10^{-46} cm^2 @ 50 GeV

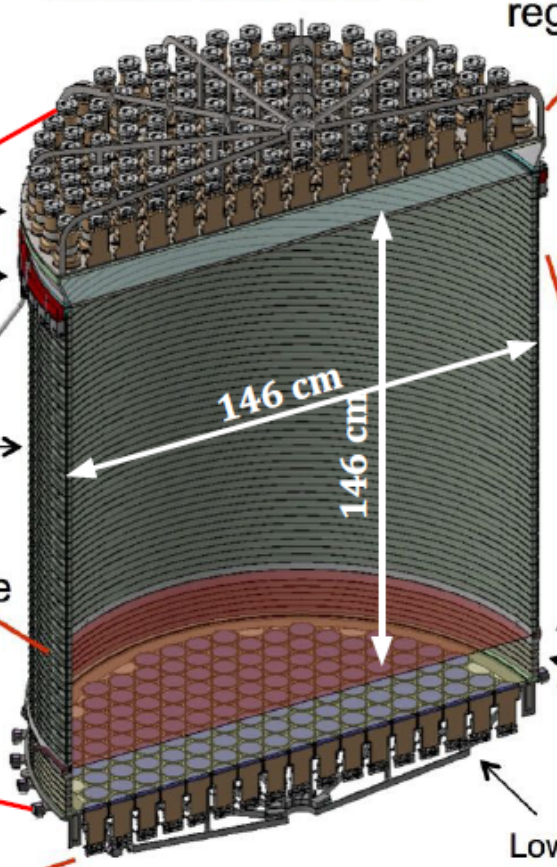


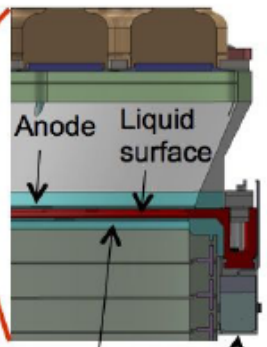
LZ

- 7-tonne active region (cathode → gate), 5.6 tonne FV
- 2 × 241 3" φ PMTs (activity ~mBq; high QE)
- TPC lined with high-reflectivity PTFE ($R_{PTFE} \geq 95\%$)*
- Instrumented "Skin" region optically separated from TPC

Low background Ti vessels

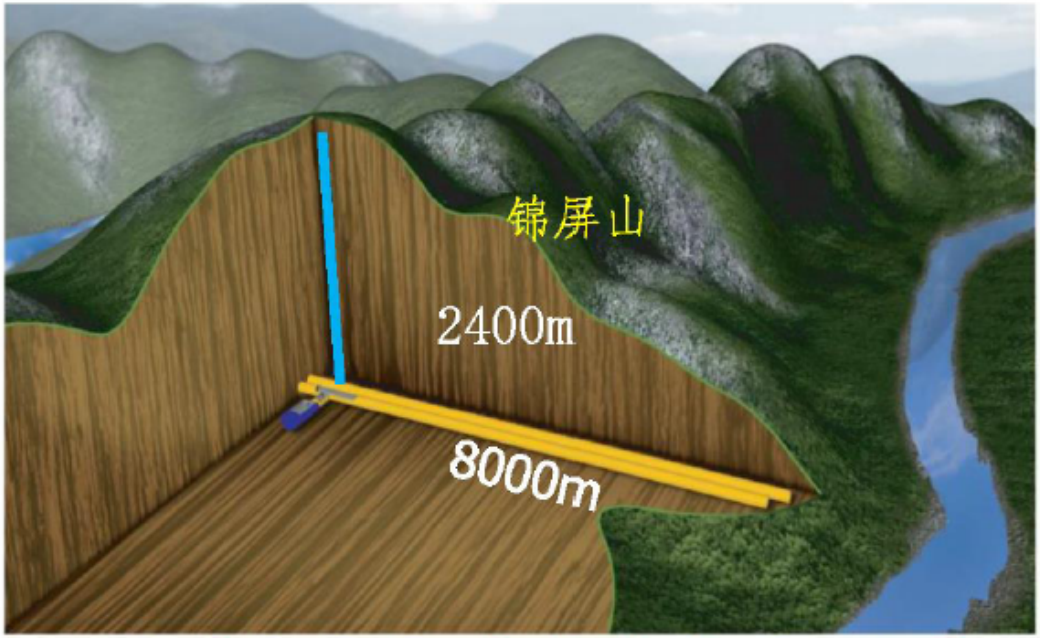


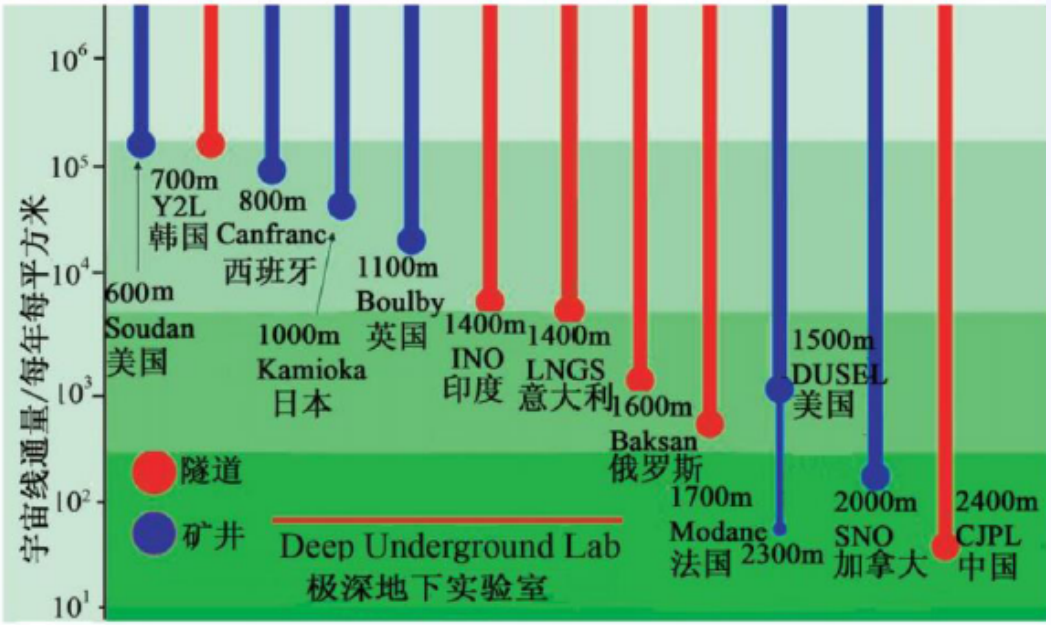




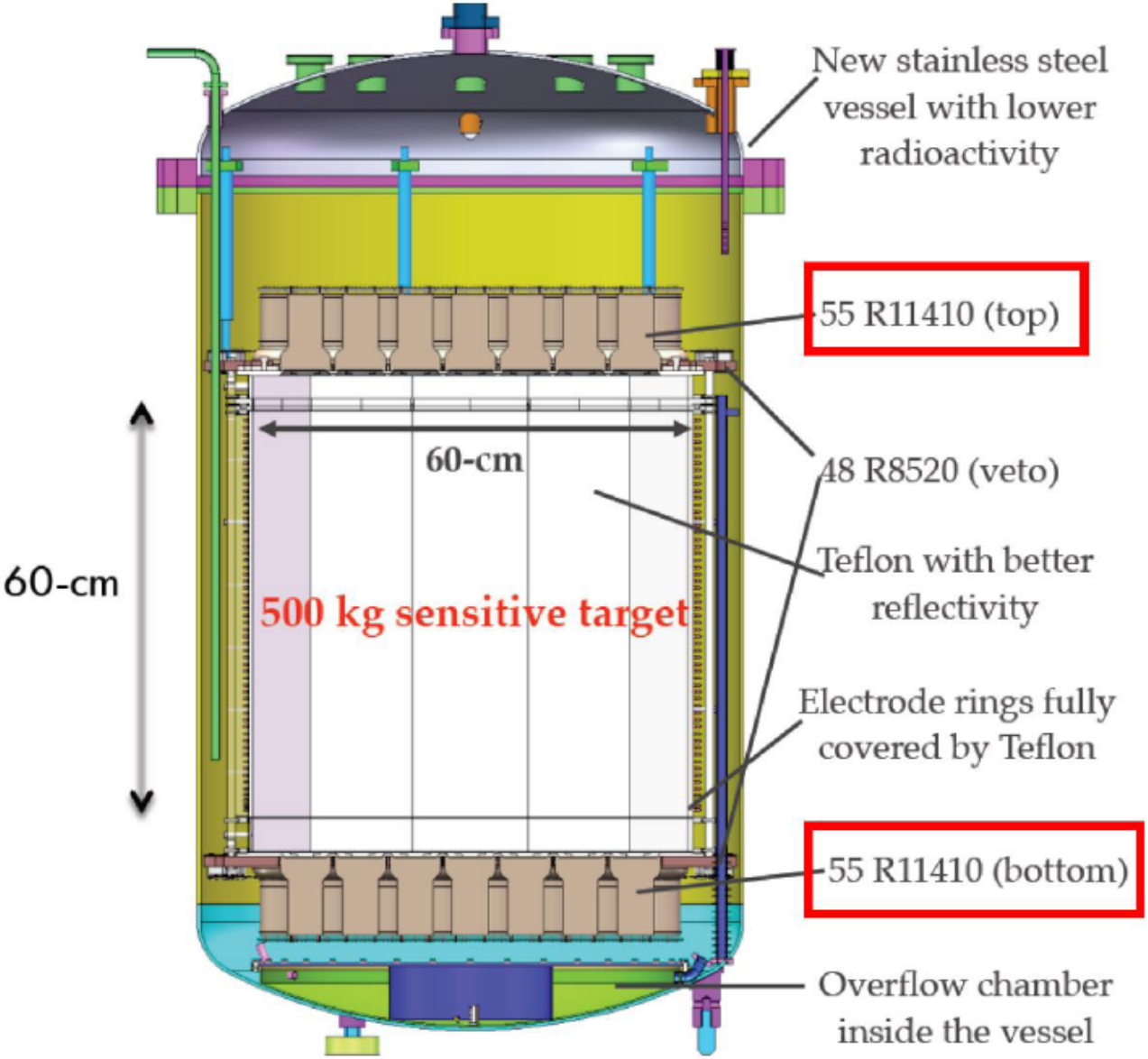
PandaX

Deepest in the world (1μ/week/m²) and Horizontal access!



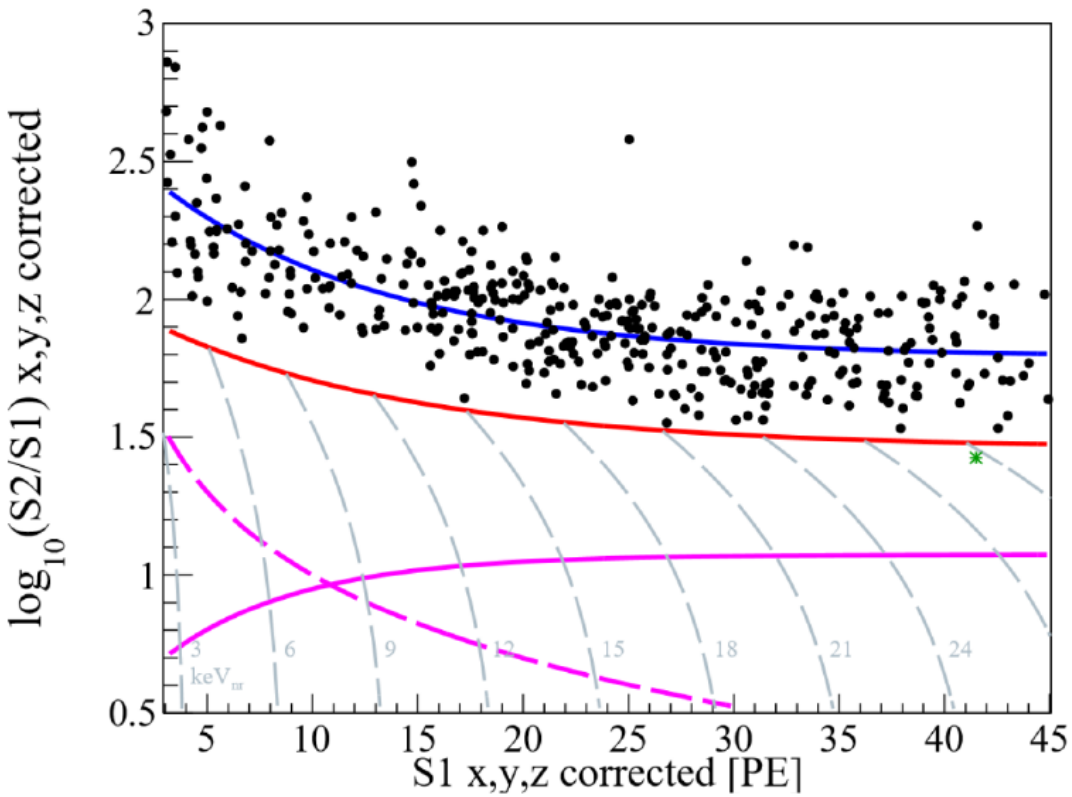


PandaX II



- New inner vessel with clean SS
- New and taller TPC with brand-new electrodes
- More 3" PMTs and improved base design
- New separate skin veto region

PandaX II Results



	ER	Accidental	Neutron	Total Expected	Total observed
Below NR median	1.2	0.84	0.35	2.4±0.7	1

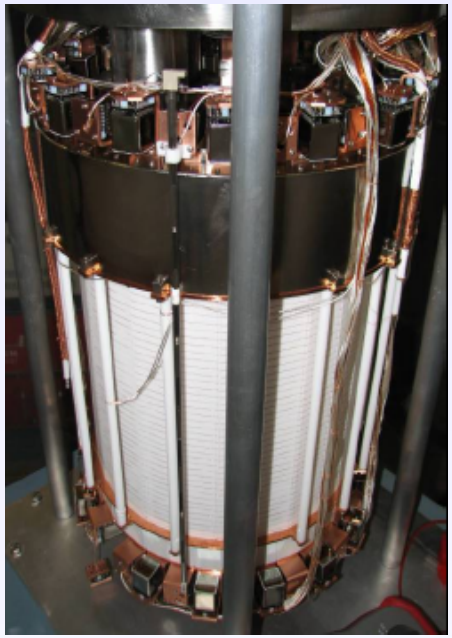
- 98.7 days live time
- Spans two runs (one with high Kr)
- 33 ton-days exposure

- 2.4 Backgrounds expected
- 1 event observed
- Tritium calibration inconsistent with ER background data

Derived limit based on results
Almost identical to LUX result
2.5 X 10^{-46} cm^2 @ 40 GeV

The XENON Program

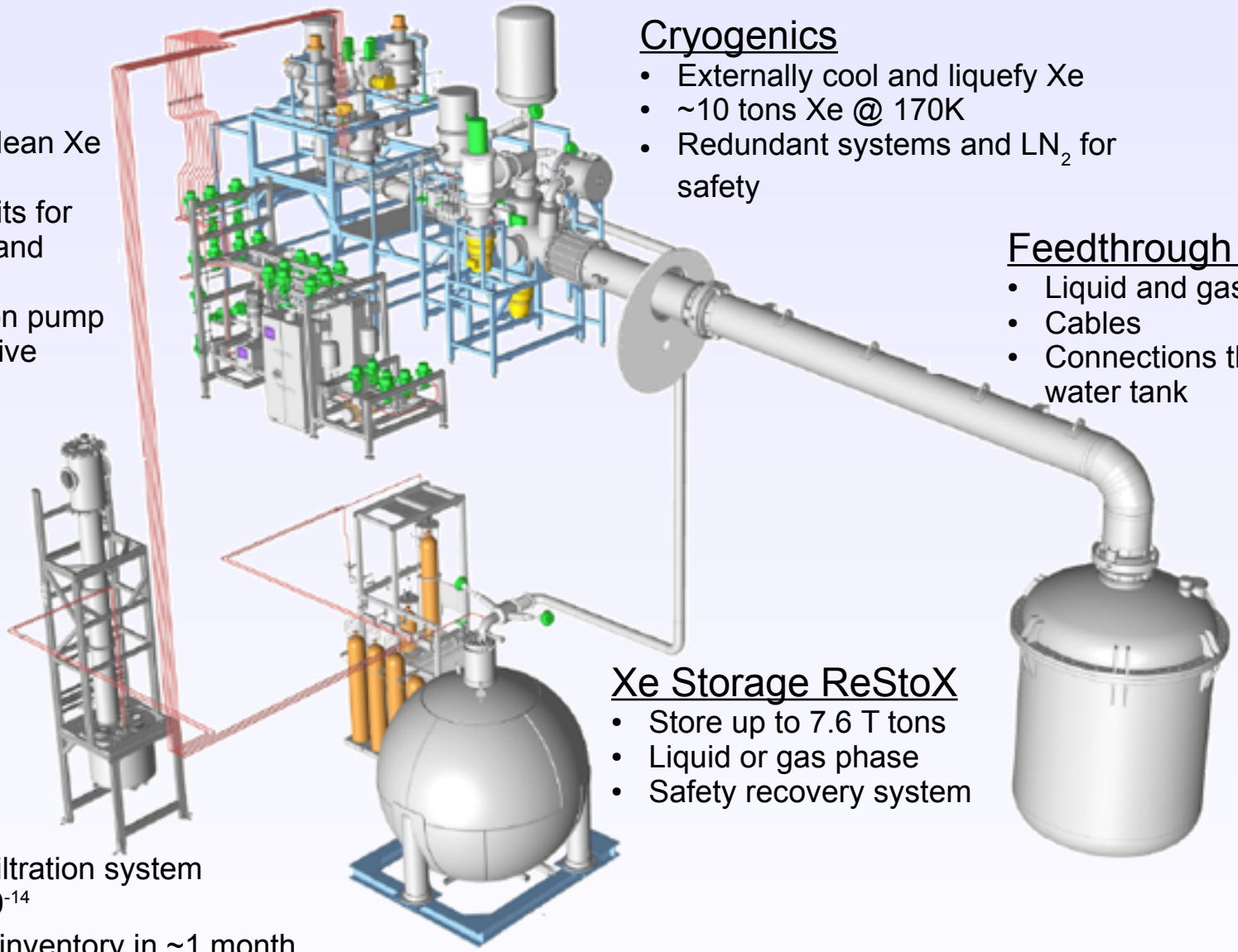
J. Angle, et al. (XENON Collaboration), Phys. Rev. Lett. 100, 021303 (2008)



2005 - 2007	2008 - 2016	2011 – 20xx	2018 – 20xx
XENON10	XENON100	XENON1T	XENONnT
$\sigma_{SI} < 8.8 \times 10^{-44}$ cm^2	$\sigma_{SI} < 2.0 \times 10^{-45}$ cm^2	$\sigma_{SI} \sim 2 \times 10^{-47}$ cm^2 (projected)	$\sigma_{SI} \sim 2 \times 10^{-48}$ cm^2 (projected)

E. Aprile et al. (XENON100), Phys. Rev. Lett. 109, 181301 (2012)

XENON1T



Purification
- Continually clean Xe
- ~100 SLPM
- Parallel circuits for optimization and maintenance
- Custom xenon pump
  - Chart QDrive

Cryogenics
- Externally cool and liquefy Xe
- ~10 tons Xe @ 170K
- Redundant systems and LN_2 for safety

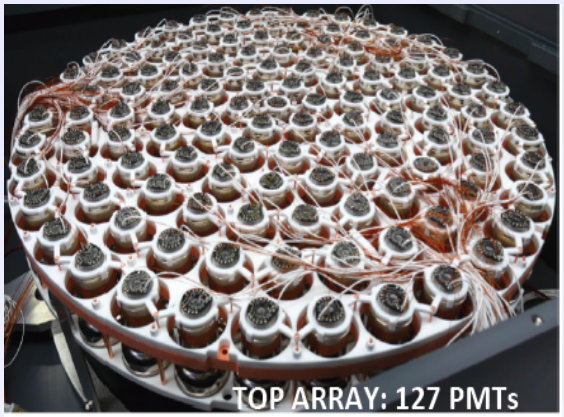
Feedthrough Pipe
- Liquid and gaseous Xe
- Cables
- Connections through water tank

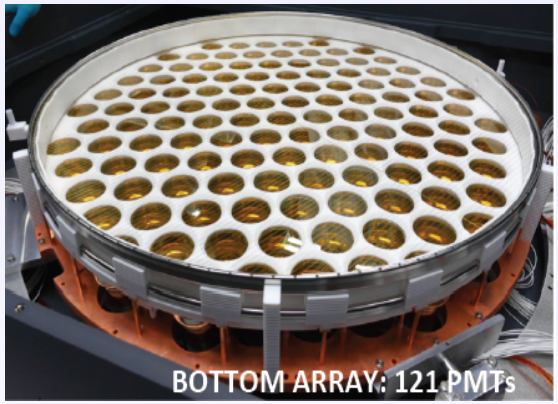
Xe Storage ReStoX
- Store up to 7.6 T tons
- Liquid or gas phase
- Safety recovery system

Distillation
- Custom Kr filtration system
- $Kr_{nat}/Xe \sim 10^{-14}$
- Process Xe inventory in ~1 month

All designed for XENON1T and XENONnT!

XENON1T Detector



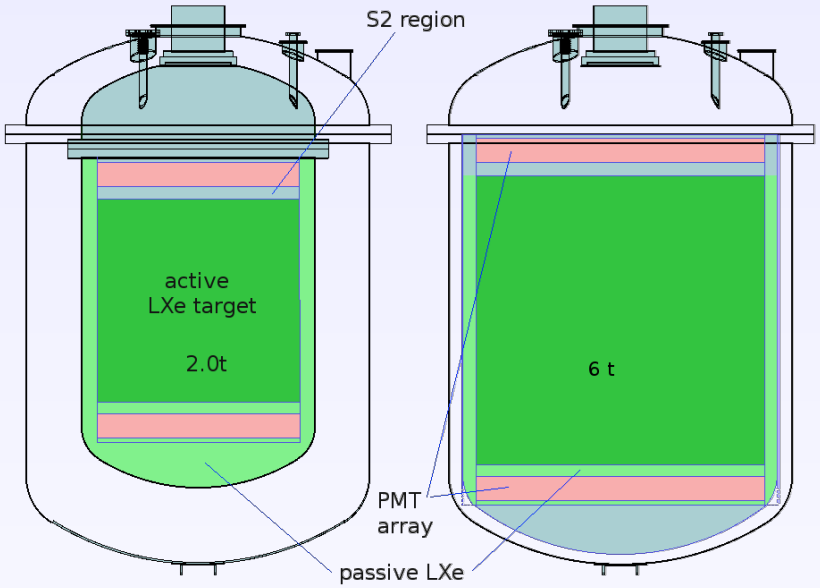


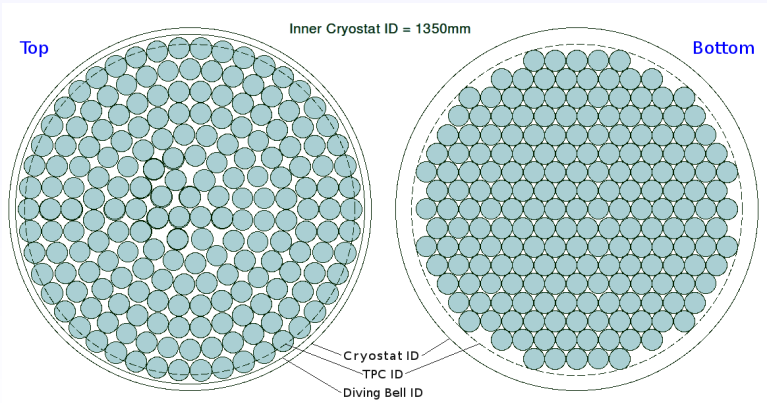
- 2.2 ton target (1t fiducial)
- 10m water cherenkov muon veto
- Finishing commissioning / starting operation
- 20 days to reach LUX/PandaX limit
- First results coming soon
- Sensitivity: 2 X 10^{-47} cm^2

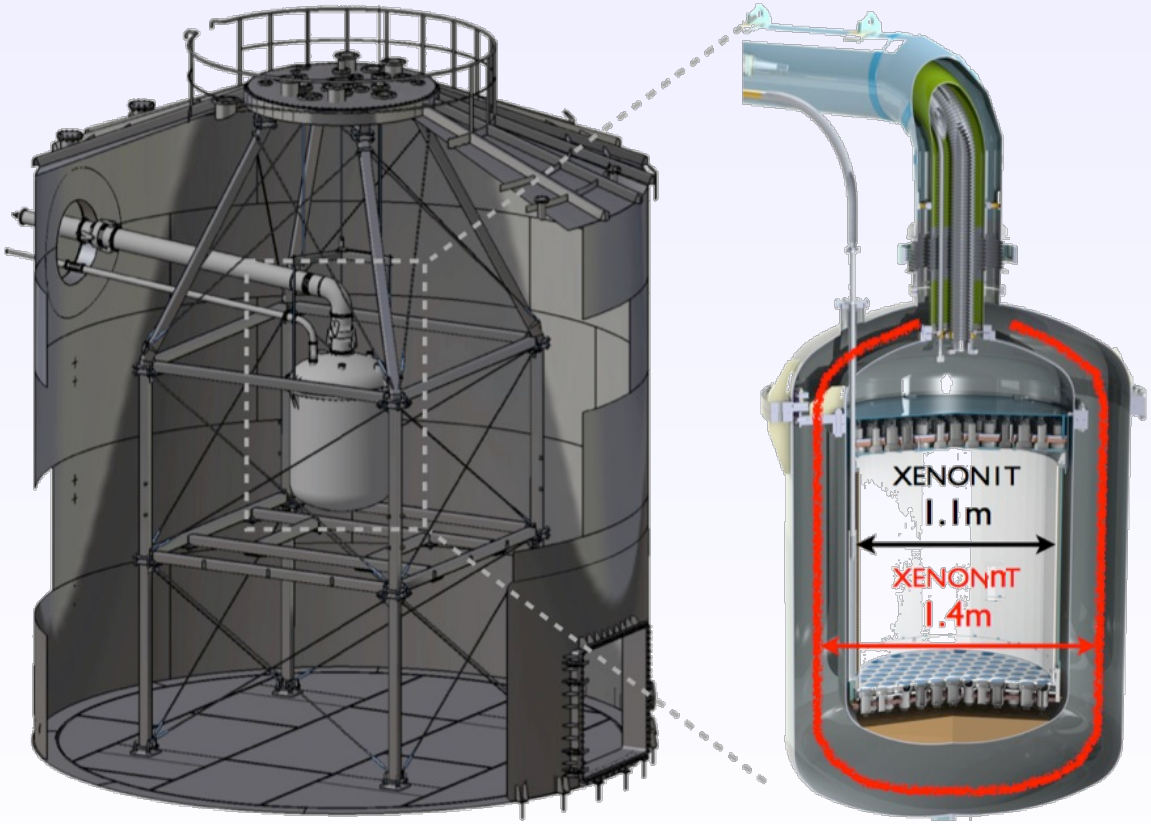
Upgrade: XENONnT

- Quick upgrade of TPC and inner cryostat
- All major systems remain unchanged
- Construct TPC in parallel to XENON1T operation
- Start data taking by 2019

- Additional PMTs
  - Same Hamamatsu R11410
    - Reuse the XENON1T PMTs
  - ~500 total (250 top and bottom)
- Additional gas
  - 7.25 t needed (7.5 t including gas)
  - 3.7 t already in place
  - Acquisition ongoing



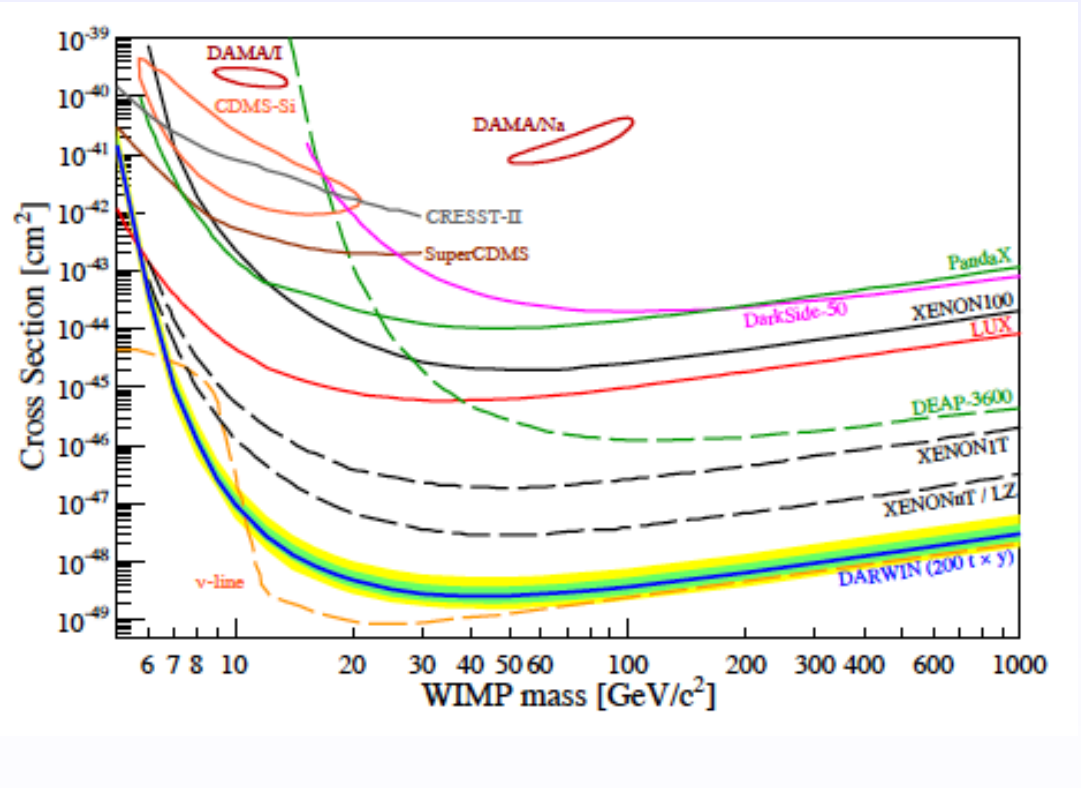




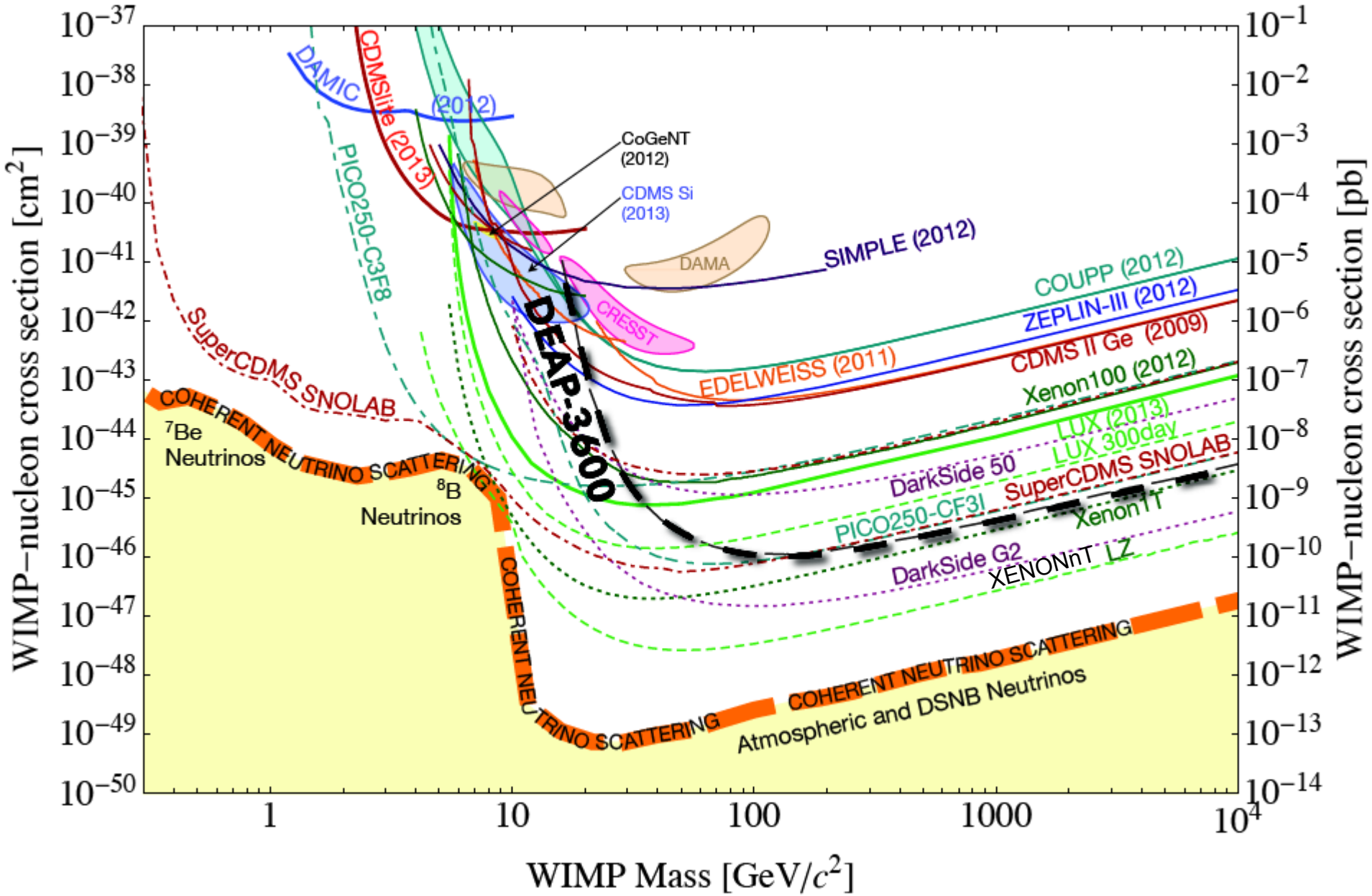
DARWIN

- The ultimate LXe detector
- Designed to reach the neutrino floor
- 50 tons Xe (30 ton fiducial)
- 200 t yr exposure

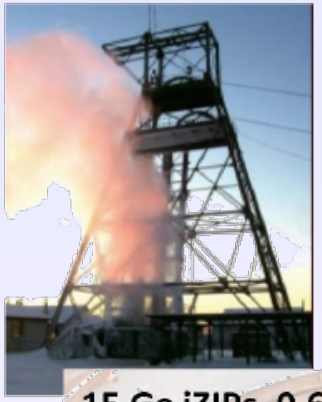
- High stats measurement of previous DM discovery
- Or push to neutrino floor
- Precision CNNS measurements
- 7.2 pp events per day
- 0vBB search with ^{136}Xe



Projections for Heavy WIMPs



SuperCDMS



SuperCDMS

SOUDAN

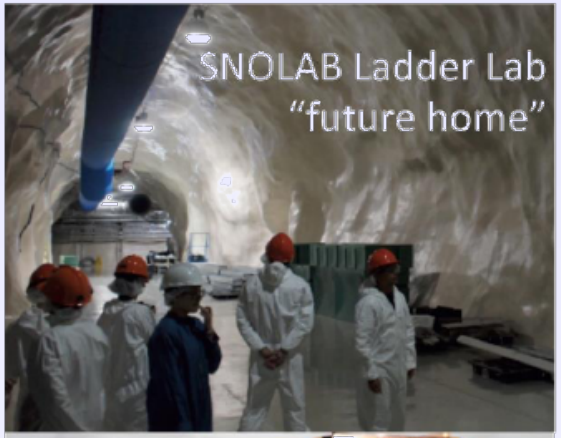
Leading limits published on low mass WIMPs

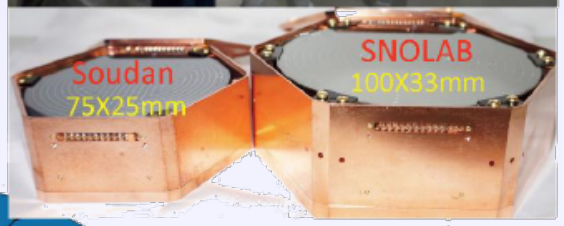
Operation ended late 2015

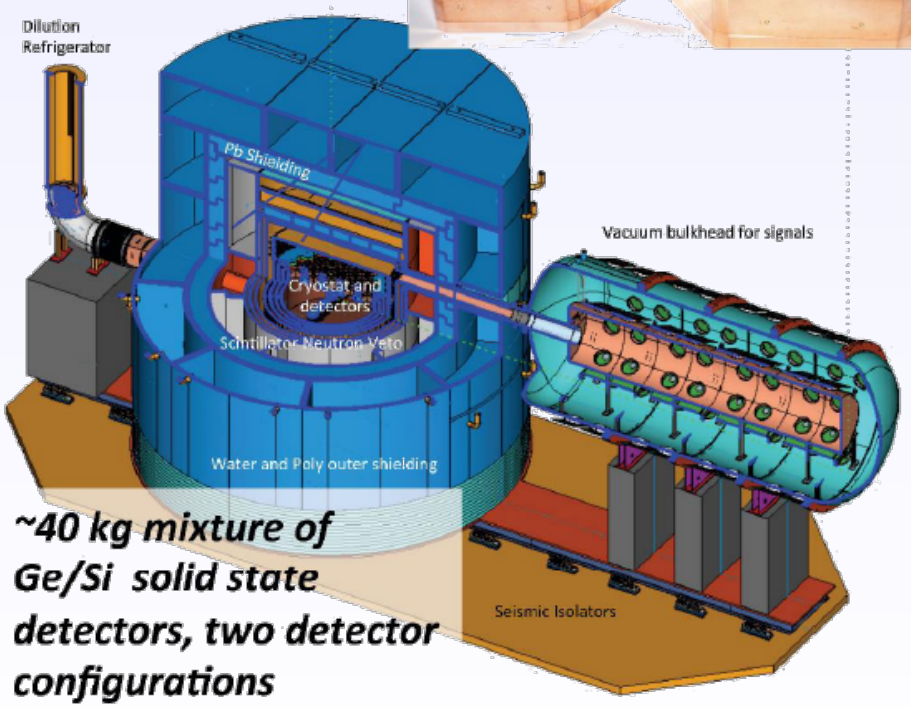
SNOLAB

Generation-2 experiment, beginning ~2019

Aiming for unique sensitivity to low mass WIMPs

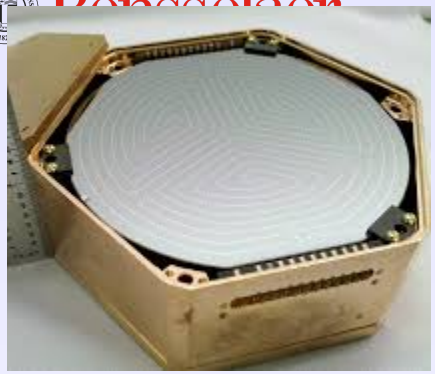




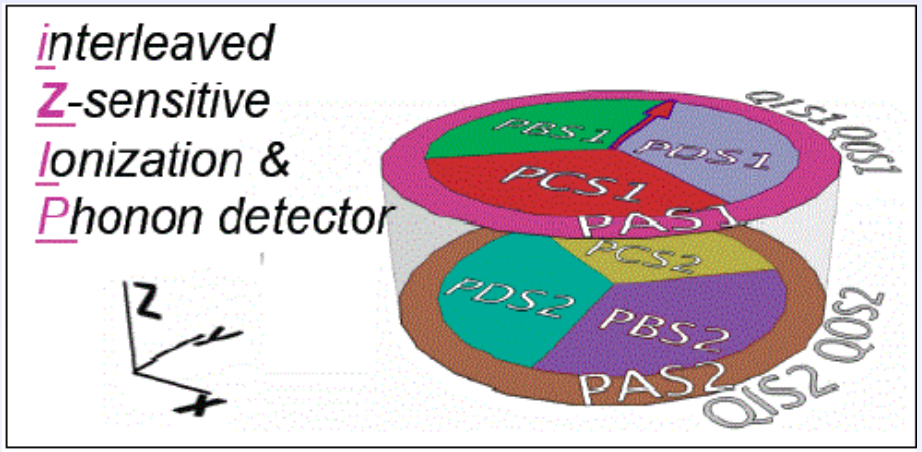


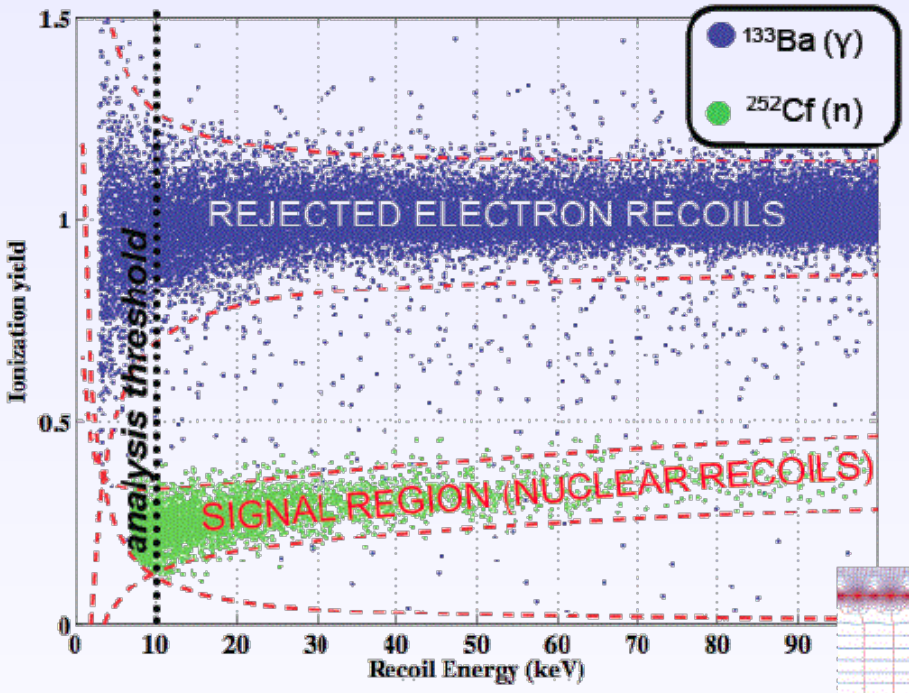
~40 kg mixture of Ge/Si solid state detectors, two detector configurations

New iZIP Detectors



iZIPs: Ionization & Phonon Detectors

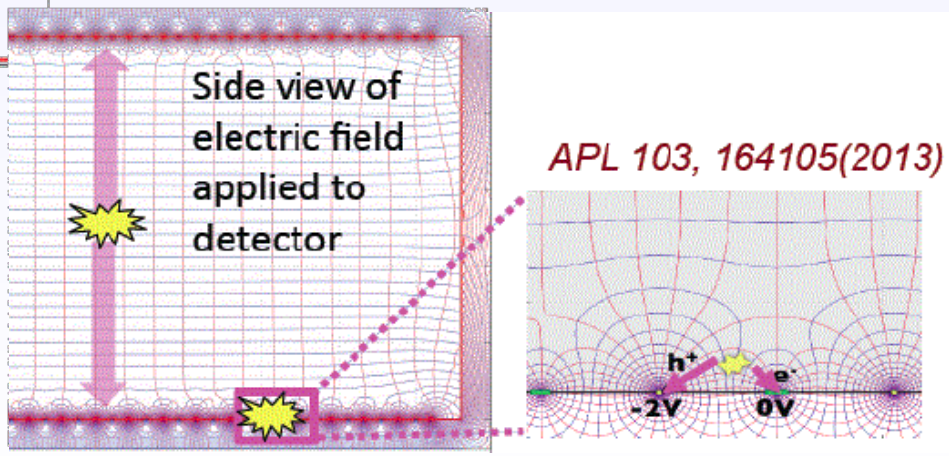




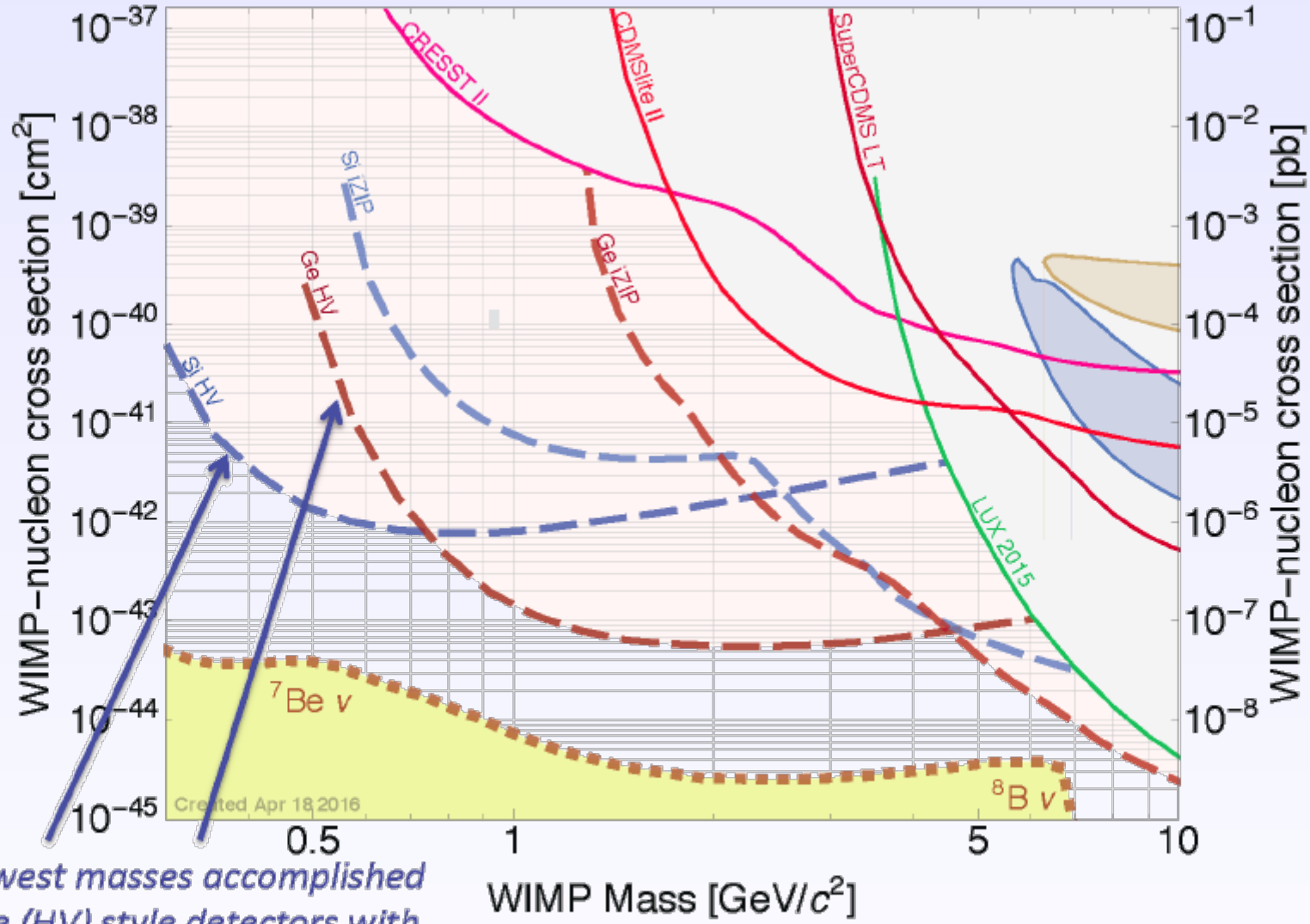
3-D fiducialization in both ionization and phonon energies allows for efficient rejection of external backgrounds down to very low energies

Simultaneous measurement of ionization and phonons provides better than 1:10^6 separation between NR and bulk ER

Operated at low bias (4V) to extract recoil energies on event-by-event basis



SuperCDMS Projections



*Reach at lowest masses accomplished w/ CDMSlite (HV) style detectors with ultra-low (< 100 eV) threshold; will be **BACKGROUND** limited*

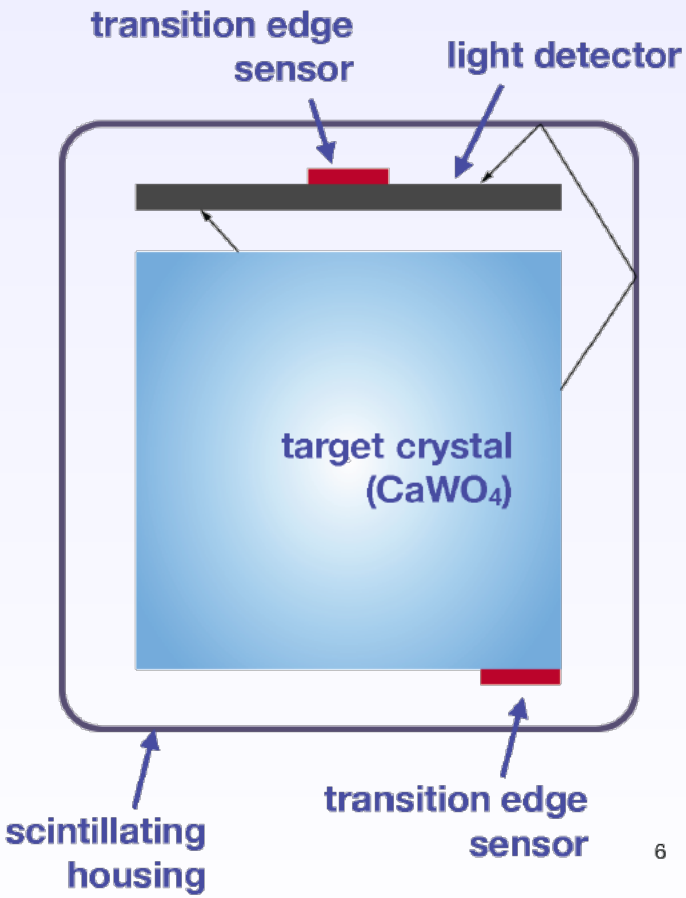
start of science runs 2020

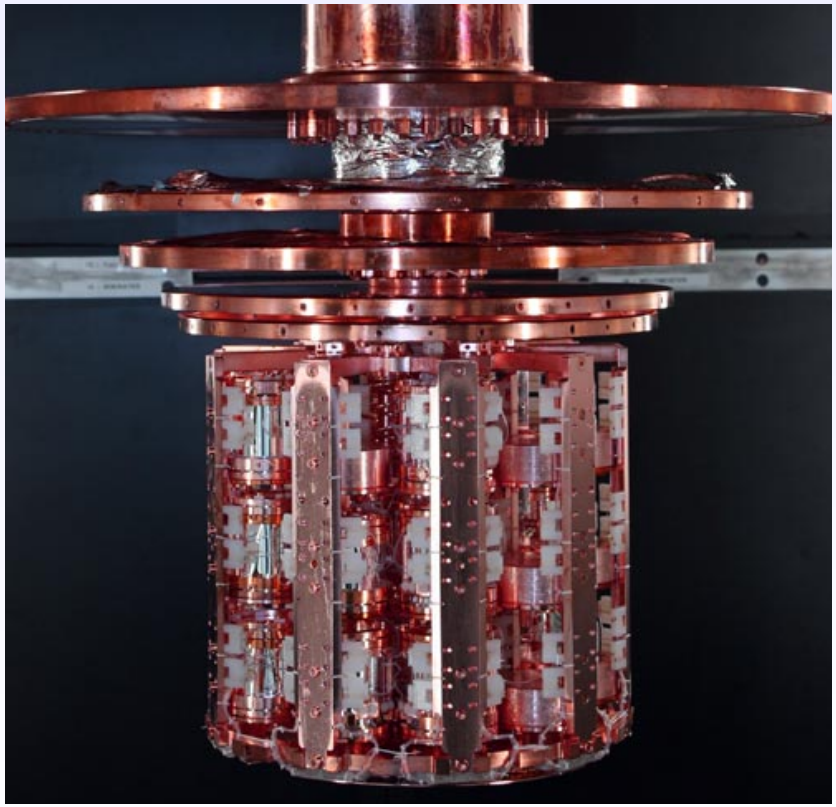
- First runs gave competitive results
- Best sensitivity from 2-4 GeV

CRESST

- Simultaneous readout of 2 signals
- Phonon channel:
  - Particle independent
  - Measure of deposited energy (recoil energy)
- Scintillation channel:
  - Different response for signal and bg
  - Quenching of nuclear recoils

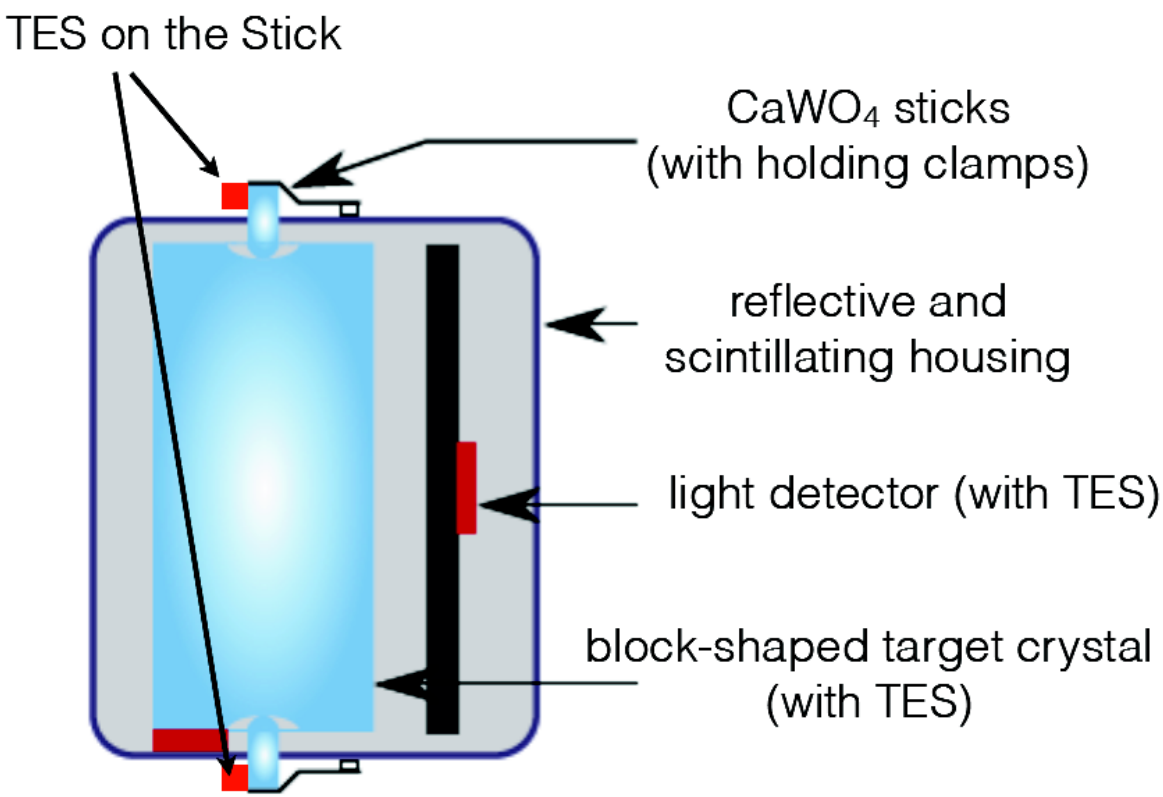
- Use TES for phonons and light
- Maintain low threshold (500 eV)
- High target mass (W)
- 29.35 kg days data
- Most sensitive below 3 GeV

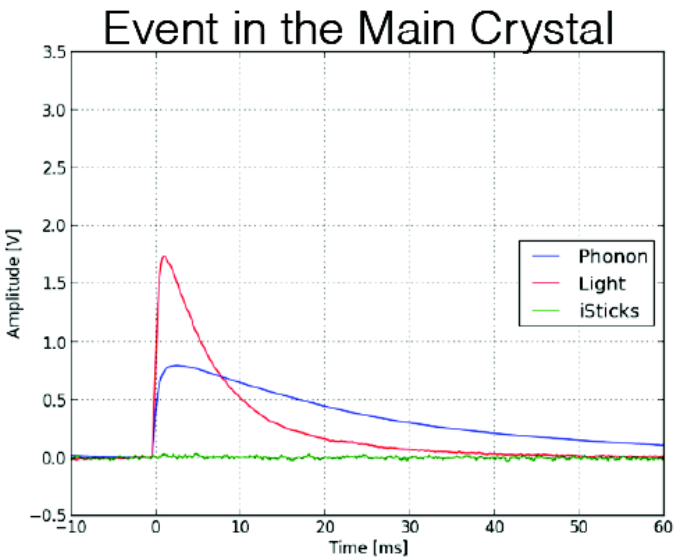


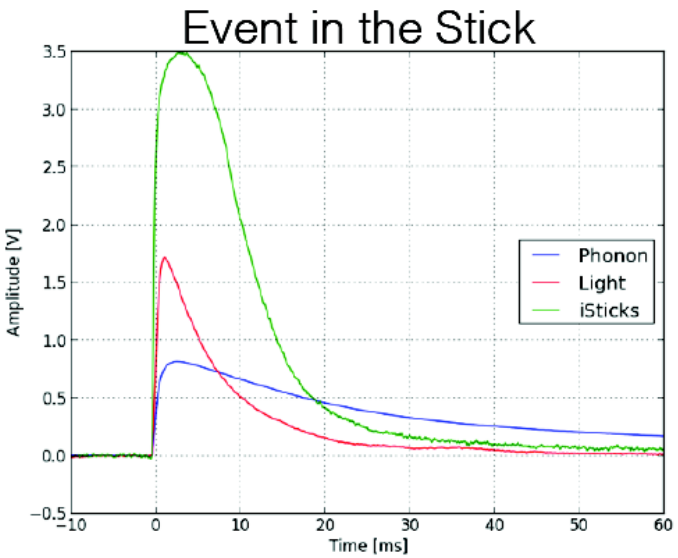


CRESST III

Background rejection: iStick



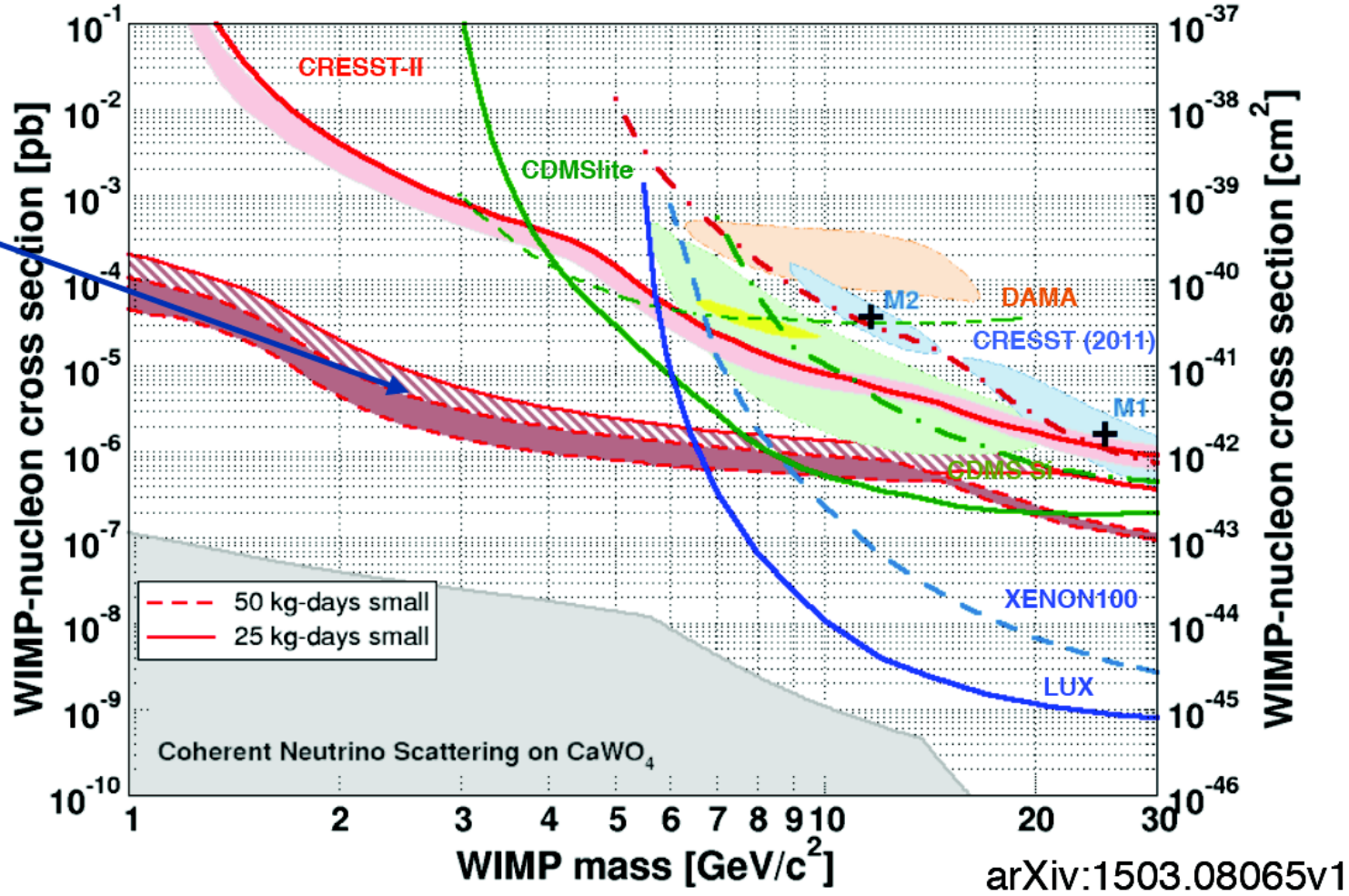




- 10 24kg modules installed
- Cryogenic commissioning complete
- Gamma calibrations underway

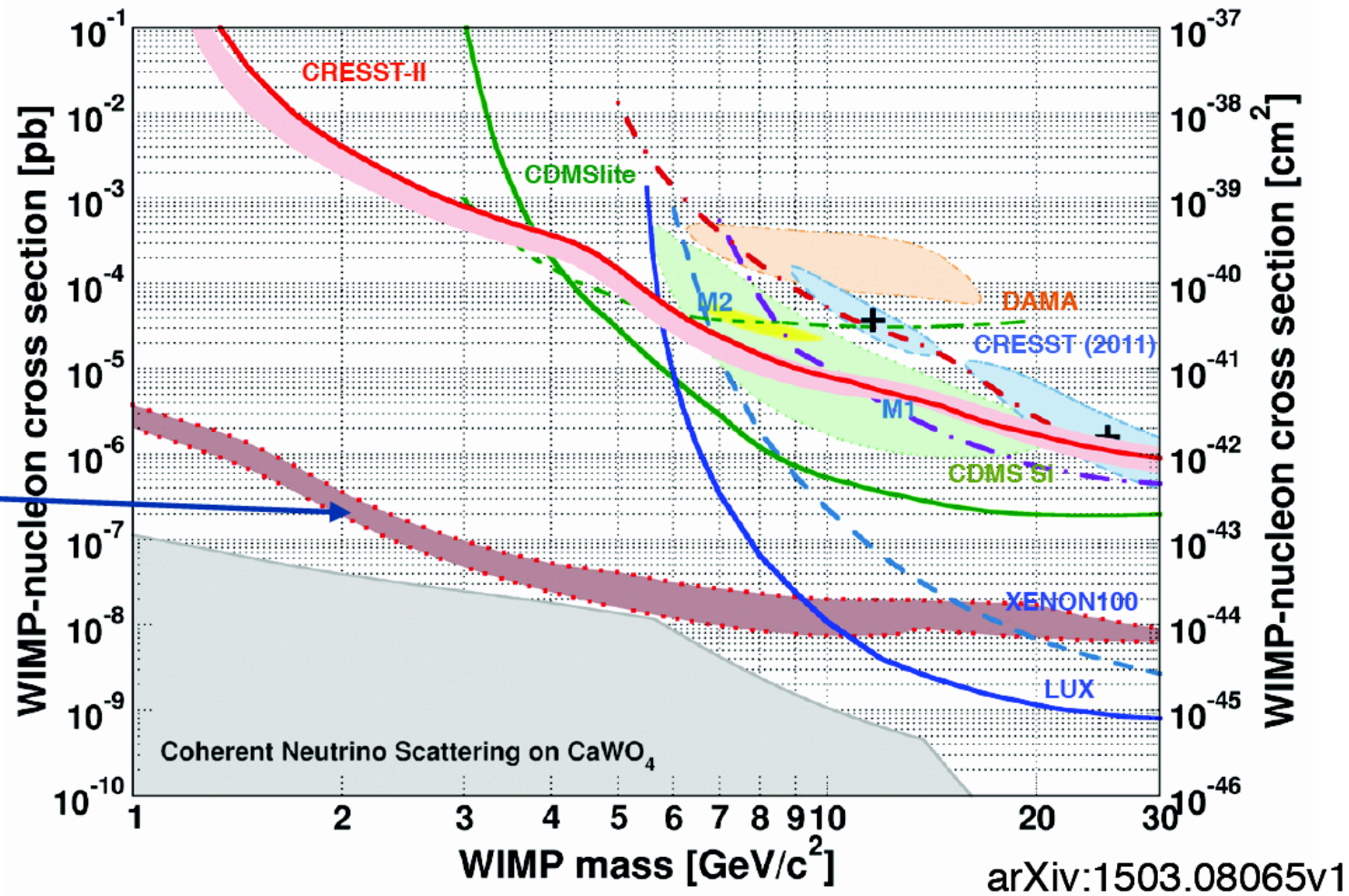
CRESST III Projections

Phase 1:
- 50kg days: 10 modules, 1 year



CRESST III Projections

Phase 2:
- 1 tonne days: 100 modules, 2 years
- crystal radiopurity improved by ~100

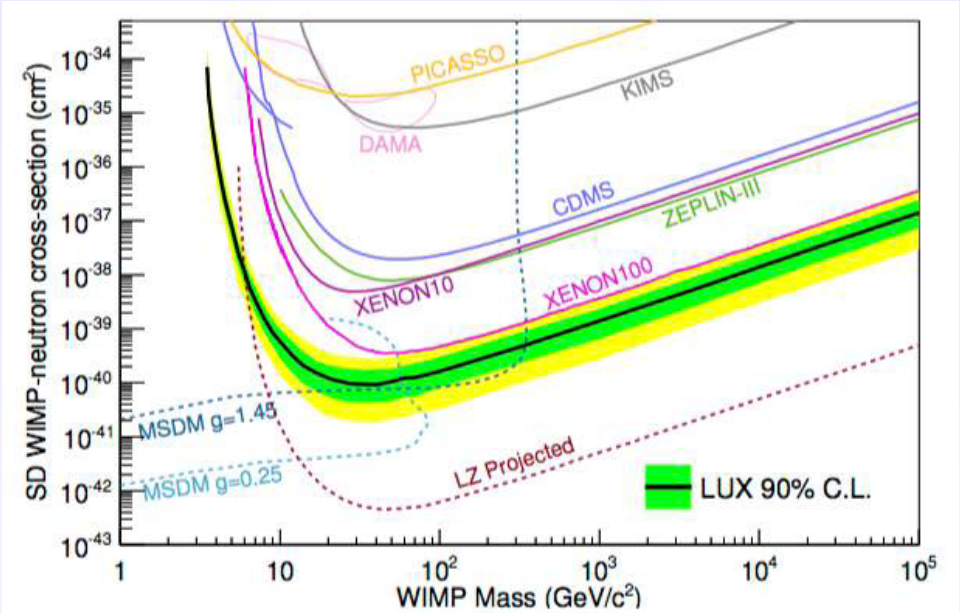


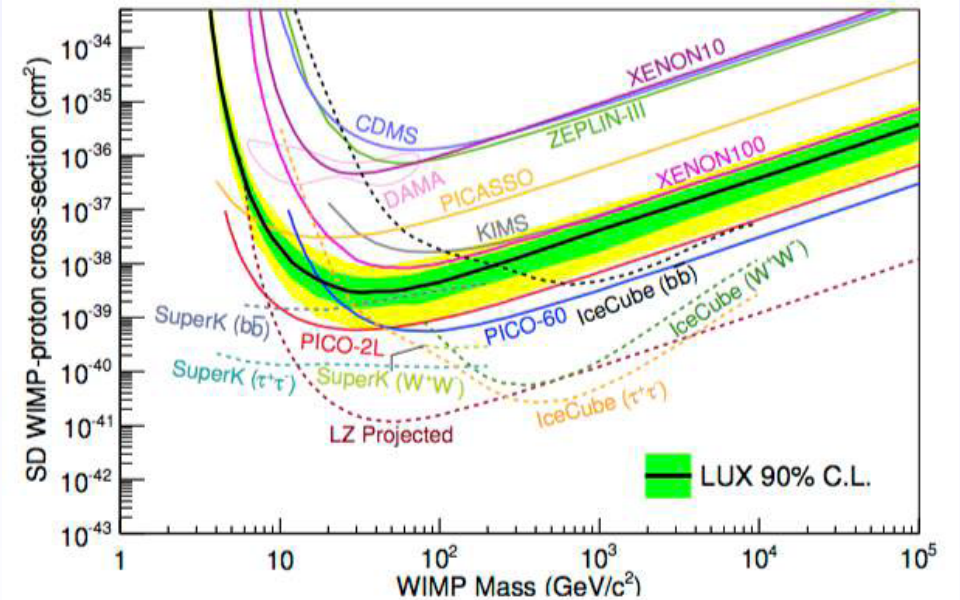
Spin Dependent Searches

- Liquid Nobles Again
- Xenon is roughly half odd isotopes
  - Unpaired neutron
  - Good sensitivity to pure neutron WIMP coupling

- LUX (XENON100 before)
- Search based on same data as SD
- Same event selection
- Best limit to neutron coupling
- 10^{-40} cm^2

- XENON1T will also perform SD search
- Order of magnitude increase in sensitivity
- Similar expectations for XENONnT/LZ

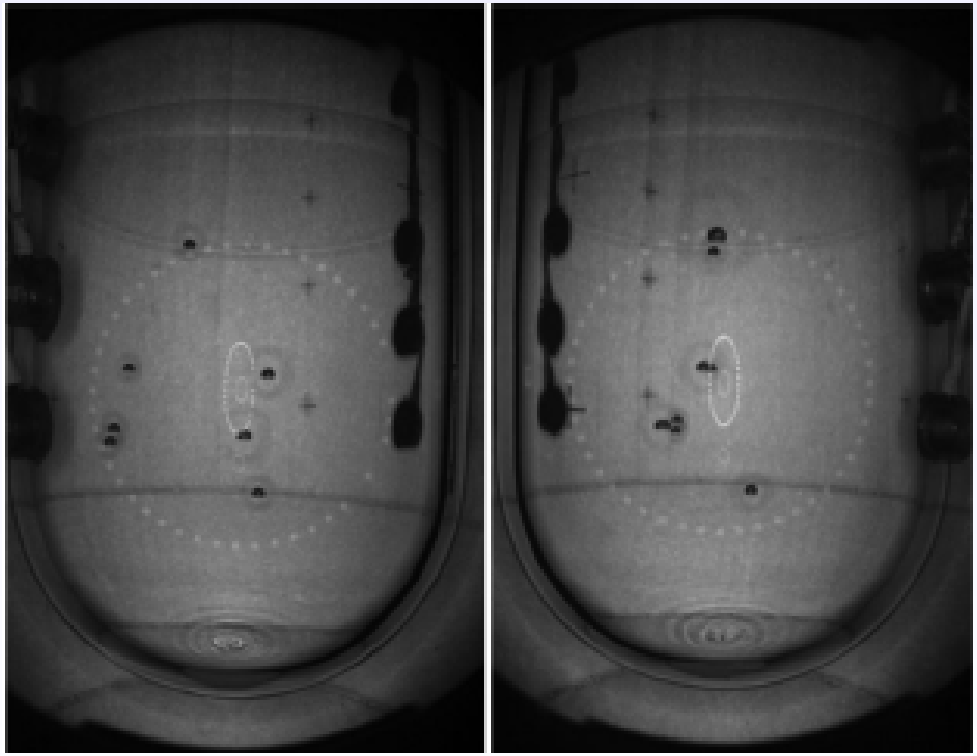


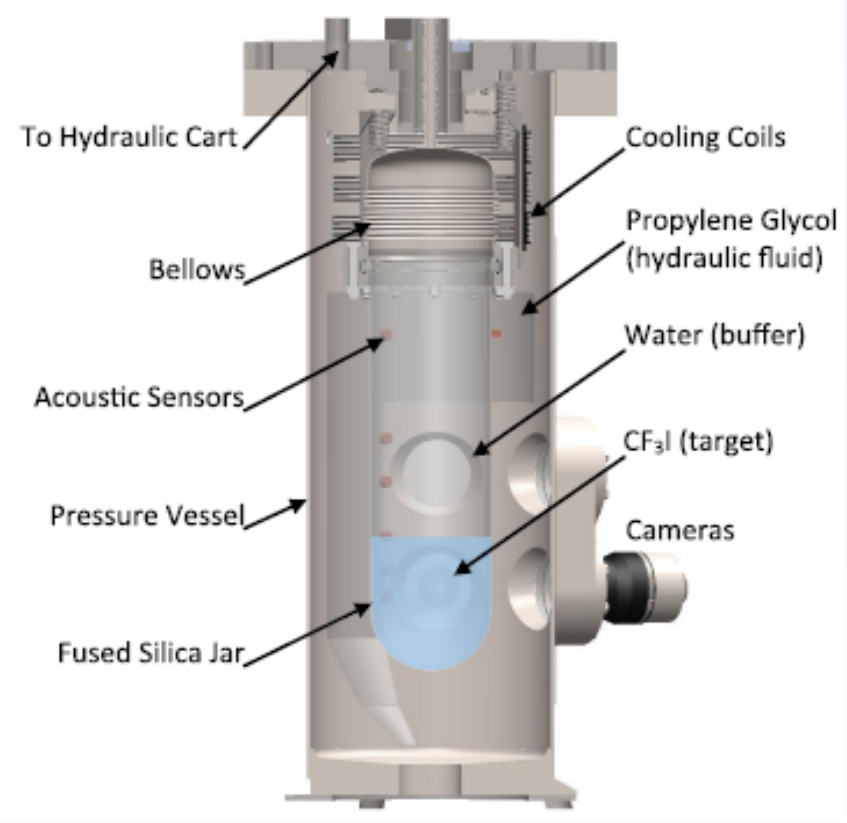


PICO 60

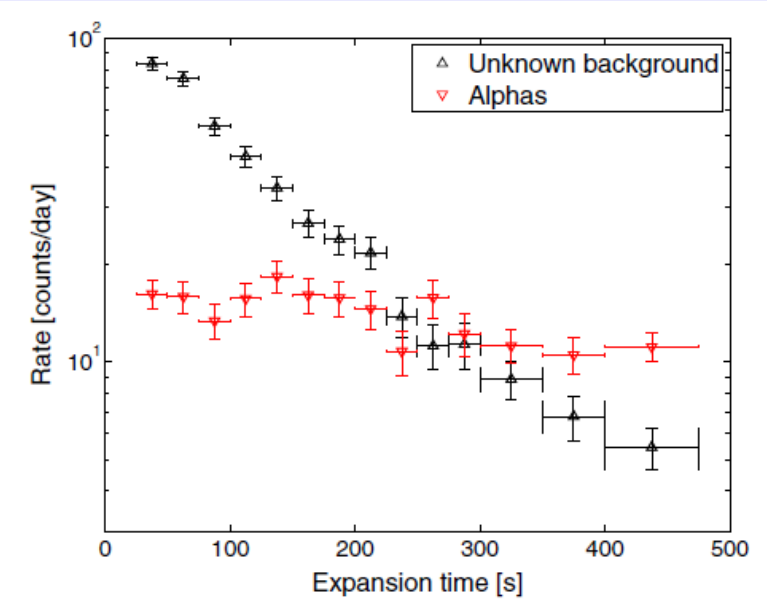
- Largest operational bubble chamber
- 36.8 kg target
- Stable operation from June 2013 to May 2014
- Anomalous background observed
  - Correlates with time after bubble expansion

- Combination of PICASSO and COUPP
- Superheated bubble chamber
- ^{19}F, unpaired proton
- Focus on spin dependent search
- Better gamma rejection

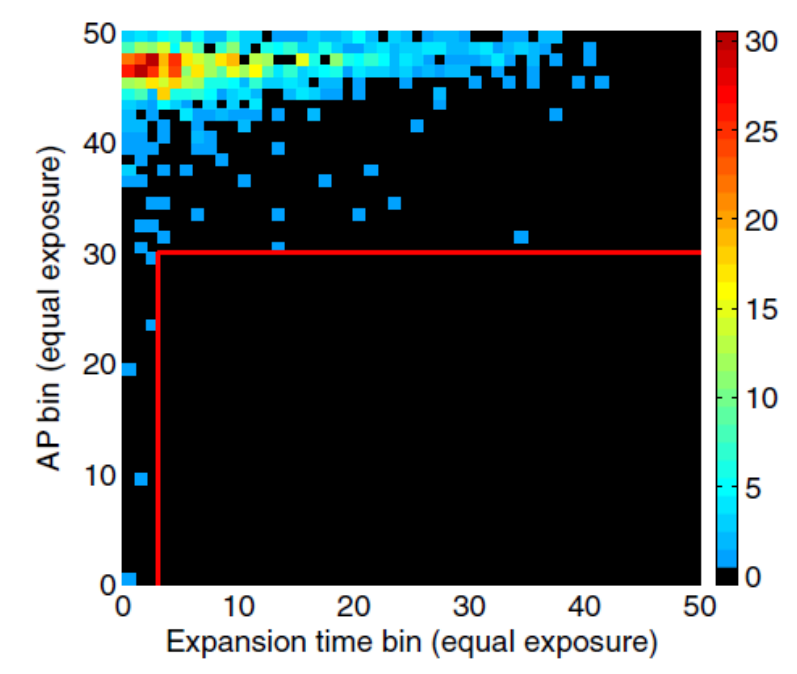


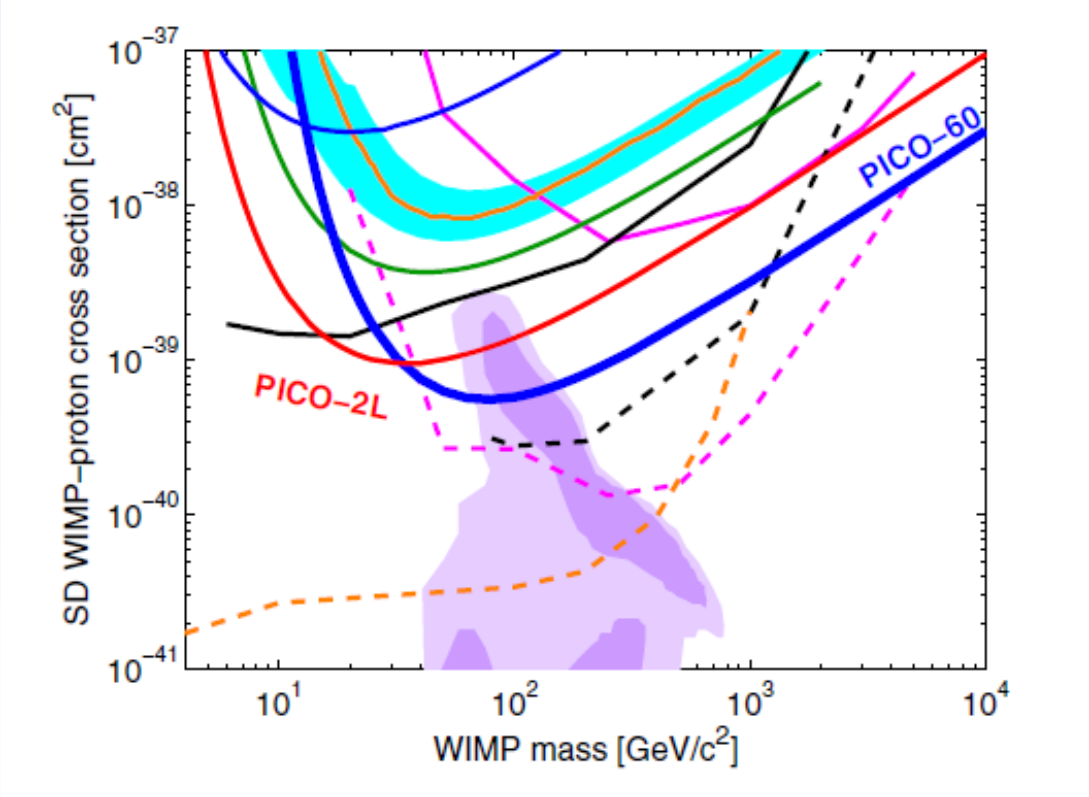


PICO Results



- Anomalous background localized in position and time
- Background free region defined for WIMP search
- Clearly biased, but accounted for with penalty in likelihood function
- Best limit set on pure proton WIMP coupling

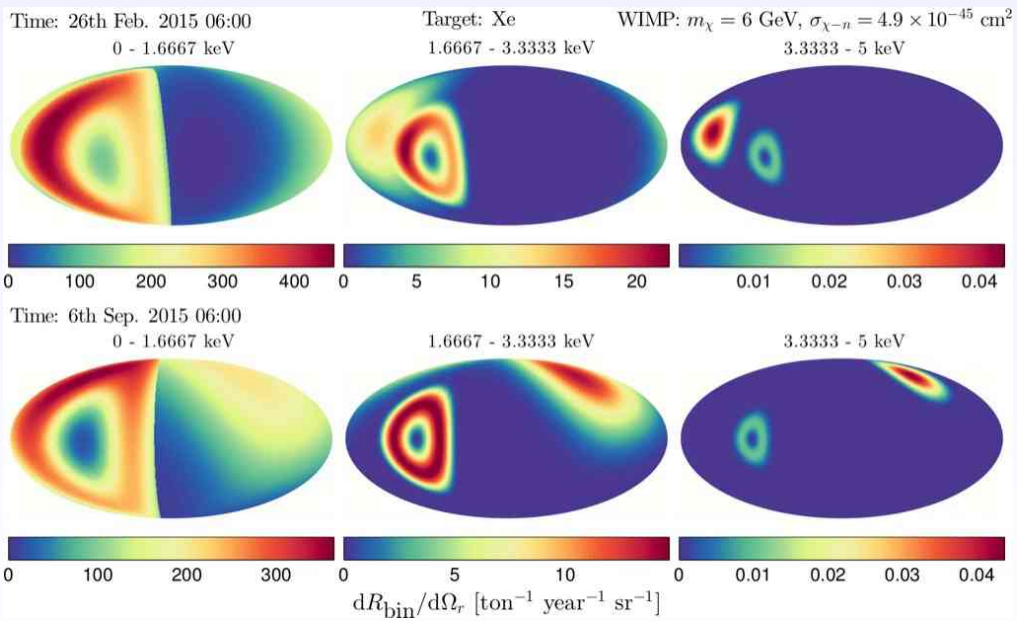


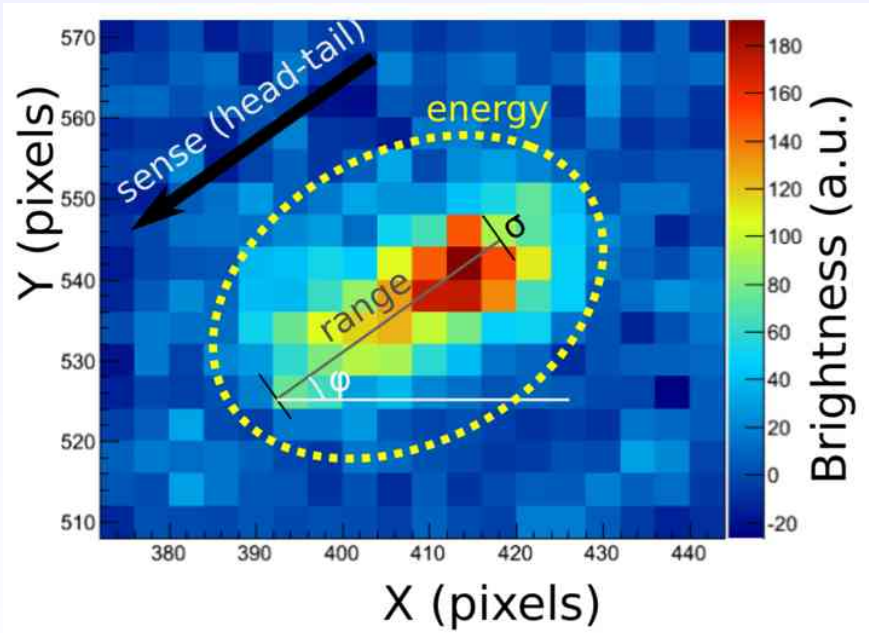


Passing the Neutrino Floor

- Directional detectors
- Distinguish arrival direction
- WIMP Wind comes from Cygnus
- Solar neutrinos from sun
- Several experiments under development
  - DMTPC, MIMAC, DRIFT, NEWAGE, D^3, HPXe, and more

DMTPC
- Measure tracks of nuclear recoils
- Gaseous target (~mm track length)
- Need to scale to huge target mass
- Already thinking of the future of direct detection!





Summary

Heavy WIMPs (Liquid Noble Detectors)

- Liquid Argon
  - DEAP-3600 (single phase)
    - In commissioning
  - DarkSide 50
    - Results released
  - DarkSide 20k / ARGO
    - Future upgrades to reach neutrino floor
- Liquid Xenon
  - LUX, PandaX
    - Best sensitivity to date
  - XENON1T
    - Starting now
    - Will reach 2 X 10^{-47} cm^2
  - XENONnT/LZ
    - Will reach 10^{-48} cm^2
  - DARWIN
    - Ultimate LXe detector
- Directional detectors
  - Suppress CNNS background

Light WIMPs (Cryogenic Crystals)

- SuperCDMS
  - iZIP detectors
  - Variety of target materials
  - Will probe low mass phase space to neutrino floor
- CRESST
  - Best sensitivity at below 3 GeV
  - Upgrades will probe down to neutrino floor at low mass

Spin Dependent

- Liquid Xenon
  - LUX (previously XENON100)
    - Best limit for pure neutron coupling
    - 10^{-40} cm^2
  - New results for XENON1T forthcoming
- PICO
  - Superheated bubble chamber
  - BG limited search
  - Best limit for pure proton coupling
  - New run started
  - Upgrade planned