Dark Matter Searches

Canada's Capital University

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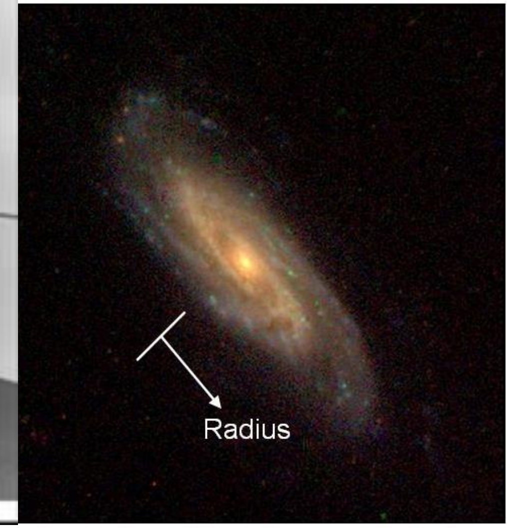
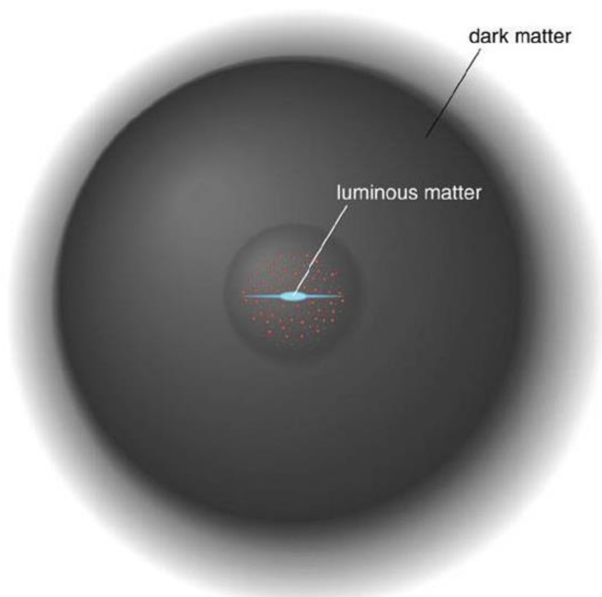
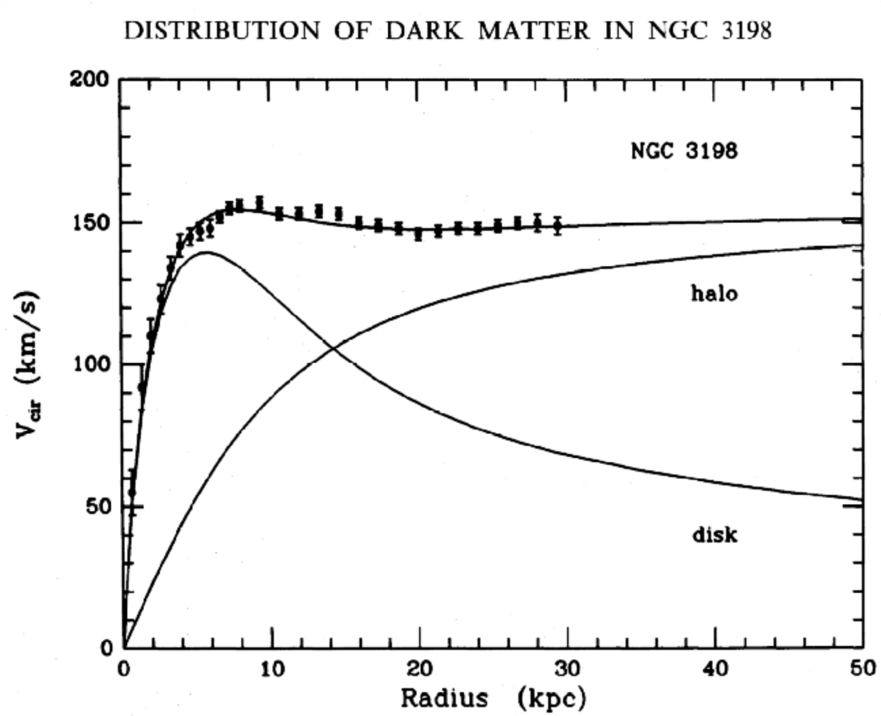
Canada

The Dark Matter Problem

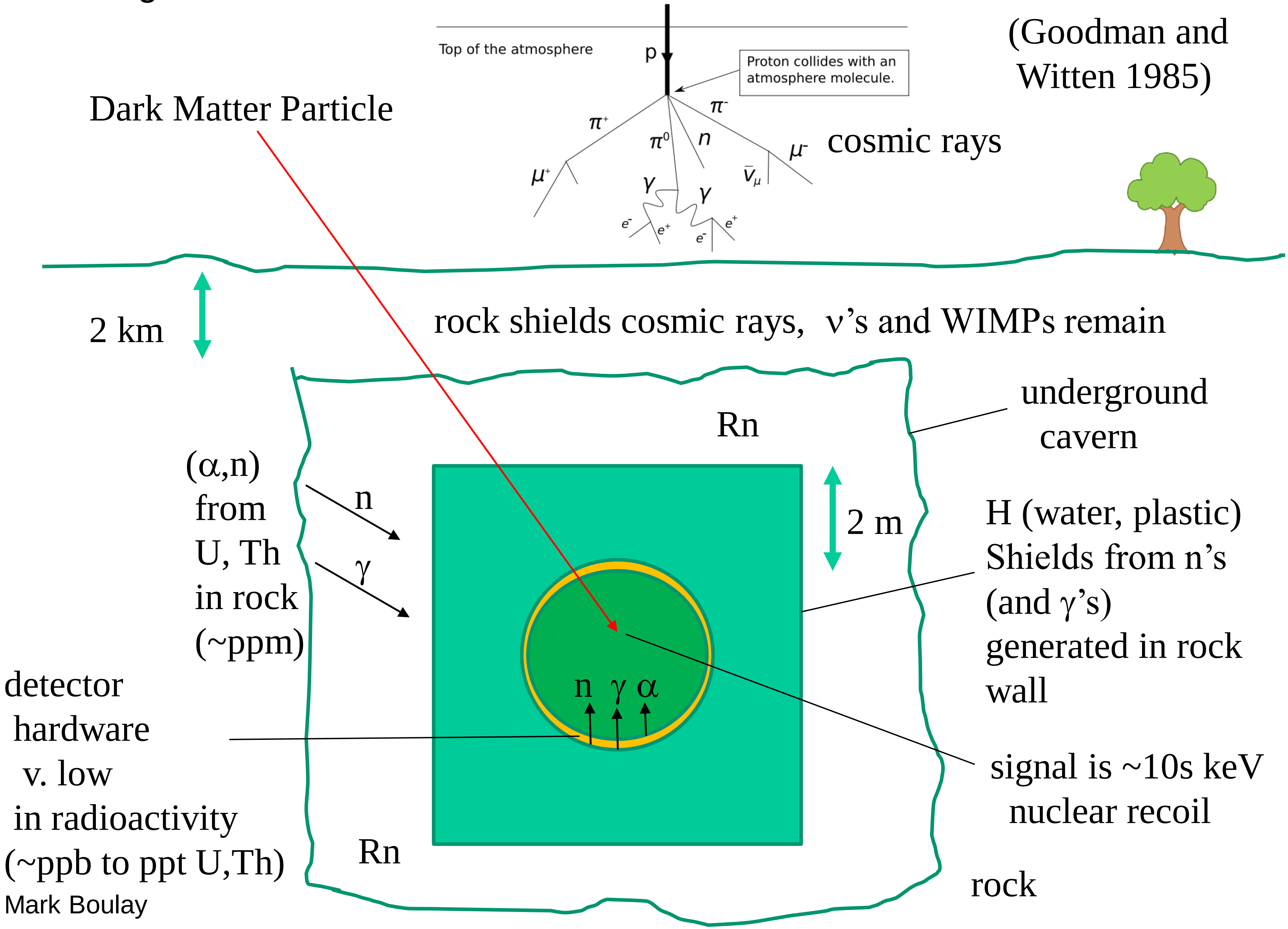
- Rotation curves measure the mass distribution
- Mass density distributed more broadly than visible objects
- Non-luminous halo required to describe rotation curves
- First found in 1933 by Zwicky from Coma Galaxy Cluster analysis







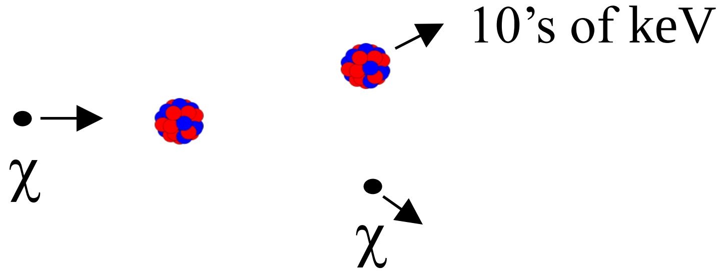
Underground recoil searches for WIMP Dark Matter



Mark Boulay

Looking for WIMPs

1. Pick a target, build a detector for low energy nuclear recoils. Detection can include one or more channels (ionization, scintillation, heat, etc.) to aid with background discrimination.
   Mitigate all sources of backgrounds.



2. Collect data. If no recoils beyond background, rule out regions of mass vs cross-section model space

3. If backgrounds are seen, go back to step 1.

4. If signal is seen, preferably confirm with multiple targets.

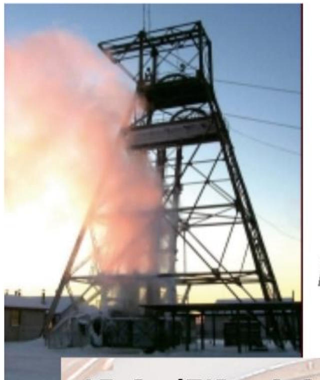
(Steps 1 to 3 typically ~10 years. Step 4 TBD.)

- LUX & LZ
- XENON-100 & 1T
- CRESST
- PICO
- XMASS
- DEAP-3600 & beyond
- NEWAGE
- DMTPC
- DAMA/NaI
- DAMA/LIBRA
- NEWS-SNO
- SuperCDMS-Soudan
- SuperCDMS-SNOLAB
- DAMIC
- CDEX
- KIMS-NaI
- PandaX-II
- DarkSide-50 & 20k

- SABRE (N&S)
- MiniCLEAN
- Cogent
- DRIFT
- DARWIN
- Edelweiss
- DM-Ice
- COSINE
- KIMS
- ANAIS
- TREX-DM
- NEWS

… 20 min talk, will try to provide a summary and outlook for recoil DM detectors

not covered here, but equally important are axion searches

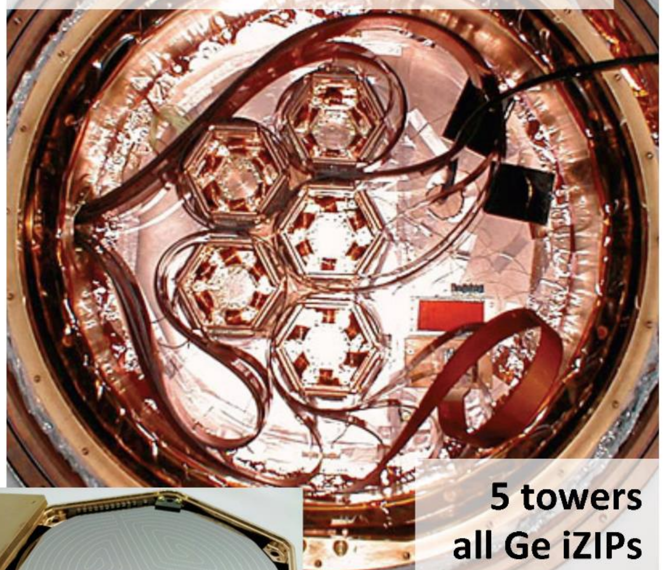


SuperCDMS

SOUDAN

Leading limits published on low mass WIMPs

15 Ge iZIPs, 0.6 kg each
Operational Mar. 2012 – Nov. 2015
In CDMS II location



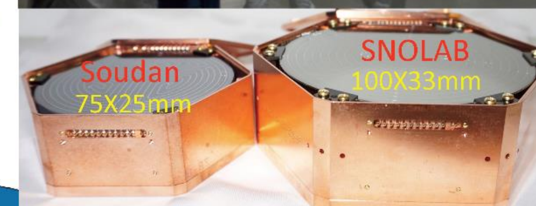
5 towers all Ge iZIPs

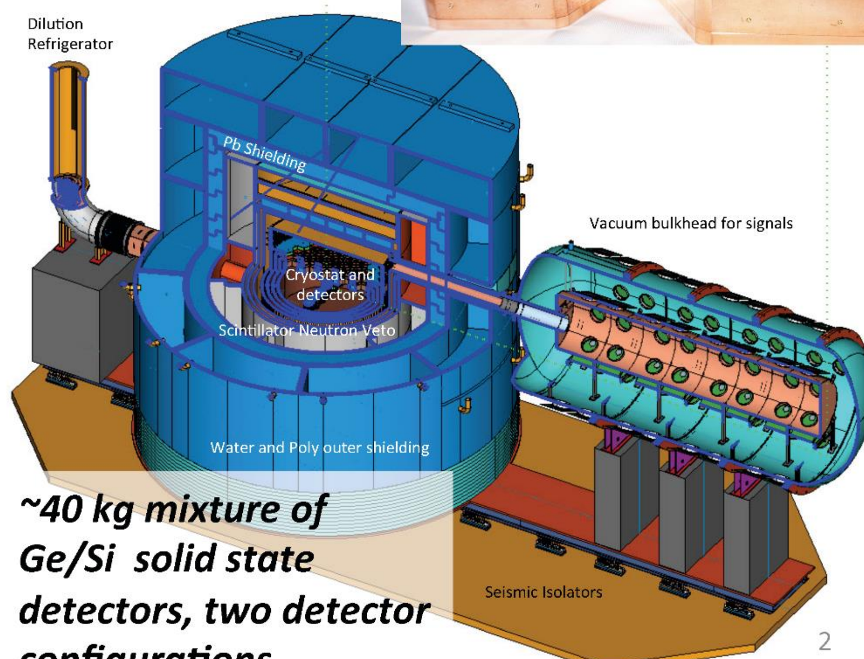
Operation ended late 2015

SNOLAB

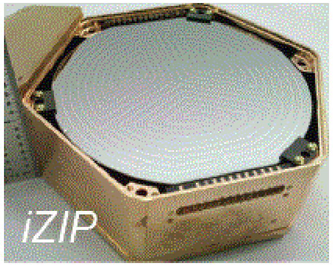
Generation-2 experiment, beginning ~2019

Aiming for unique sensitivity to low mass WIMPs

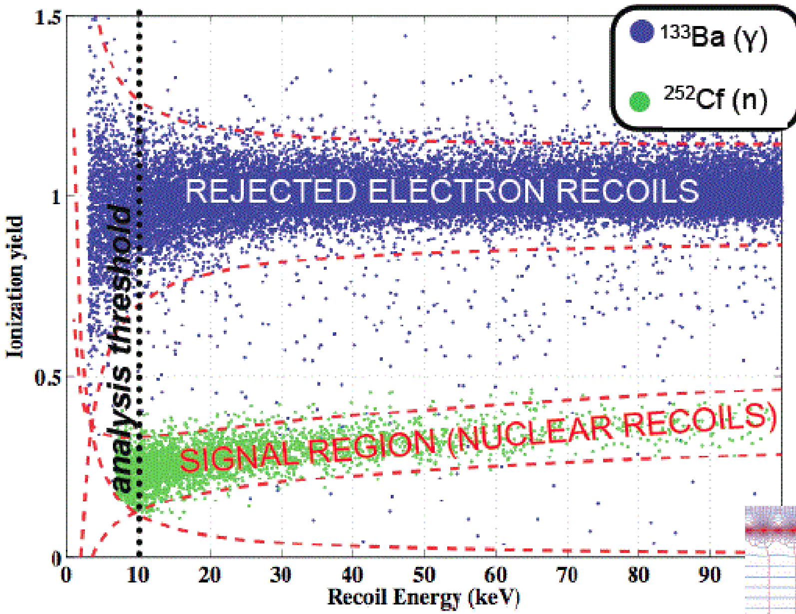


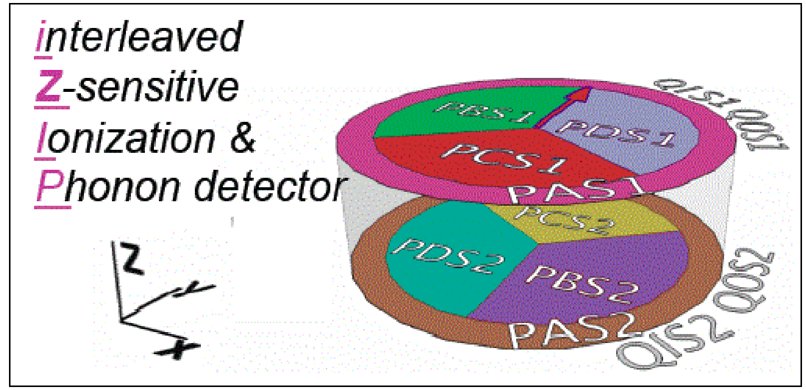


~40 kg mixture of Ge/Si solid state detectors, two detector configurations



iZIPs: Ionization & Phonon Detectors

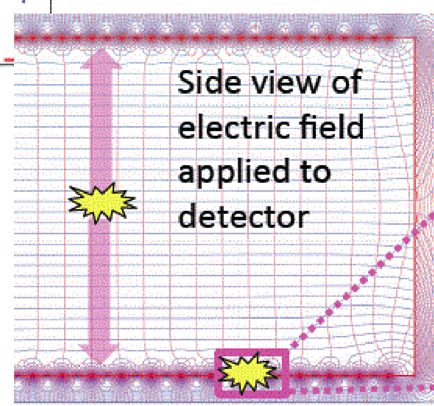




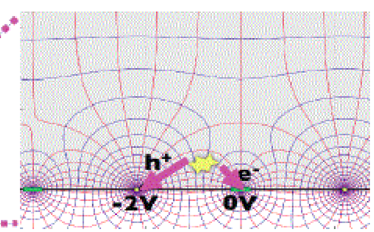
3-D fiducialization in both ionization and phonon energies allows for efficient rejection of external backgrounds down to very low energies

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

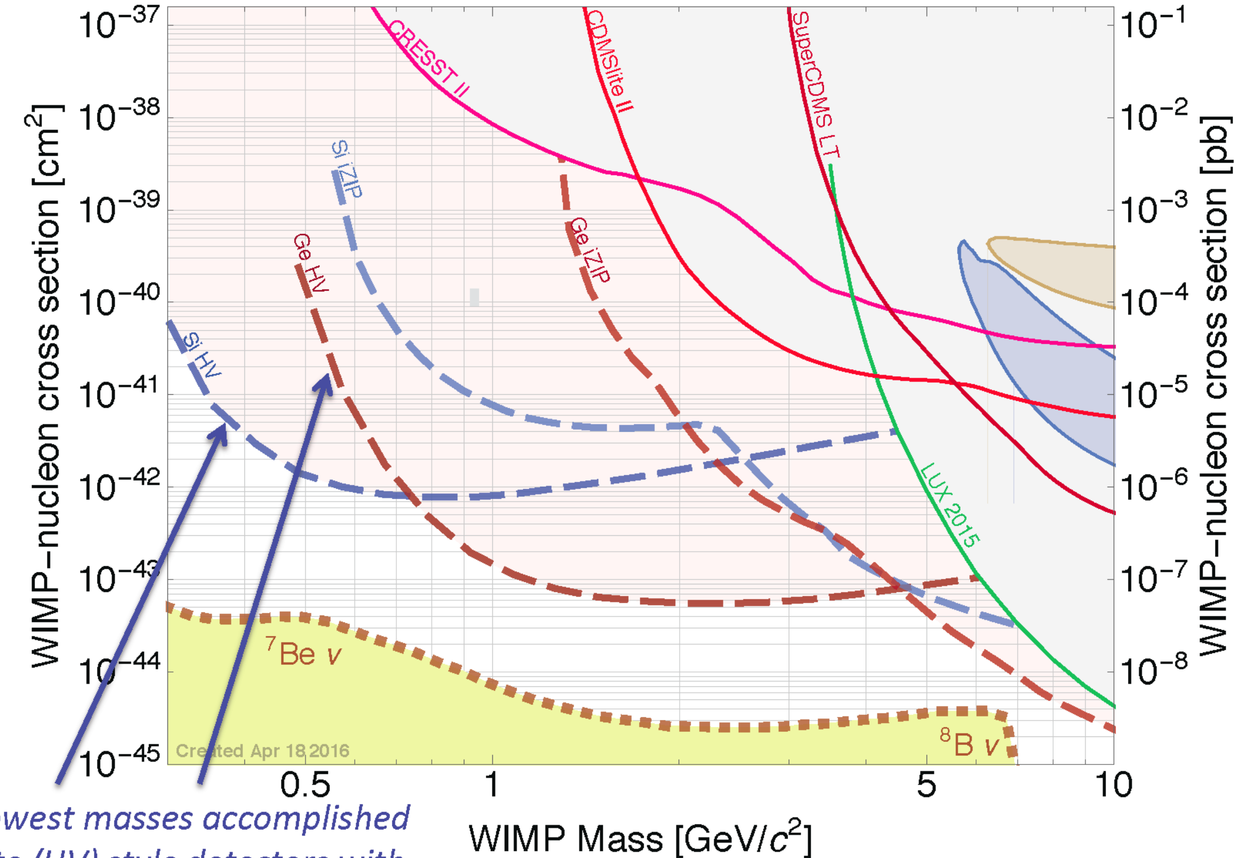
Operated at low bias (4V) to extract recoil energies on event-by-event basis



APL 103, 164105(2013)



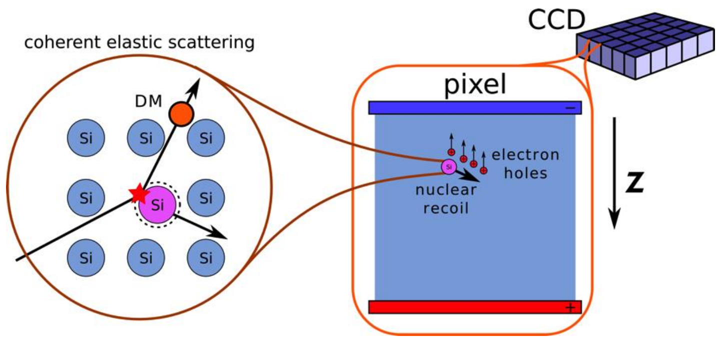
SuperCDMS SNOLAB Projections



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

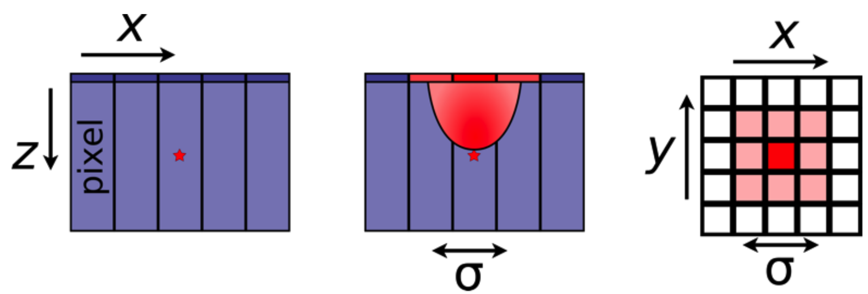
start of science runs 2020

Dark Matter in CCDs



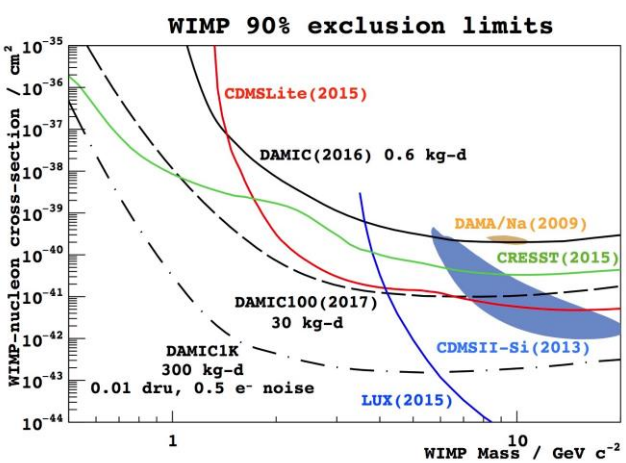
Point-like energy deposits from nuclear recoils induced by WIMP interactions

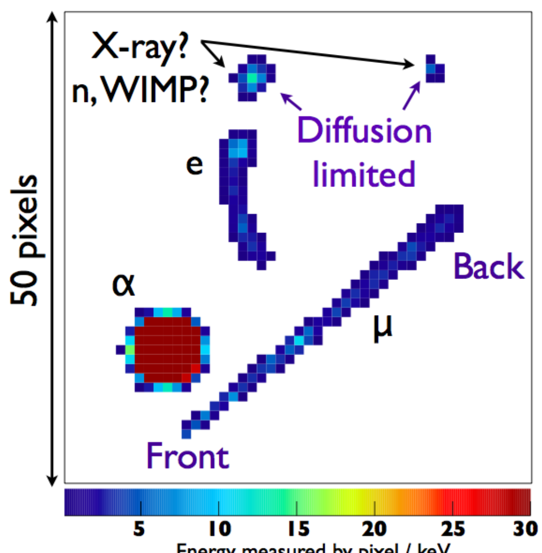
DAMIC (SNOLAB)

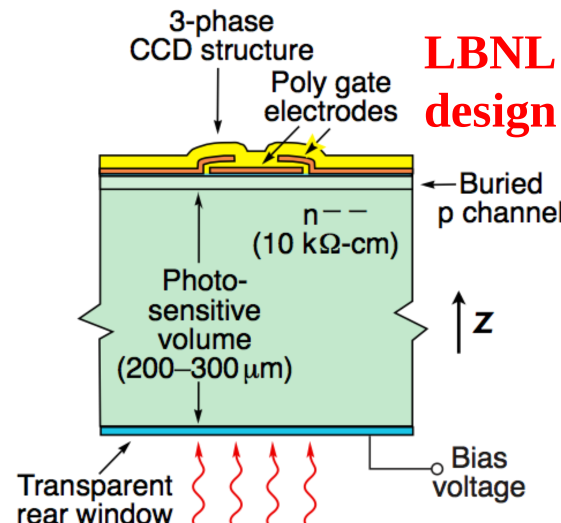


Charge diffuses towards the CCD pixels gates, producing a “diffusion-limited” cluster

1) High-resistivity (10^{11} donors/cm^3), extremely pure silicon, fully-depleted over several 100s μm (typical CCDs few tens of μm)





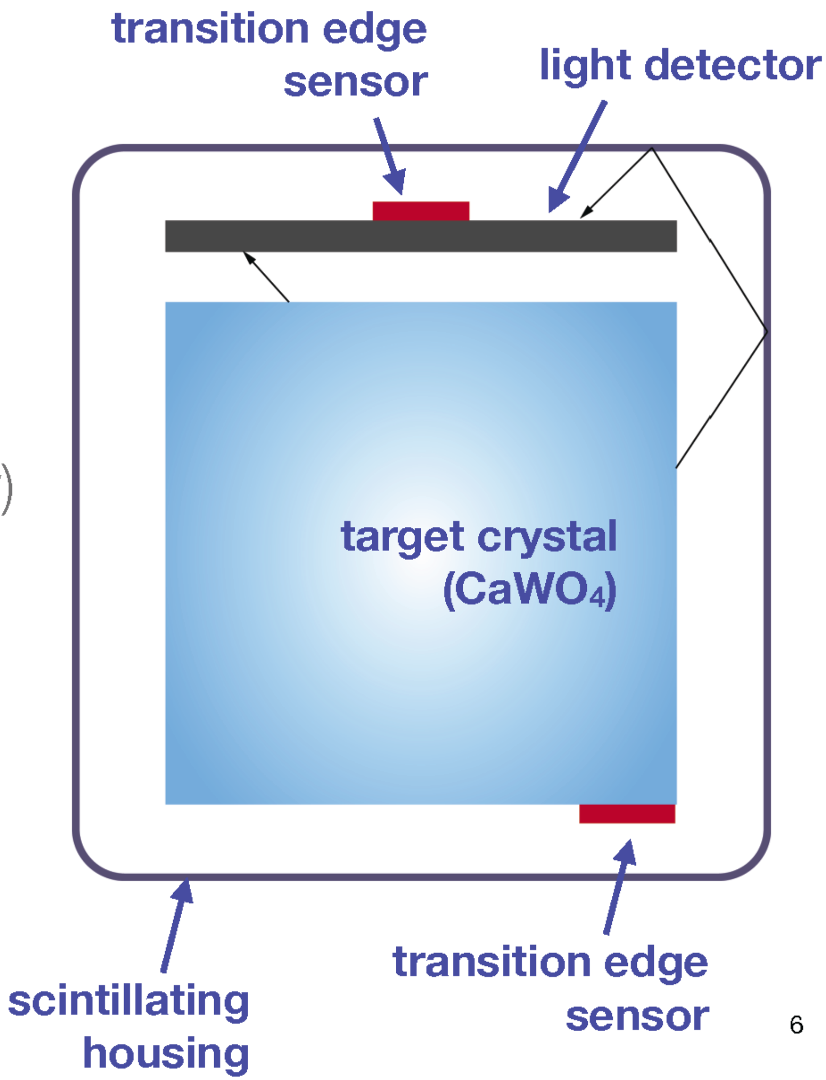


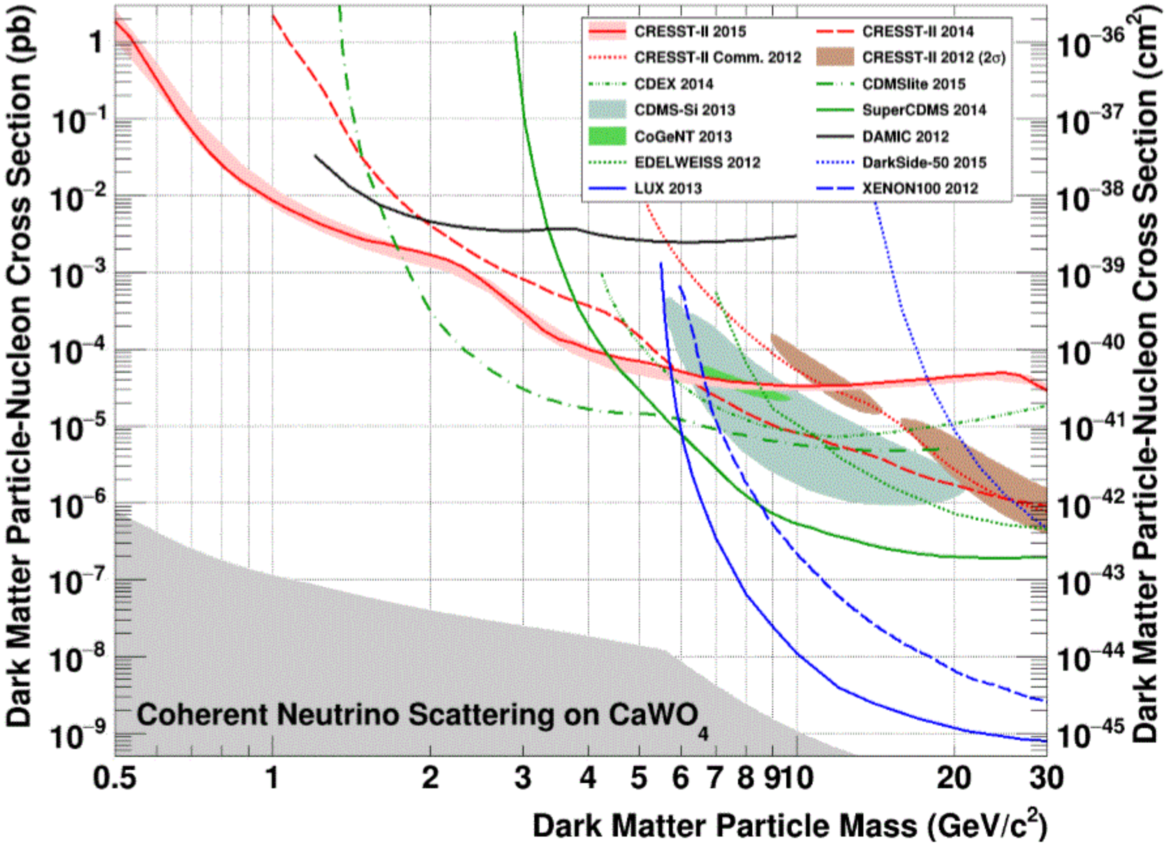
LBNL design

CRESST - Detection Principle I

simultaneous read-out of two signals

- **phonon channel:**
  particle independent measurement of deposited energy (= nuclear recoil energy)
- **(scintillation) light:**
  different response for signal and background events for background rejection ("quenching")





Recent result from CRESST-II (arxiv 1509.01515)

CRESST-III Run LNGS starting August 2016

Expect x100 increase in sensitivity (arxiv 1503.08065)

Several other projects planning increase in low-mass sensitivity, many good ideas.

Noble liquid detectors

Noble liquid detectors can be scaled to the large target masses needed to probe the low cross-sections for ~high mass WIMPS (20-30+ GeV to TeVs)

Two-phase detectors (TPCs): large target mass, S1+S2 signal allows background discrimination (β/γ vs recoil) and position reconstruction

Single-phase (scintillation-only): simple detector designs, large target masses with little internal components

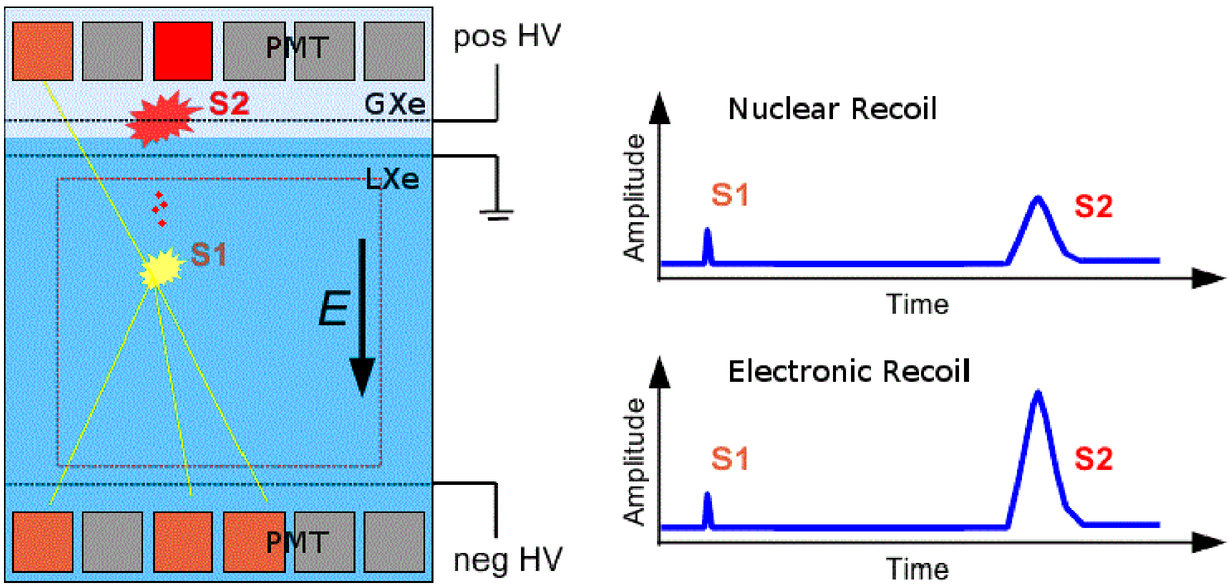
Two-phase xenon: XENON-100, XENON-1T, XENON-nT, LUX, LZ, PandaX-II and PandaX-xT

Single-phase xenon: XMASS

Two-phase argon: DarkSide-50, DarkSide-20k, Argo (300 tonnes), ArDM

Single-phase argon: DEAP-3600 (& beyond), miniCLEAN

Dual phase TPC for DM



Scintillation light (S1) and ionization charge from primary event, which is converted to proportional scintillation (S2) in gas phase. Time between S1/S2 and top PMT pattern used to localize event. S2/S1 provides recoil discrimination.

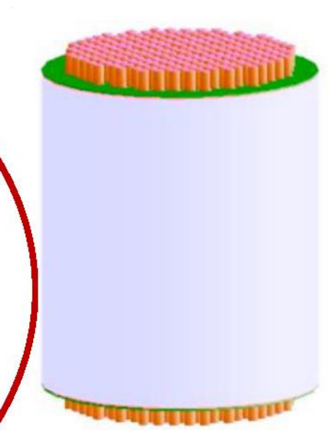
relatively "new" application in DM, about 10 years

PandaX experiment

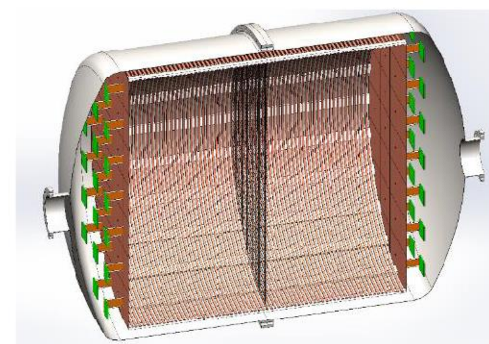
PandaX = Particle and Astrophysical Xenon Experiments

Phase I:
120 kg DM
2009-2014

Phase II:
500 kg DM
2014-2017



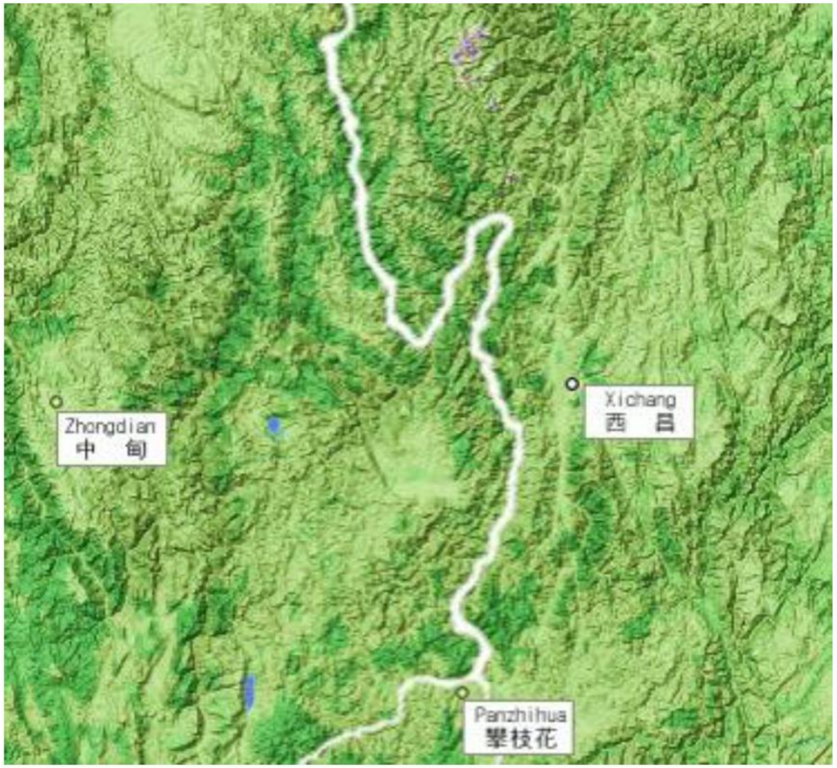
PandaX-xT:
multi-ton DM
future

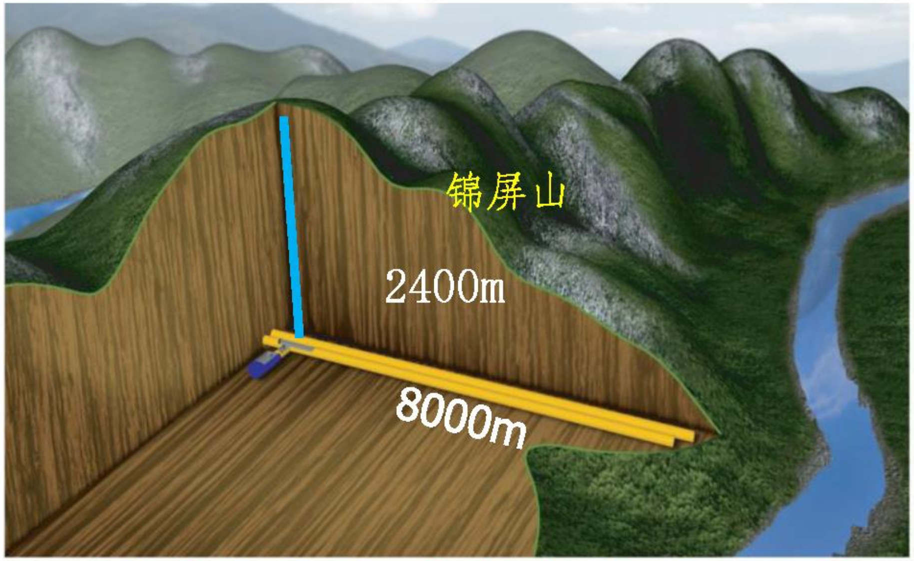


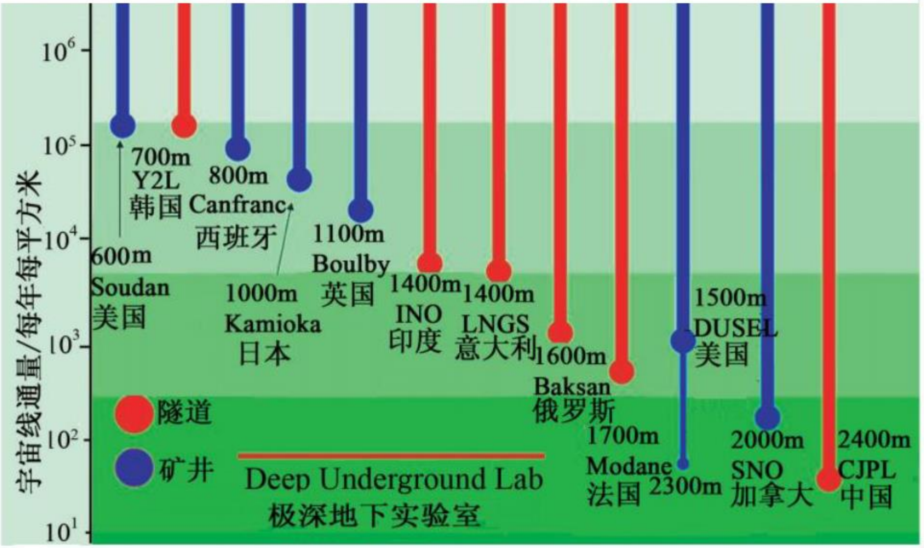
PandaX-III:
200 kg to 1 ton
^{136}Xe 0vDBD
future

China Jinping Underground Laboratory

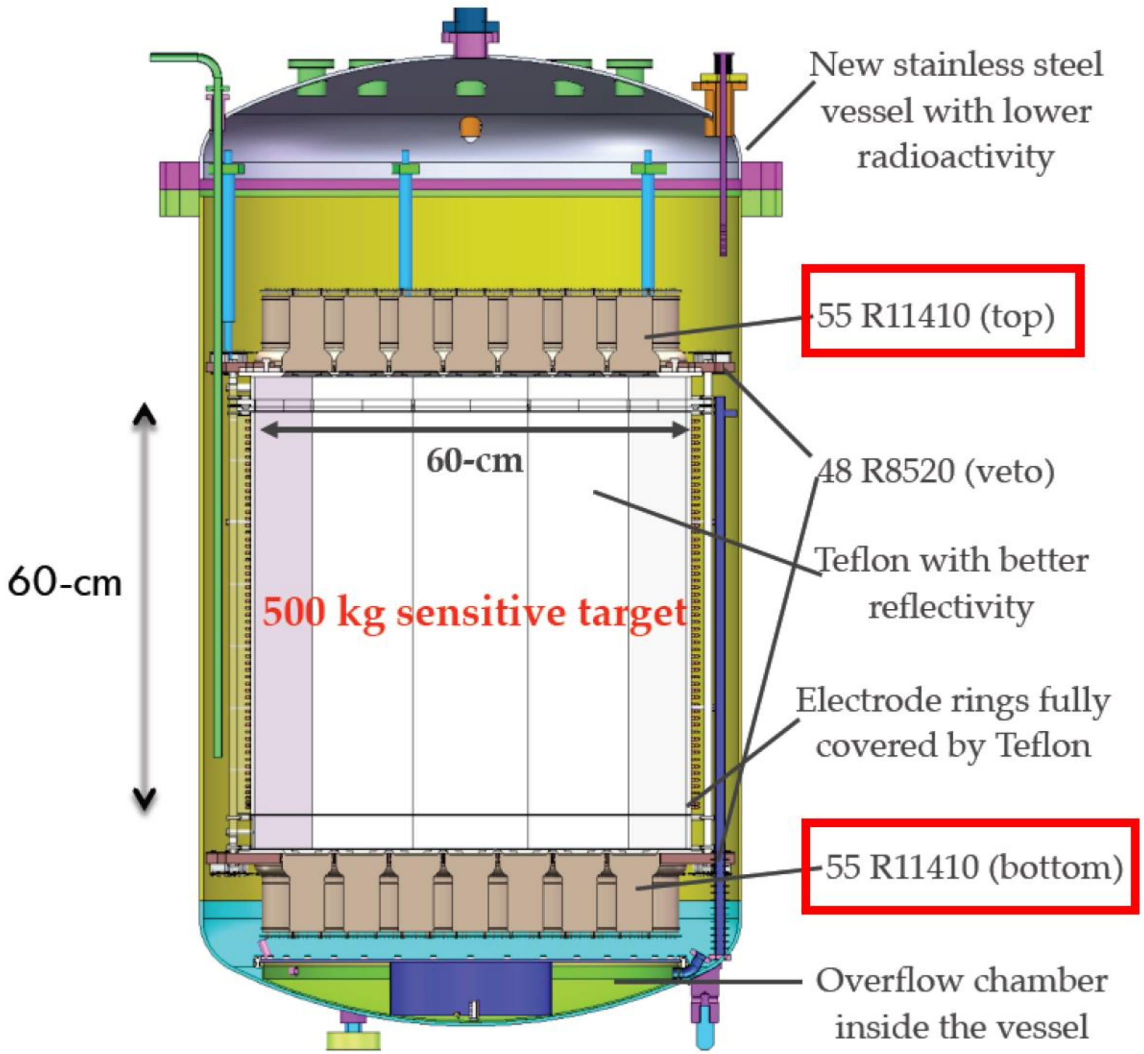
Deepest in the world (1μ/week/m^2)
and Horizontal access!







PandaX-II



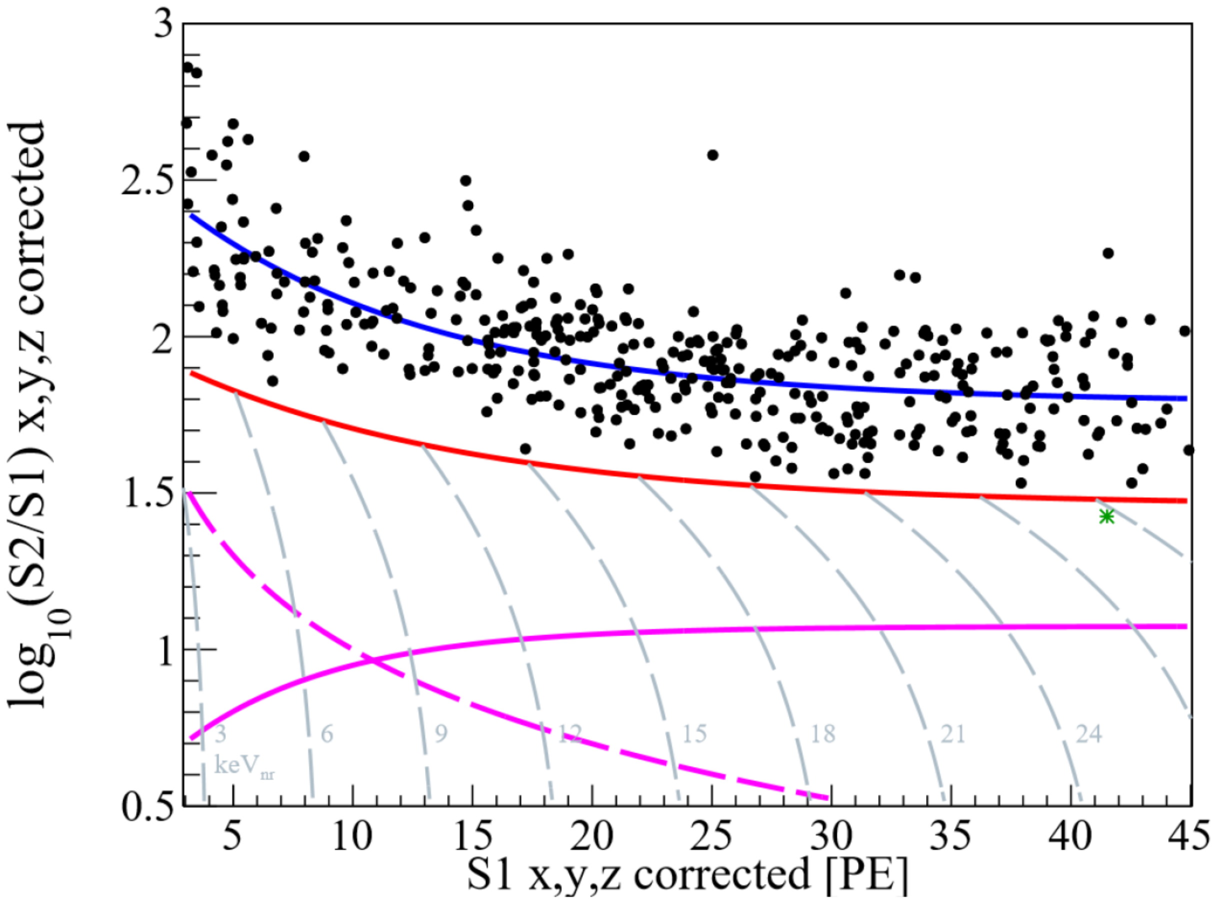
- New inner vessel with clean SS
- New and taller TPC with brand-new electrodes
- More 3" PMTs and improved base design
- New separate skin veto region

Run history

- **2014.10**: Detector installation at CJPL
- **2015**: Series of Engineering runs
- Nov 22 – Dec 14, Physics commission (Run8, 19 days, stopped due to high Krypton background)
  Phys. Rev. D. 39, 122009 (2016)
- **2016**: Distillation and re-started (Run9, 80 days)

Run8+Run9=98.7 days
Exposure:3.3x10^4 kg-day

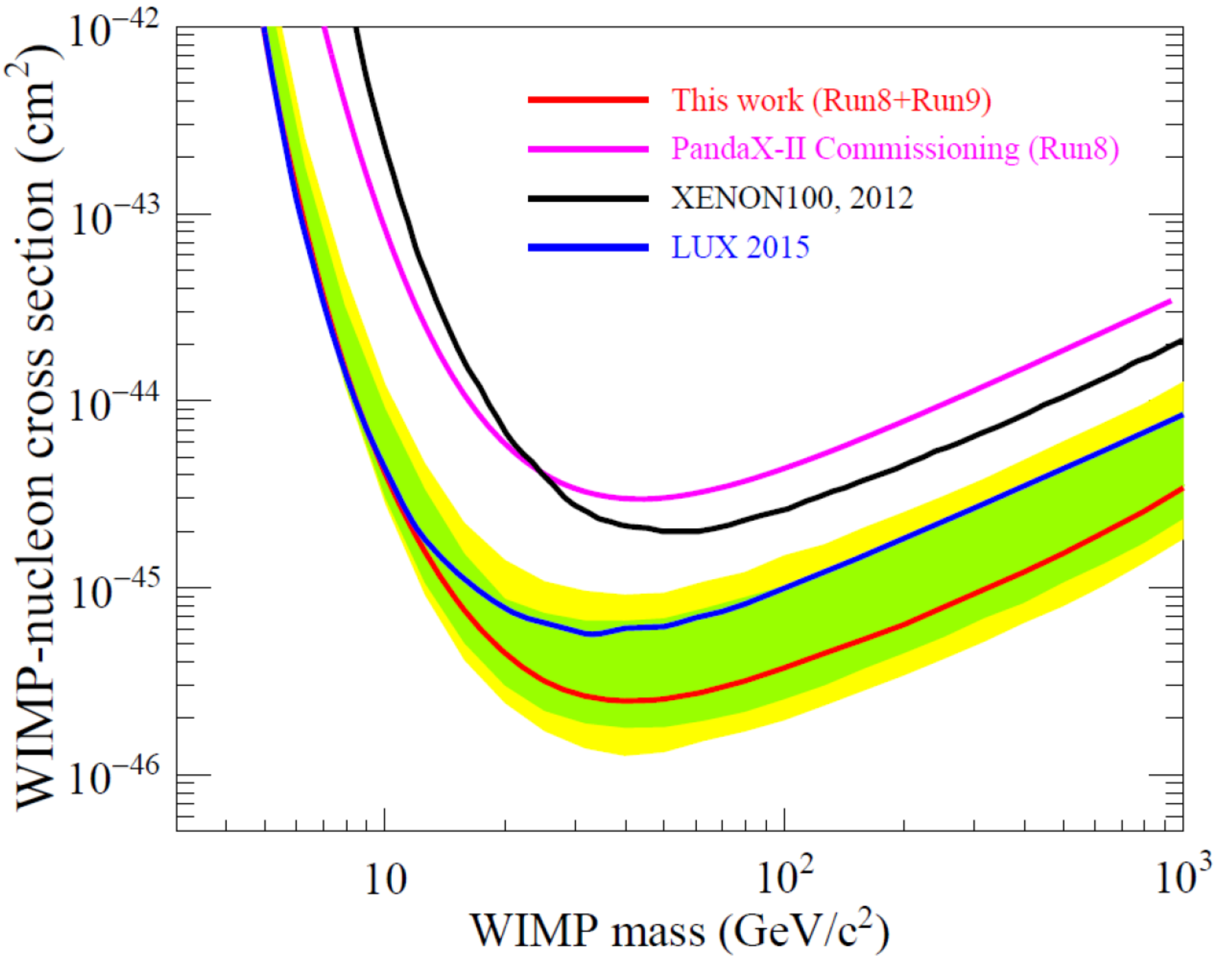
Final candidates



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

Combined results

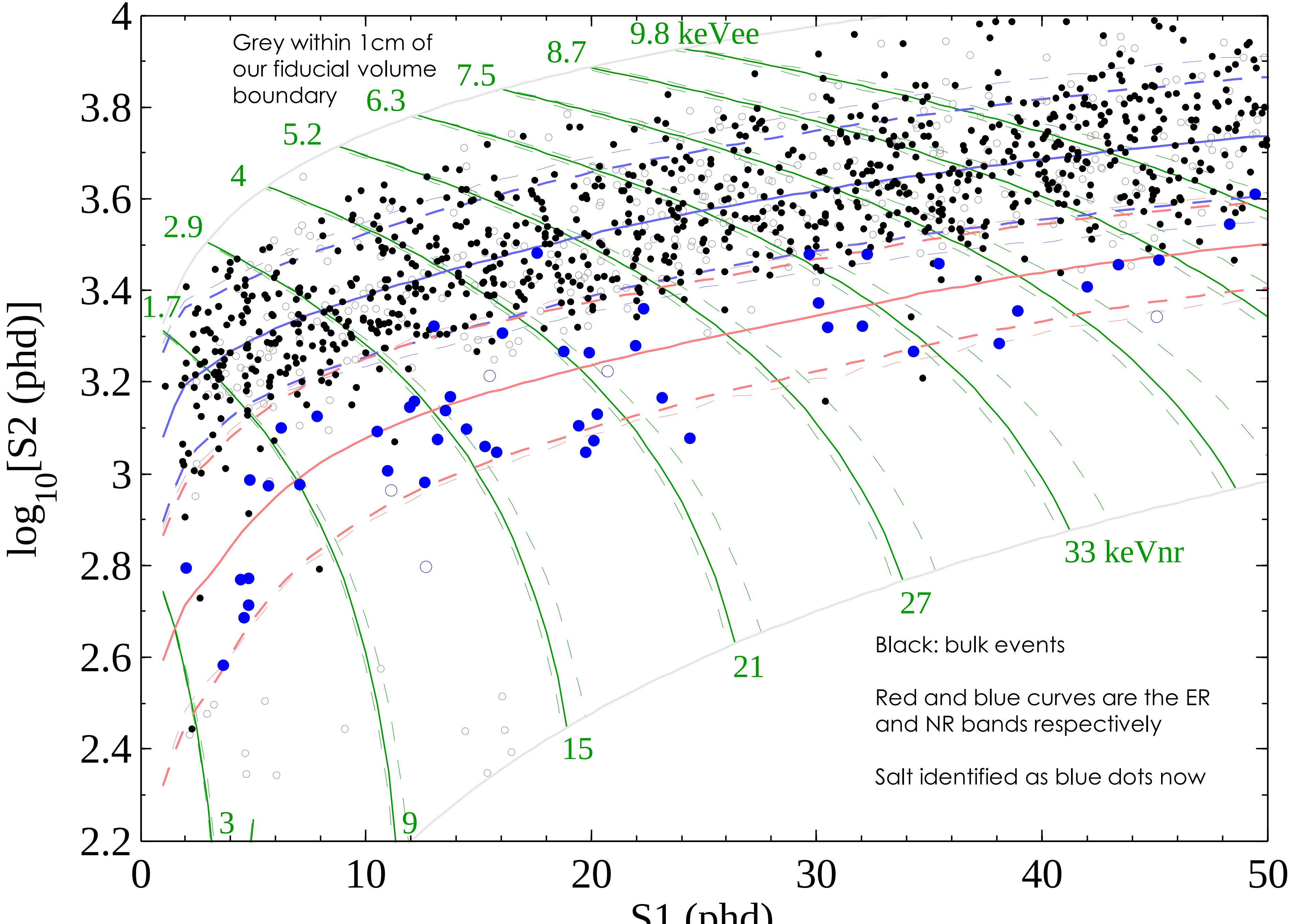
arXiv:1607.07400 Submitted to PRL



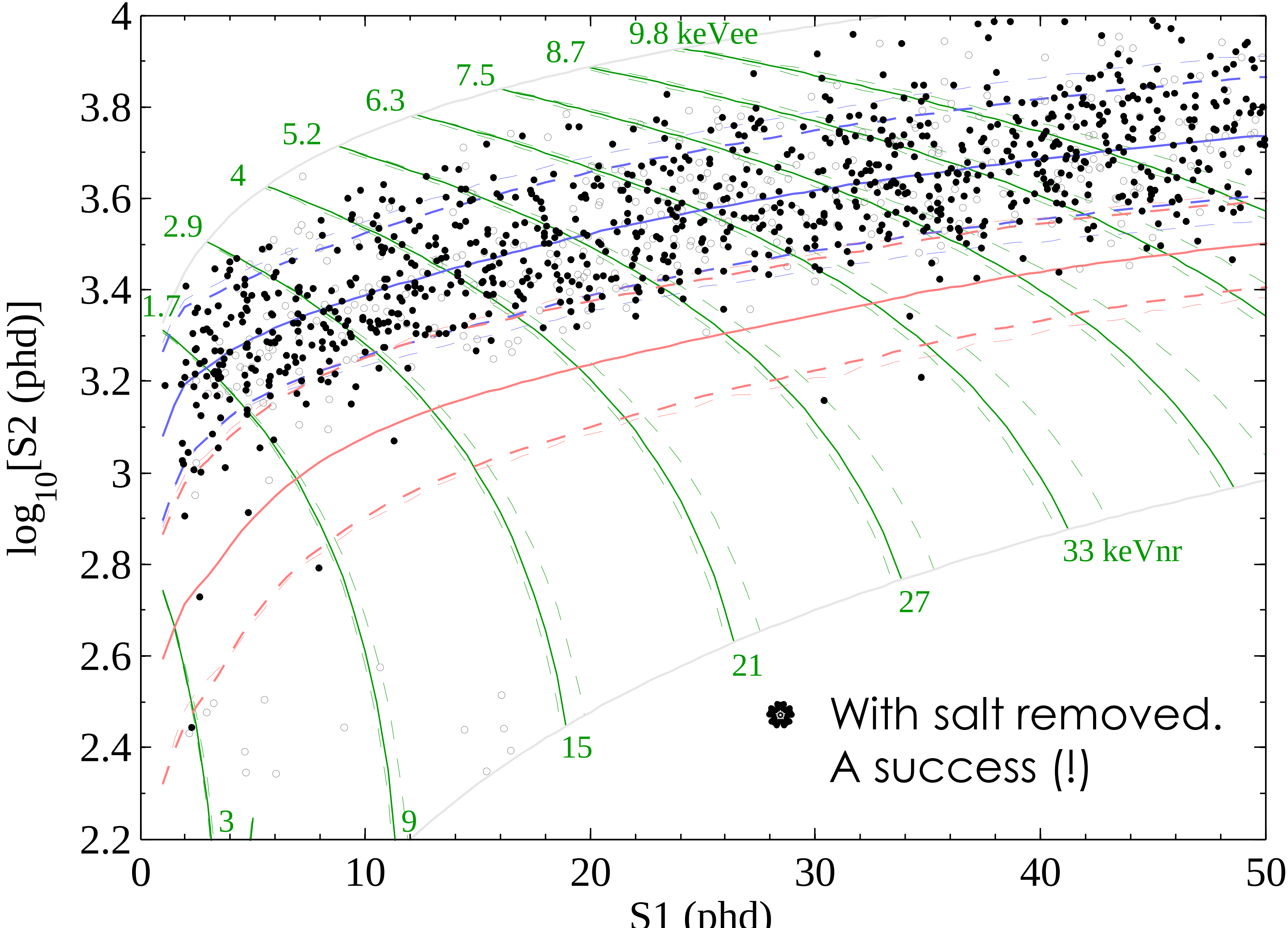
- Minimum upper limit for isoscalar SI elastic cross section reaches 2.5x10^{-46} cm^2 at 40 GeV.
- More than a factor of 2 improvement for high-mass DM compared to the LUX 2015 results

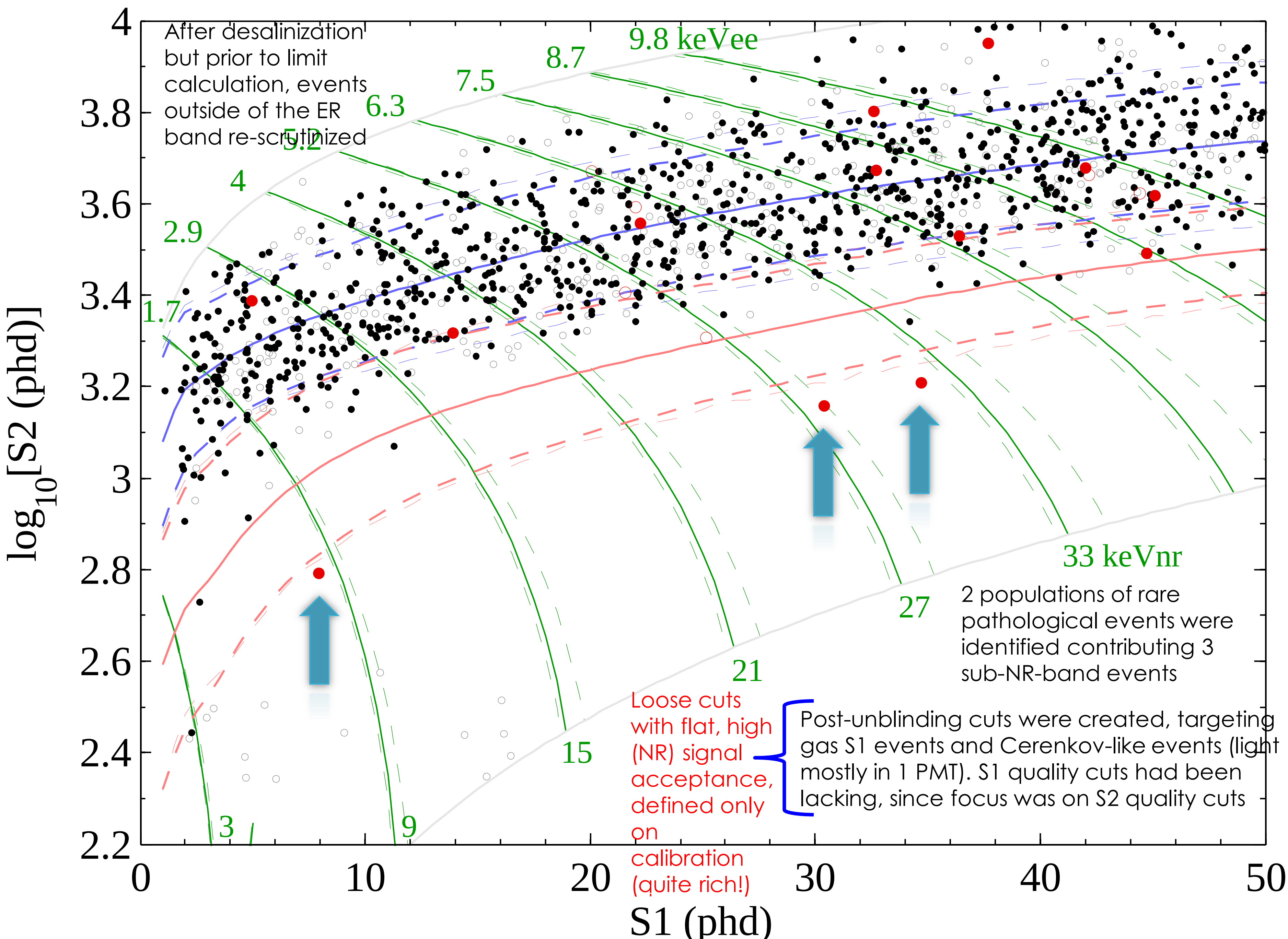
Large Underground Xenon

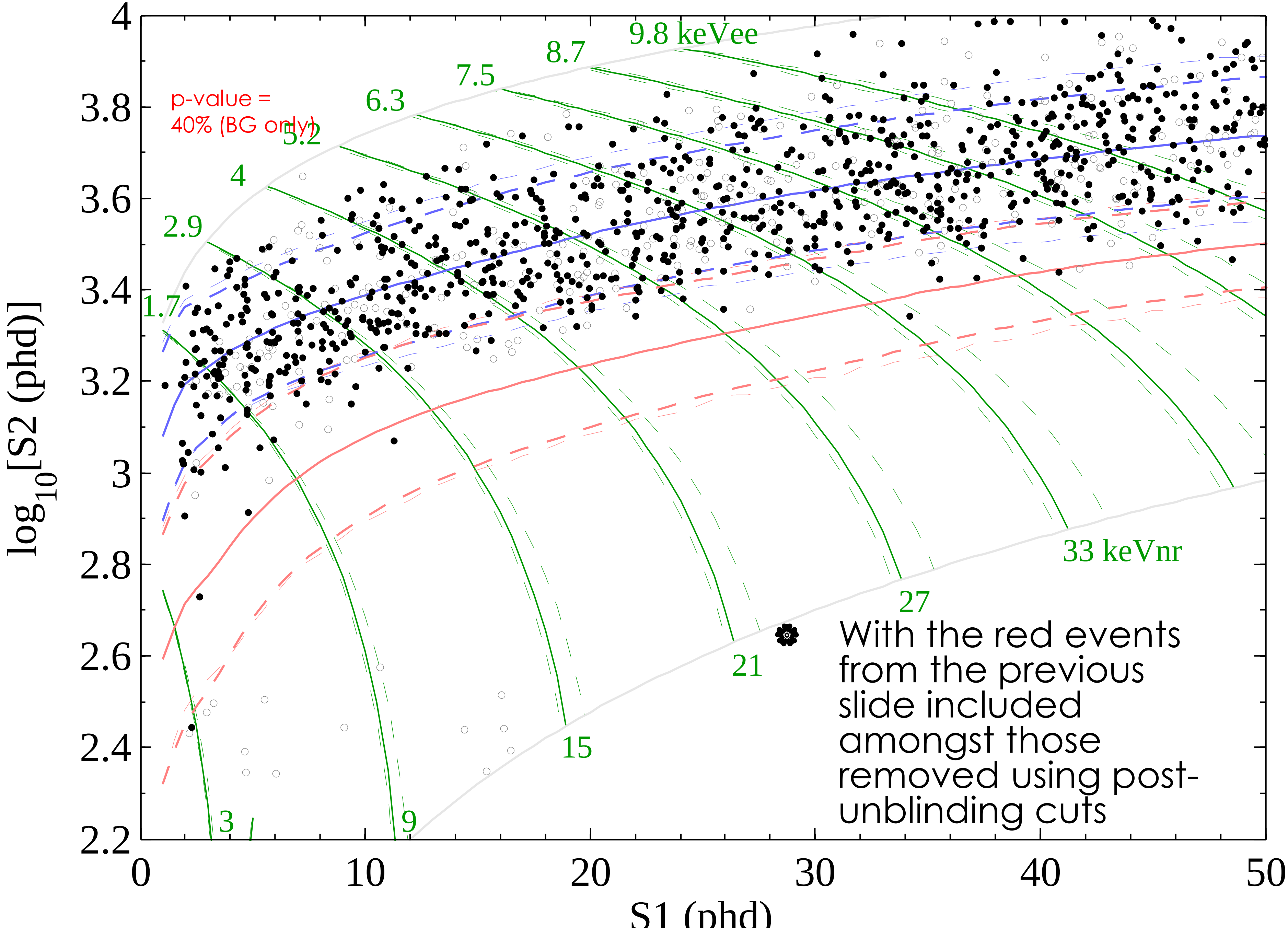
- ~1:1 ratio: 50 x 50 cm dodecagonal cylinder of highly reflective PTFE
- 370 kg LXe in total, for all crevices
  - 250 kg in active region (with field)
  - 118, 145, 100 kg fiducial across different analyses (depends on BG)
- 122 phototubes (2 x 61, top and bot)
  - Low BG, sensitive to 175 nm VUV
- Xe pre-purified of Kr-85, plus re-circulated during run for impurities
- Ultra-low BG Ti cryostat, big thermos!
- ~3-4 keV NR threshold (point of 50% efficiency pre-discrimination of ER)
- 0.2% ER leak for ~50% NR accepted (approximate, as PLR used)



Grey within 1cm of our fiducial volume boundary
9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
33 keVnr
27
21
15
9
3
Black: bulk events
Red and blue curves are the ER and NR bands respectively
Salt identified as blue dots now
log10[S2 (phd)]
S1 (phd)


9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
3
9
15
21
27
33 keVnr
With salt removed.
A success (!)
log$_{10}$[S2 (phd)]
S1 (phd)
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
0
10
20
30
40
50


After desalinization but prior to limit calculation, events outside of the ER band re-scrutinized
9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
33 keVnr
27
21
15
9
3
2 populations of rare pathological events were identified contributing 3 sub-NR-band events
Loose cuts with flat, high (NR) signal acceptance, defined only on calibration (quite rich!)
Post-unblinding cuts were created, targeting gas S1 events and Cerenkov-like events (light mostly in 1 PMT). S1 quality cuts had been lacking, since focus was on S2 quality cuts
$\log_{10}$[S2 (phd)]
S1 (phd)
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
0
10
20
30
40
50



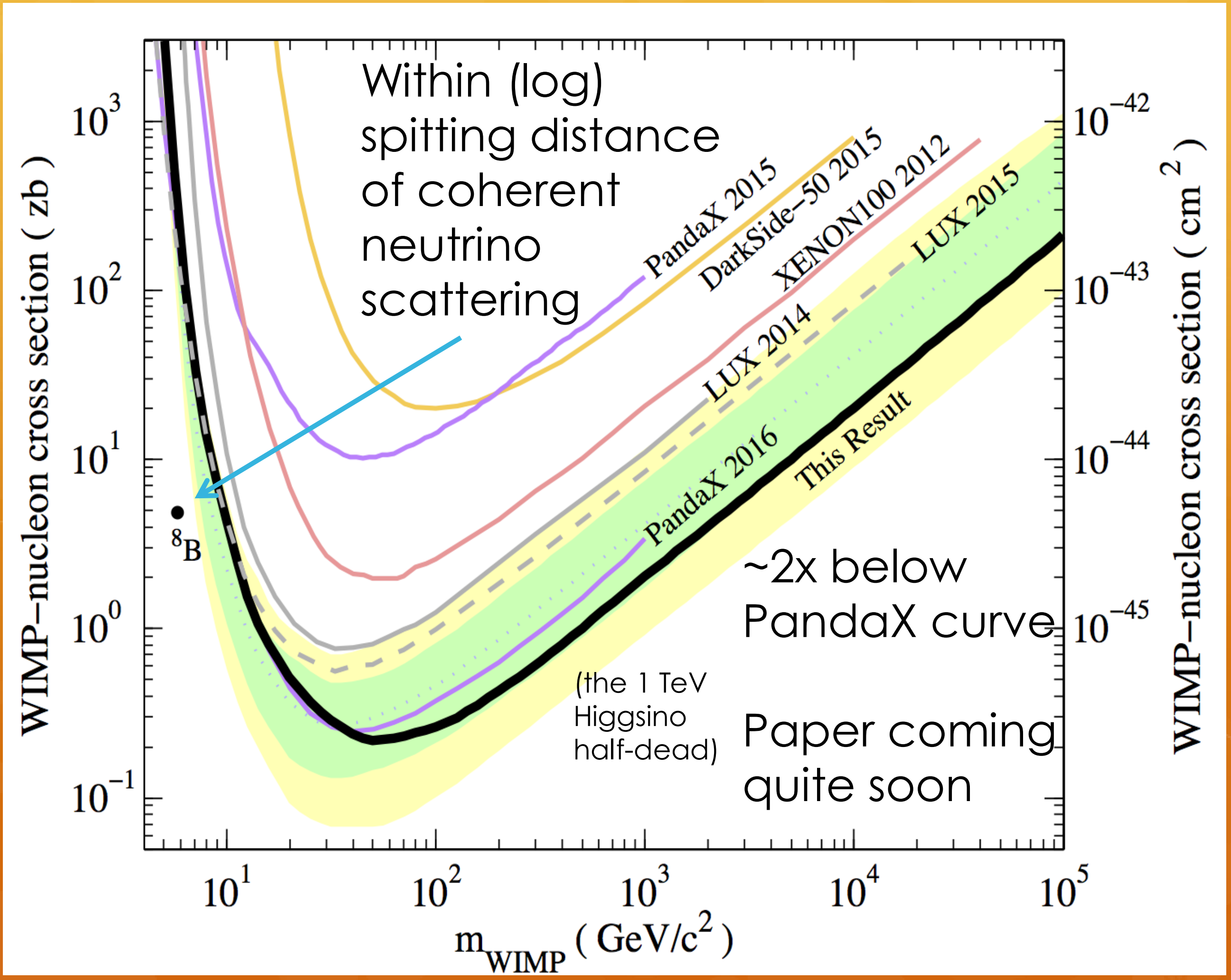
p-value =
40% (BG only)
9.8 keVee
8.7
7.5
6.3
5.2
4
2.9
1.7
3
9
15
21
27
33 keVnr
With the red events
from the previous
slide included
amongst those
removed using post-
unblinding cuts
log10[S2 (phd)]
S1 (phd)
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
0
10
20
30
40
50

WIMP-nucleon SI Exclusion

- Our best, lowest exclusion is at <u>50 GeV: 2.2 x10^{-46} cm^2</u> (That's 0.22 zeptobarns in σ!)
  - 1 order of magnitude off XENON1T
  - Within < 2 orders of LZ projection
- Comparable to LUX 2015 re-analysis of 3 months' worth of data at low mass but FOUR TIMES better at high mass. (Final G1?)

(LUX. zepto = 10^{-21})

(NOT preliminary. Analysis/limit is final. Text under internal review.)



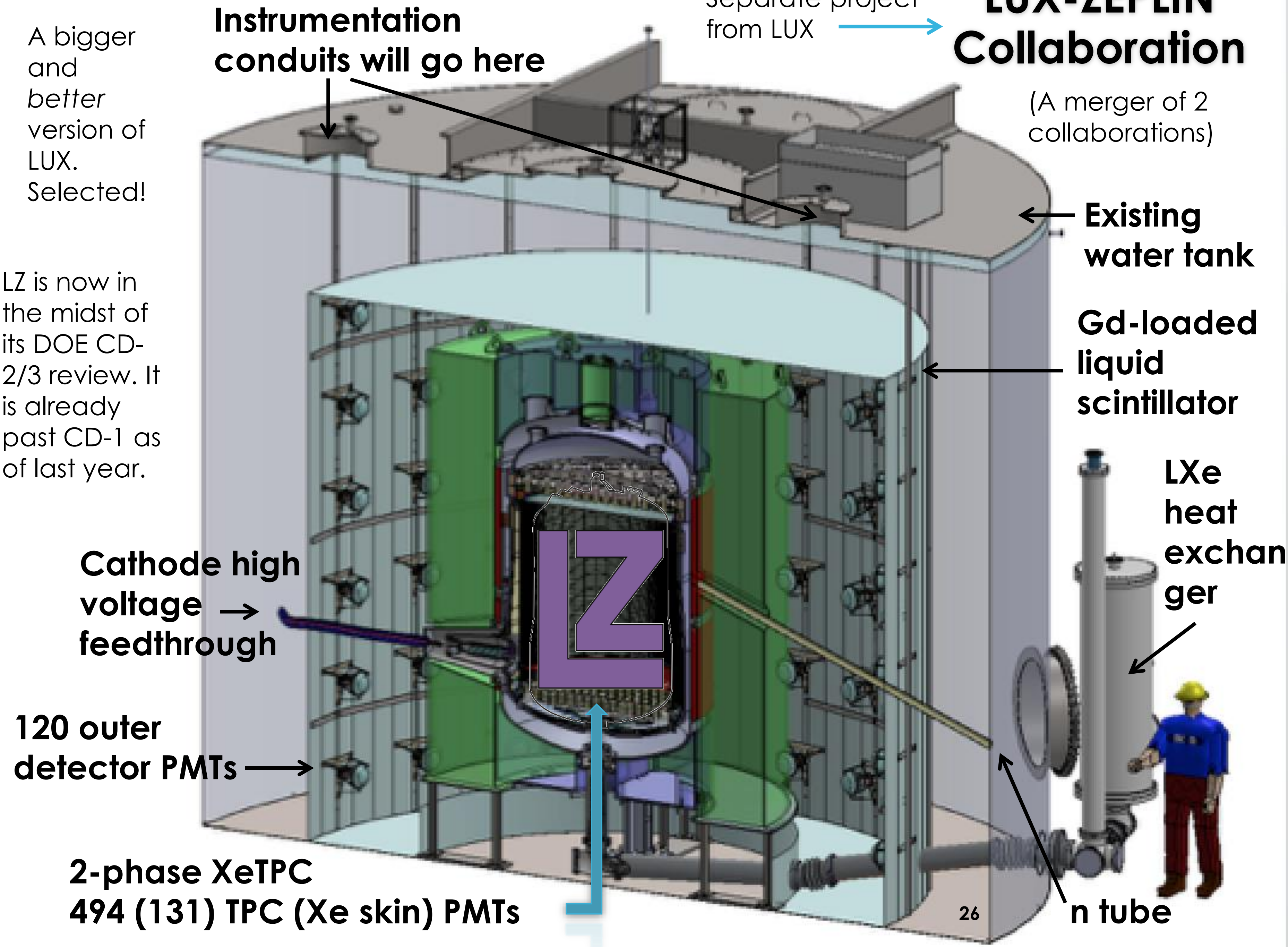
LUX-ZEPLIN Collaboration

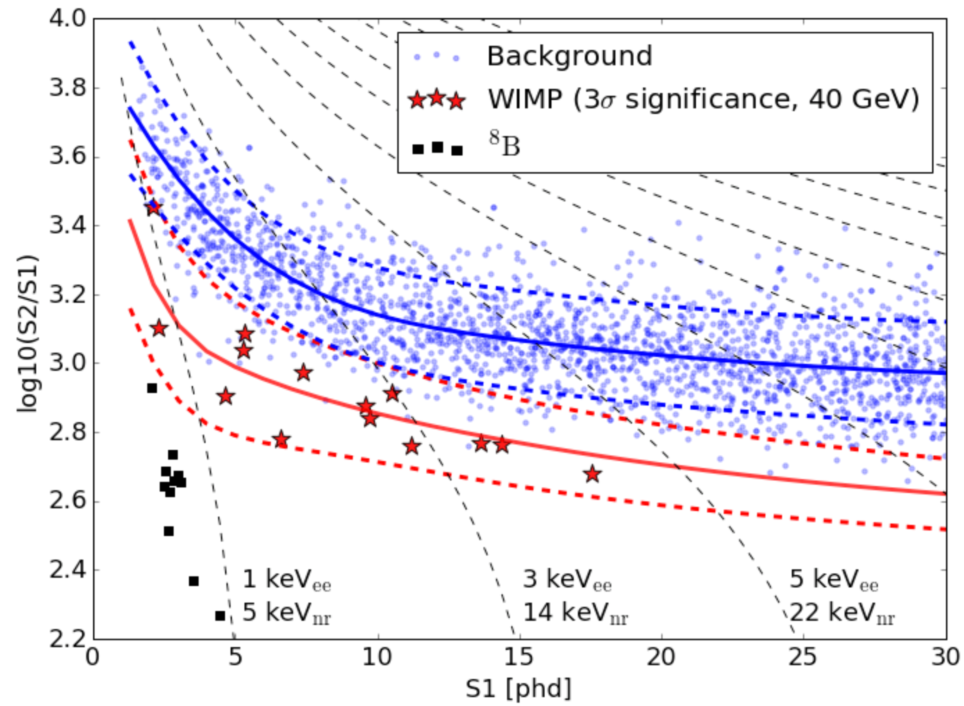
Separate project from LUX →

(A merger of 2 collaborations)

A bigger and *better* version of LUX. Selected!

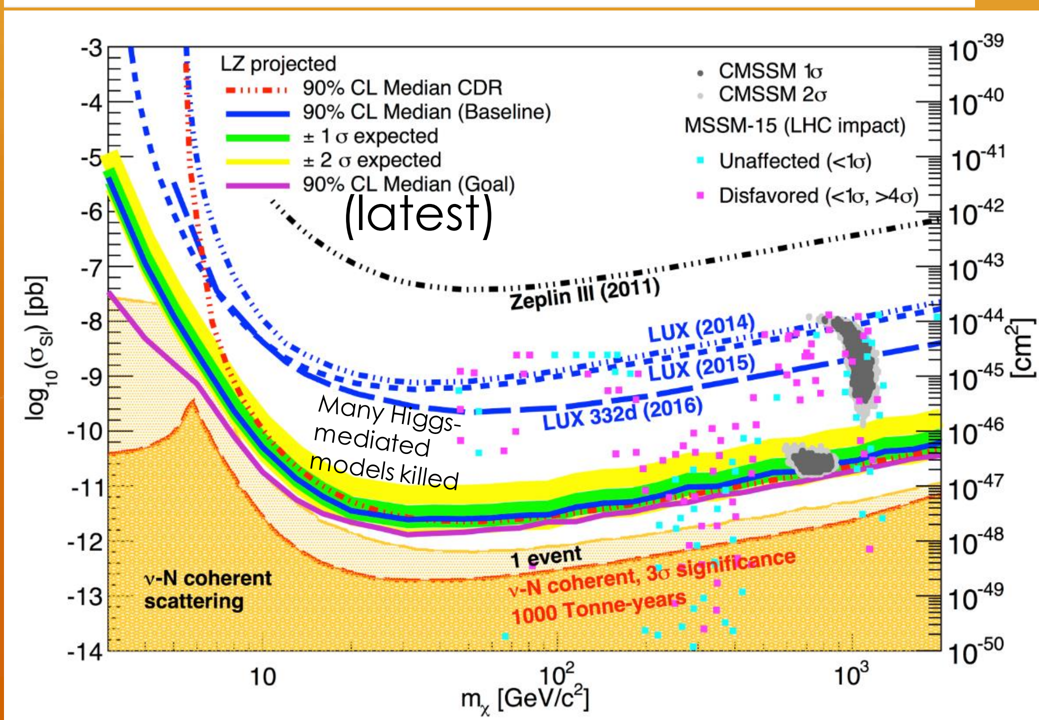
LZ is now in the midst of its DOE CD-2/3 review. It is already past CD-1 as of last year.





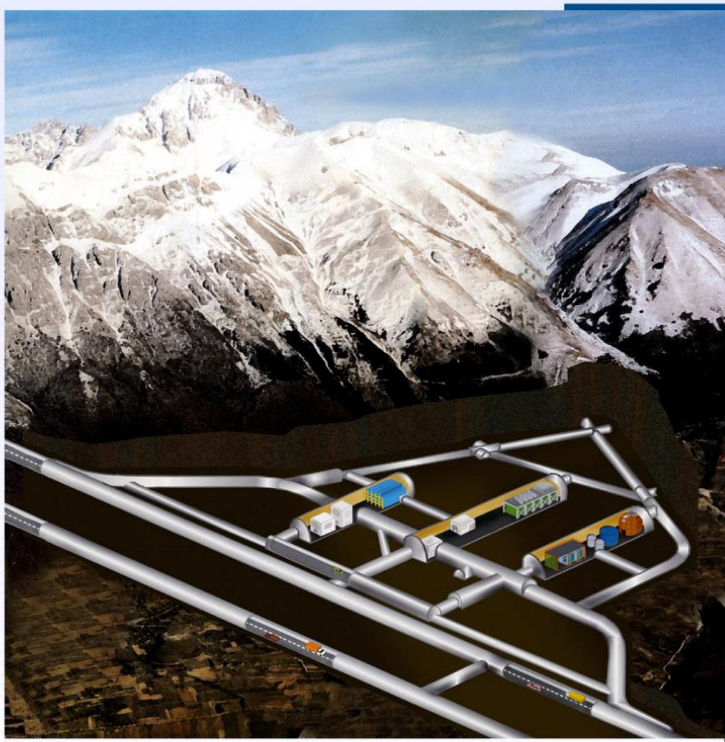
LZ's Reach

- Turning on by 2020 with 1,000 initial live-days plan
- 10 tons total, 7 tons active, ~5.6 ton fiducial mass
  - Due to unique triple veto
- GOALS: < 3 x 10^{-48} cm^2, at 40 GeV. Clip ν shoulder



*plot and models from LZ's Conceptual Design Report, arXiv:**1509.02910**

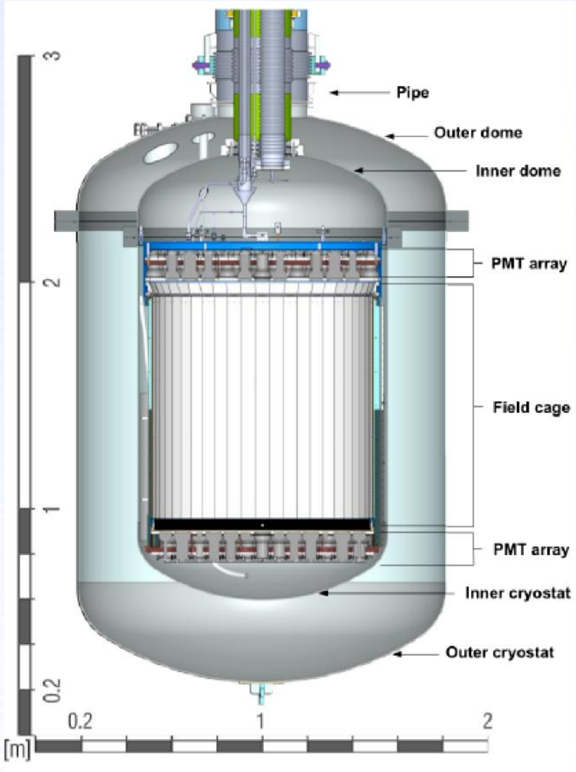
XENON1T

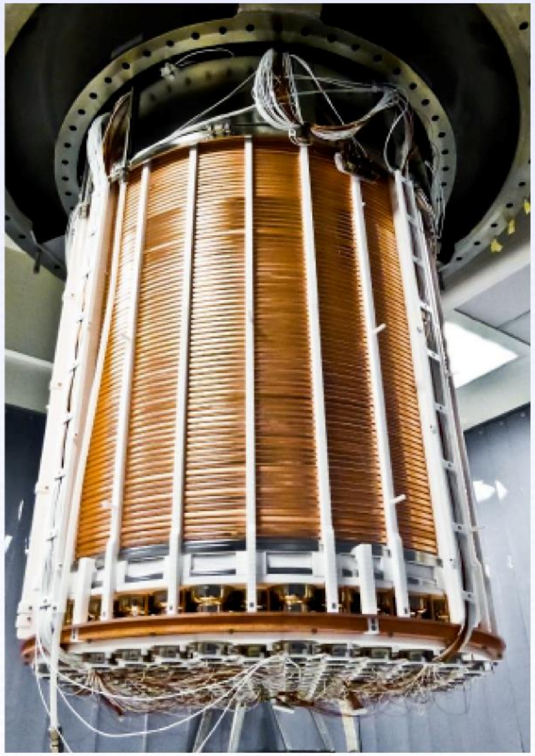


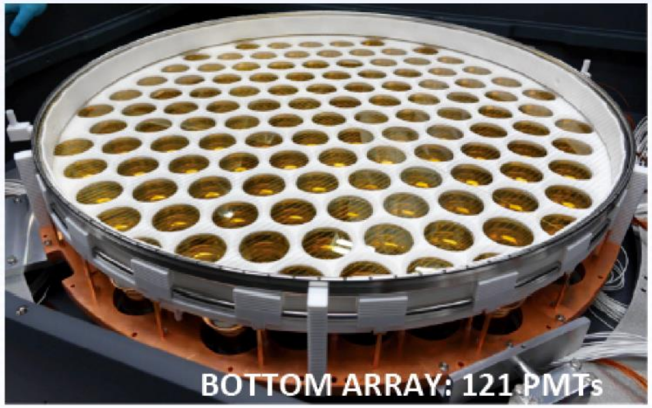
- Reduce background 100X from XENON100
  - Goal: 2 t-yr exposure
- Increase sensitivity by factor 100 compared to XENON100
  - 1.6 X 10^{-47} cm^2 @ 50 GeV WIMP

- Located in LNGS
- Many systems upgraded from successful operation of XENON100
- 3.2 tons Xe (2.0 t active volume)
- Water Cherenkov muon veto
- Cyrogenics plant for high purity xenon (~10t)

TPC



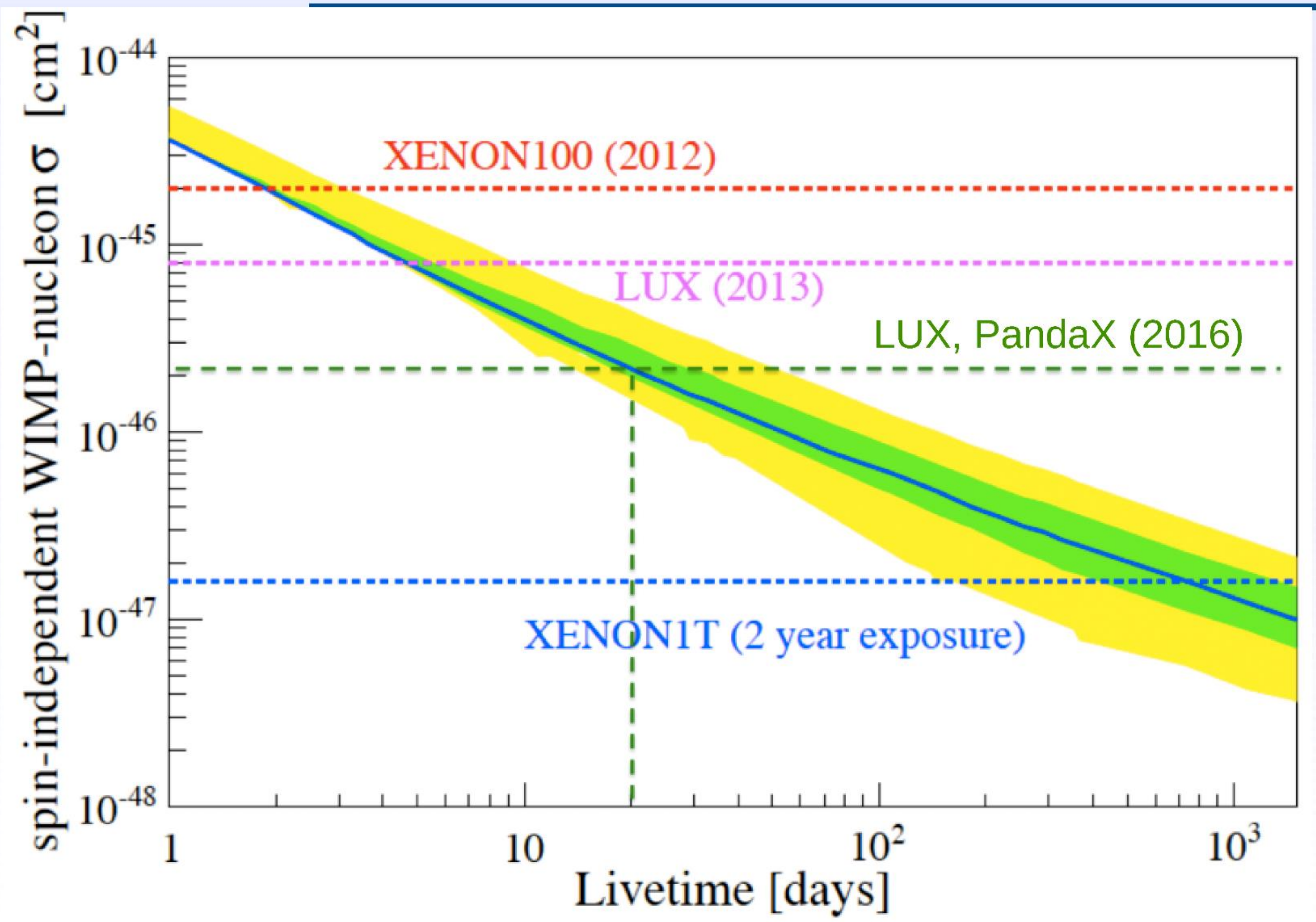




- Largest DM detector ever built!
- Filled with LXe since April 2016
- 248 PMTs
- 96 cm drift X 96 cm diameter
- High reflectivity teflon walls

- TPC now operational!
- In conjunction with commissioning of remaining systems

Projected Sensitivity

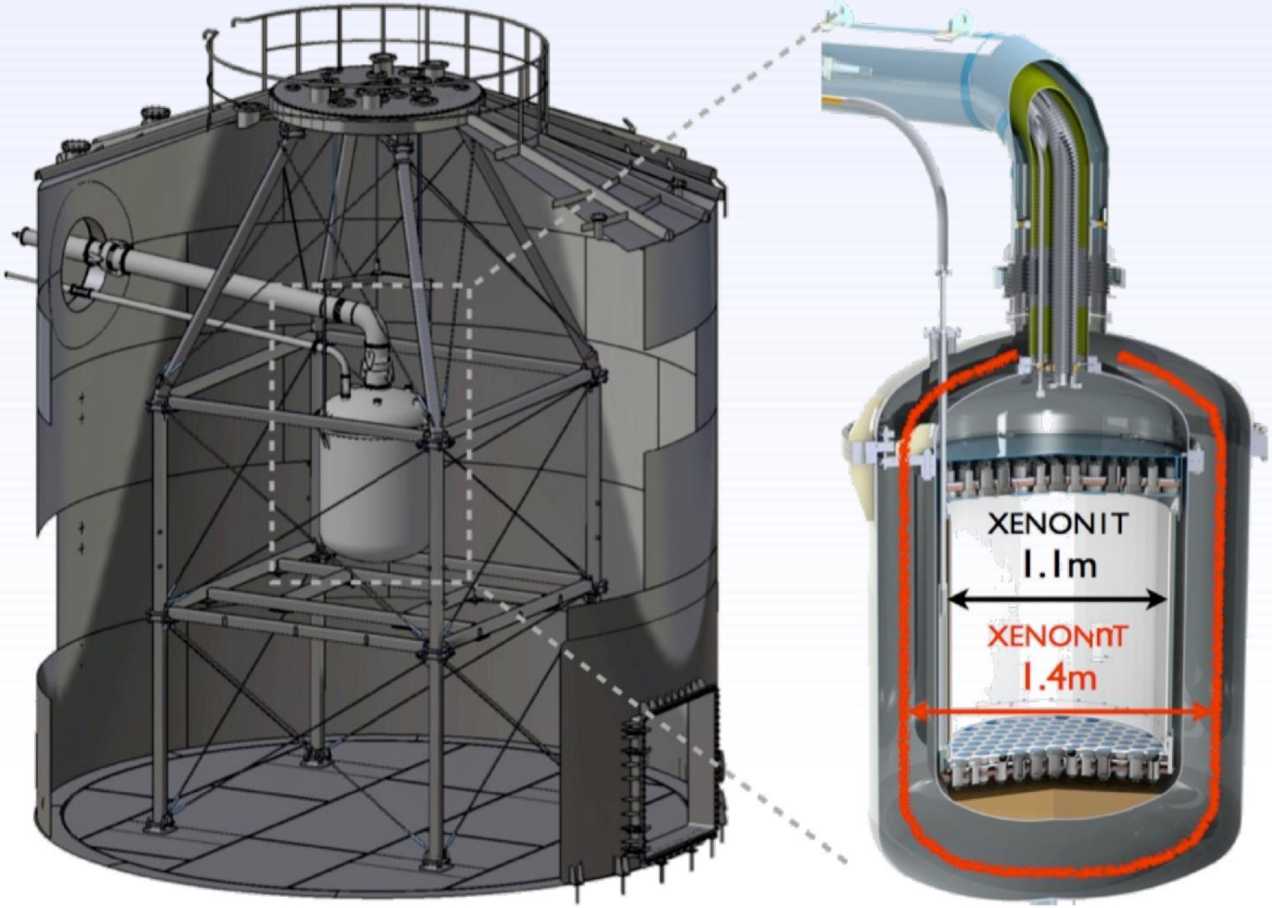


- Only need 20 days to reach LUX/PandaX sensitivity!
- Commissioning nearly complete
- Operations of TPC and other systems already underway

- 2.0 X 10^{-47} cm^2
- @ 50 GeV WIMP
- 2 t-yr data

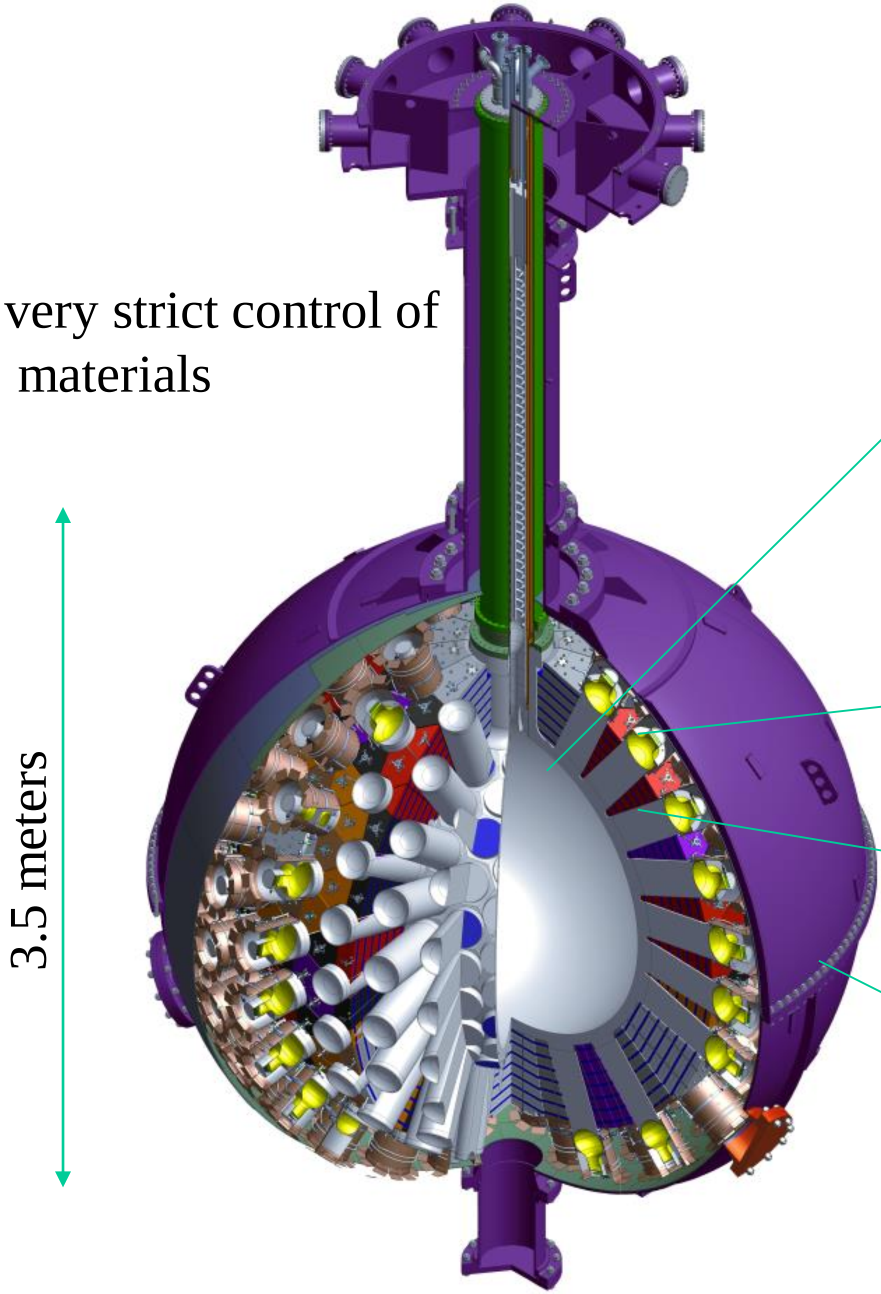
Upgrade: XENONnT

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



DEAP-3600 Detector

very strict control of
materials



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

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

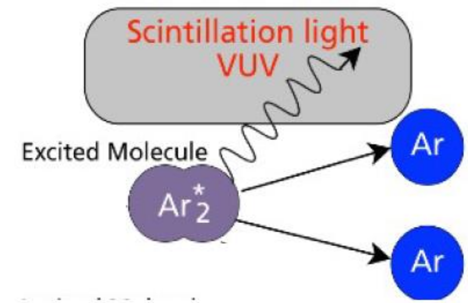
255 Hamamatsu
R5912 HQE PMTs 8-inch
(Light Sensors)

50 cm light guides +
PE shielding provide neutron
moderation

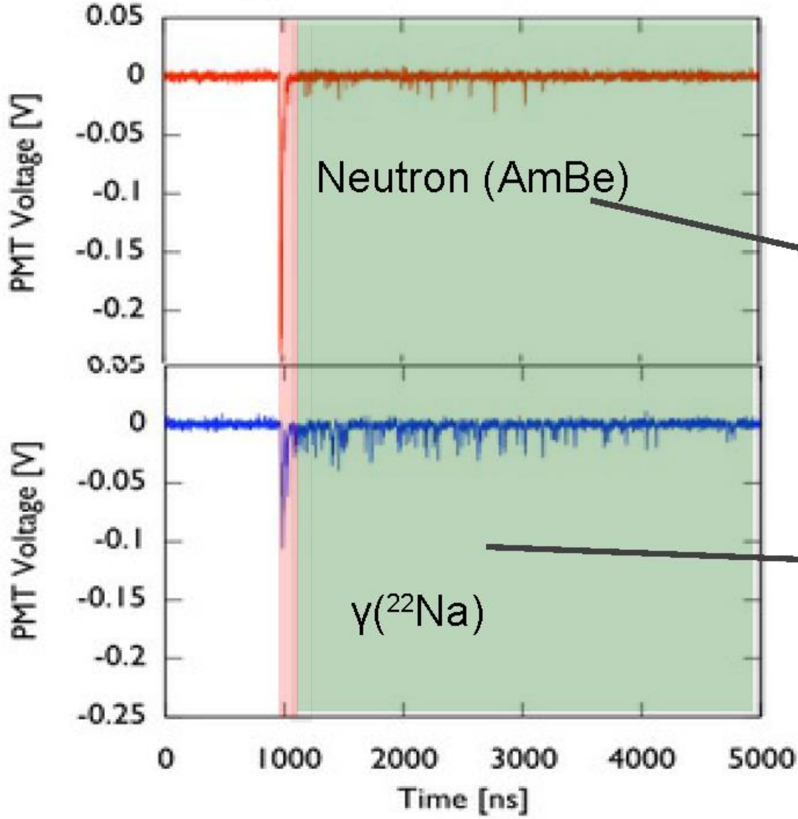
Scintillation light only – PSD
for background discrimination

Pulse shape discrimination (PSD)

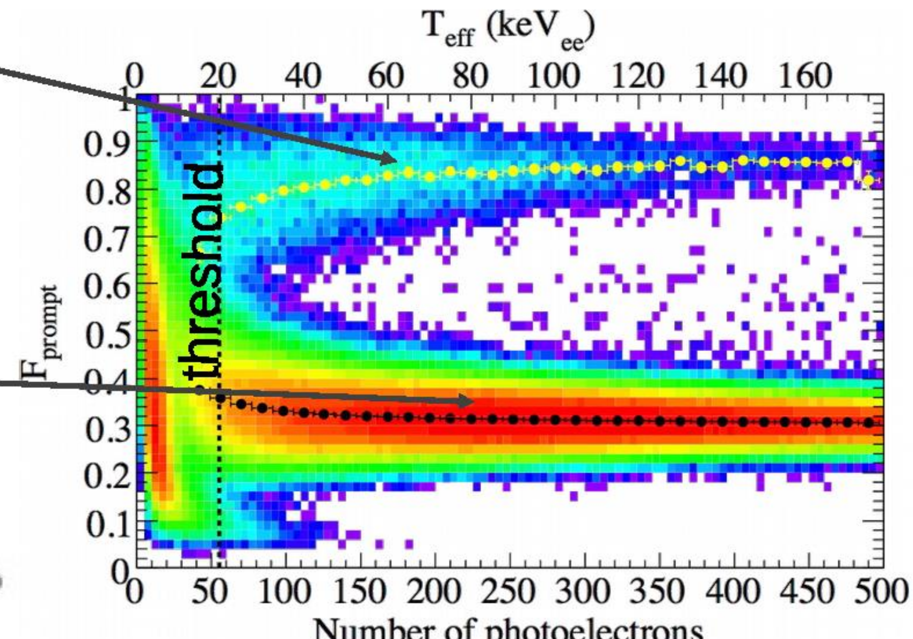
Ar singlet and triplet excited states have well separated lifetimes (7ns vs. ~1.5us)



PMT signal:



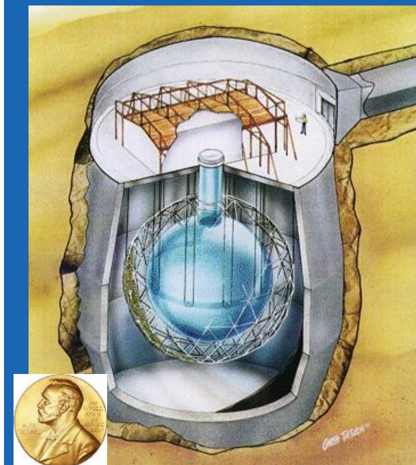
$$\text{FPrompt} = \frac{N_{prompt}}{N_{prompt} + N_{Late}}$$



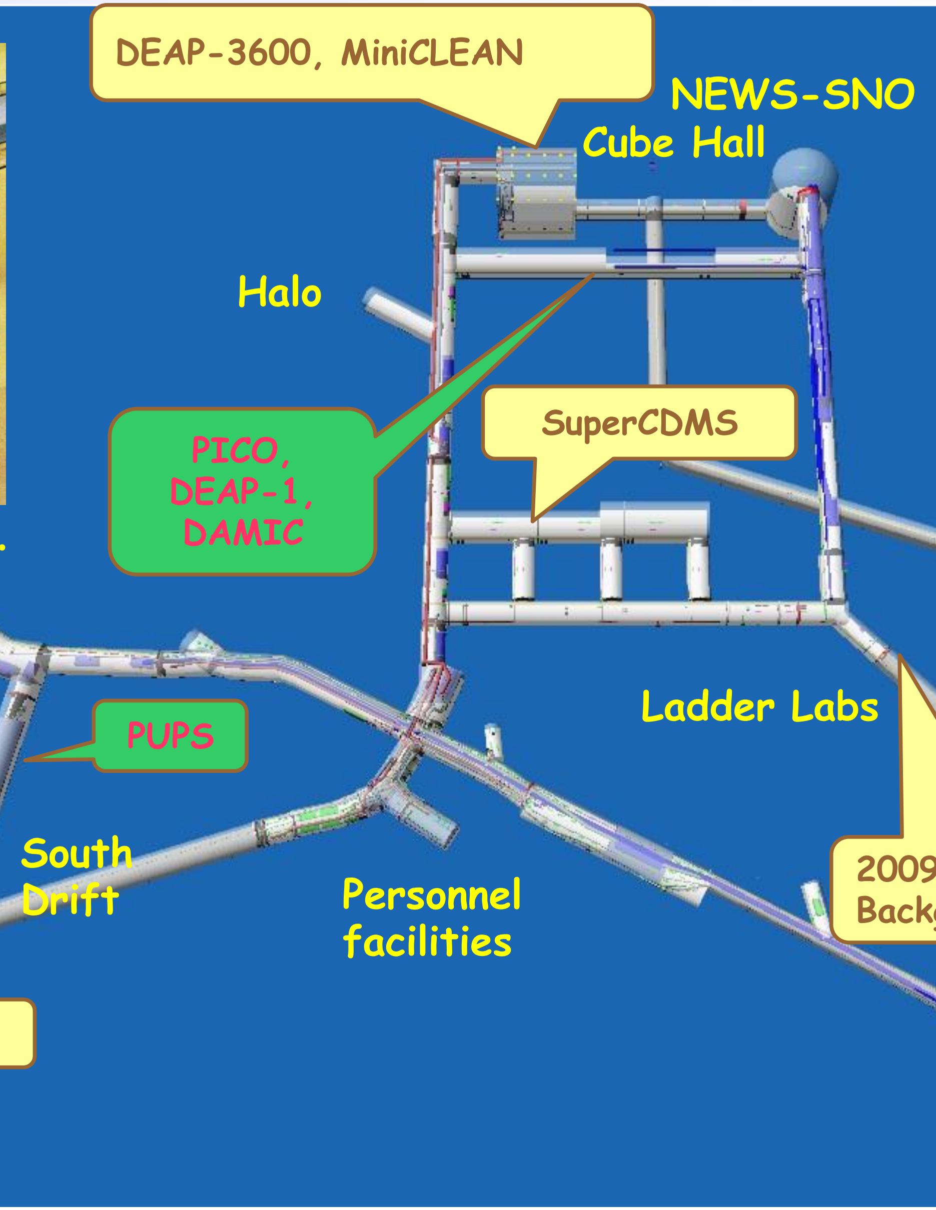
Prompt : 0-150ns
Late: 150ns-10μs

Single phase LAr:
scintillation channel is sufficient, no ionization channel

SNOLAB

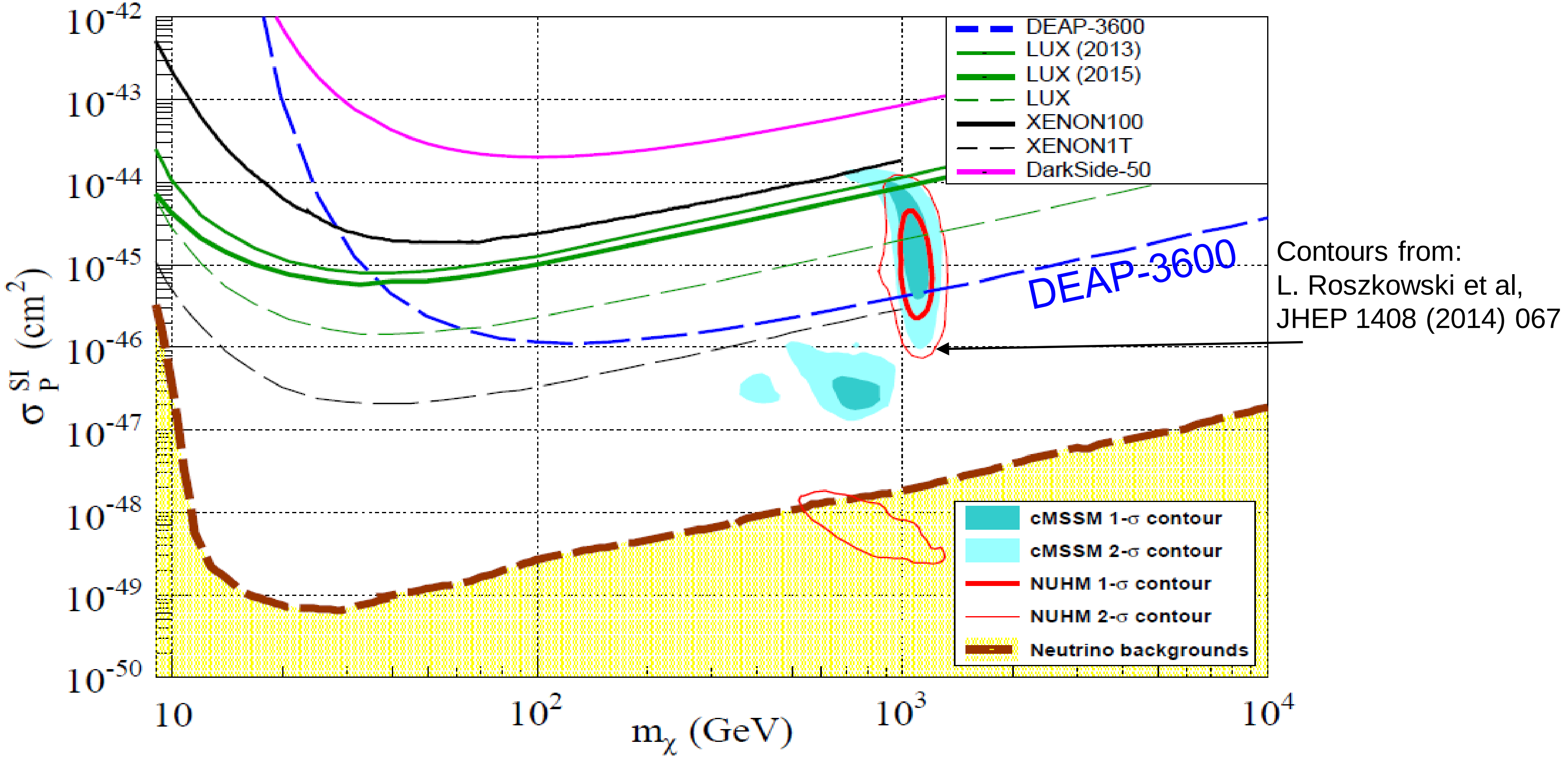


original SNO exp.



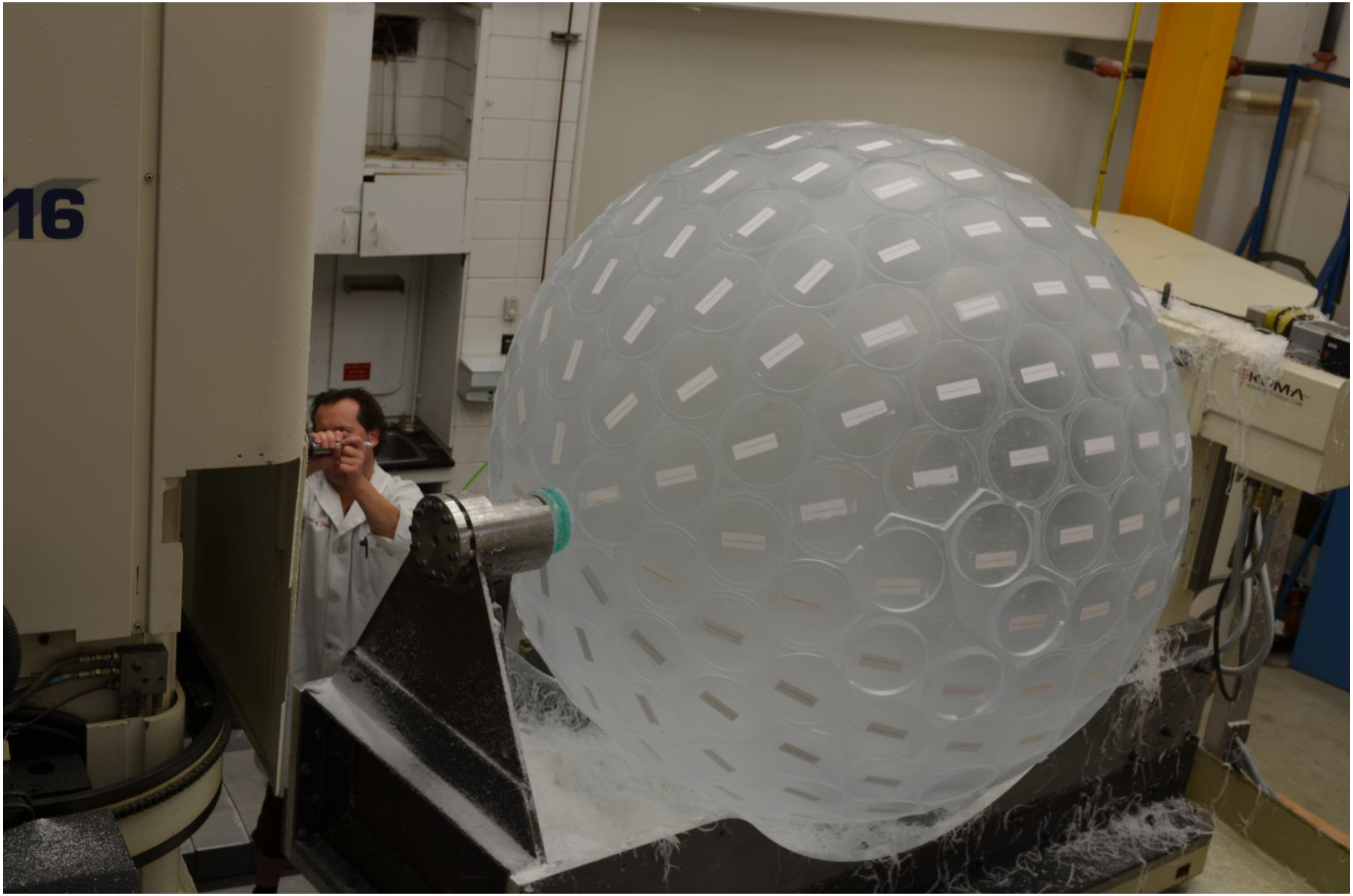
Cube Hall in 2009

Physics reach



- All available experimental data combined (LHC, LUX, Planck) are still consistent with even the simplest versions of SUSY (cMSSM, NUHM)
- Remaining parameter space is directly probed by direct WIMP searches with tonne scale detectors: DEAP-3600, XENON1T, LUX/LZ
- Complementarity with LHC (cMSSM/NUHM are mostly out of reach of the 14 TeV run!)

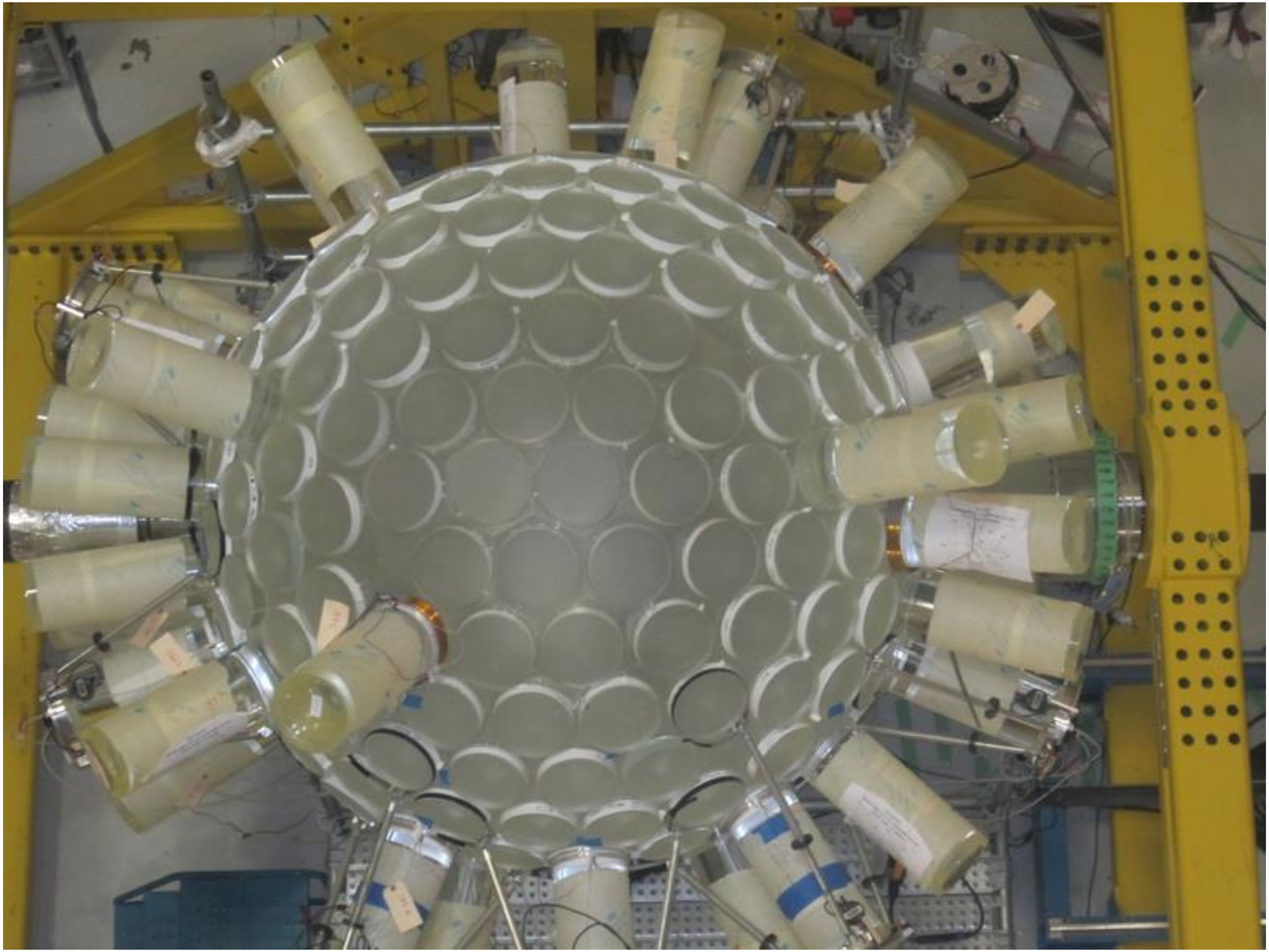
DEAP Acrylic Vessel with Light Guide “Stubs” July 2012, U Alberta



Mark Boulay

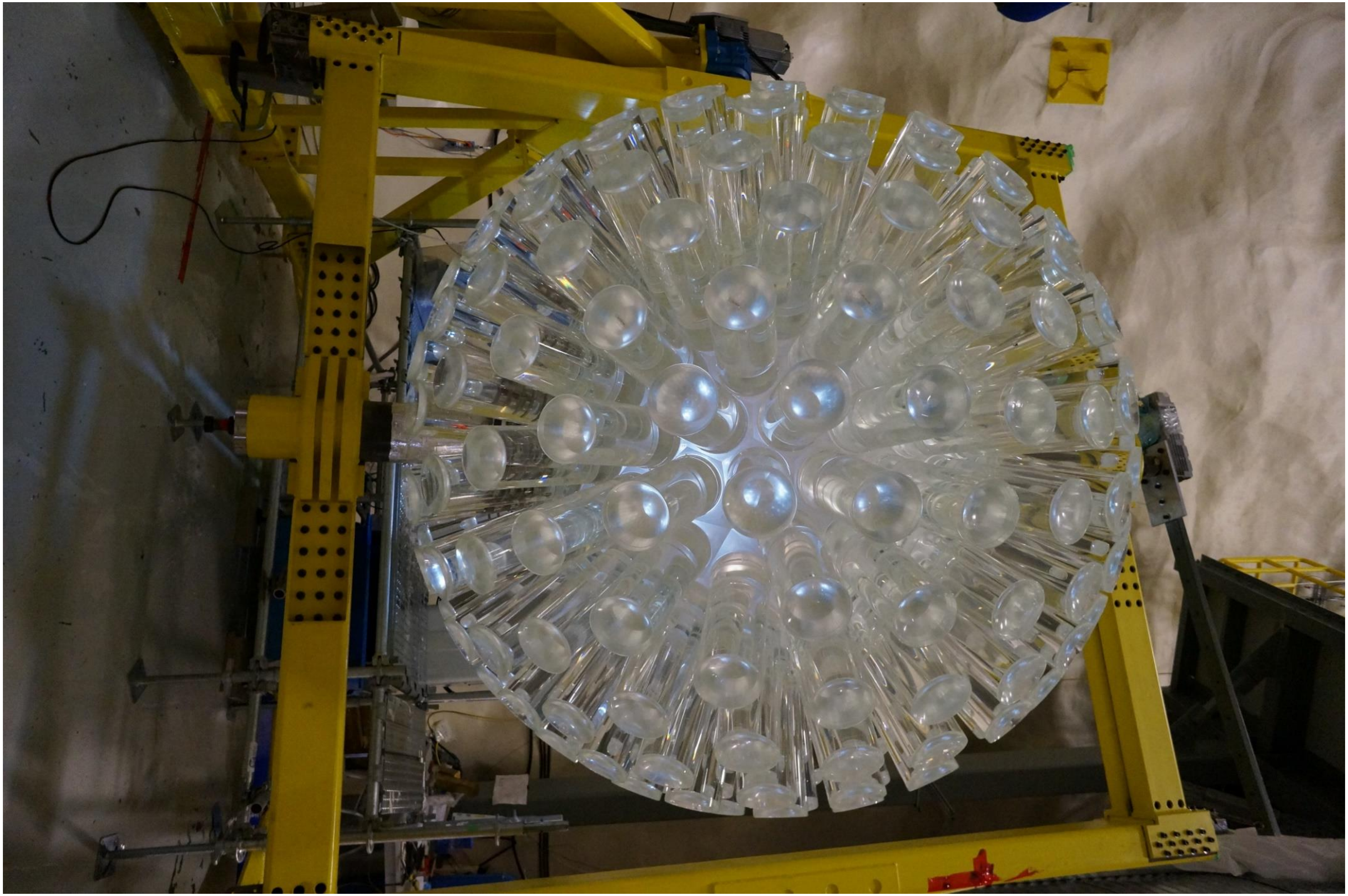
Ultrapure acrylic vessel, controlled exposure to radon

Bonding light guides to the DEAP AV, underground at SNOLAB



Mark Boulay

DEAP Acrylic Vessel (2013)

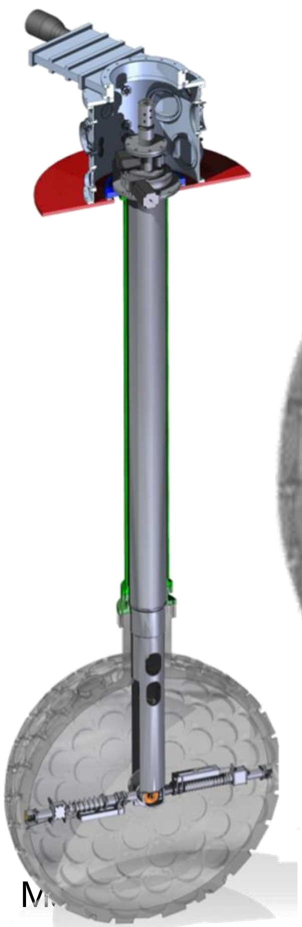


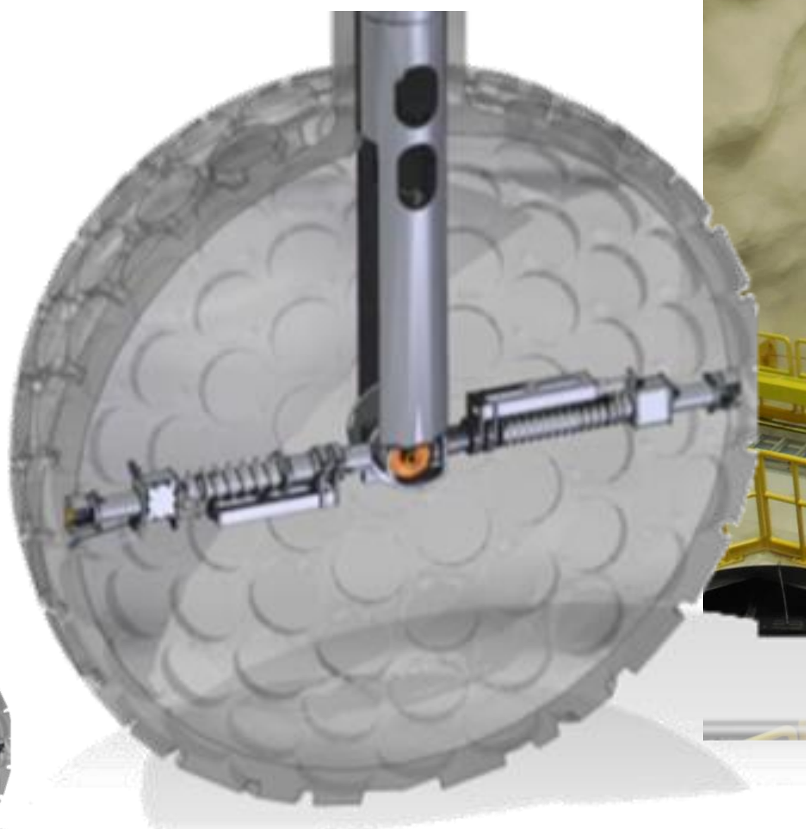
Mark Boulay

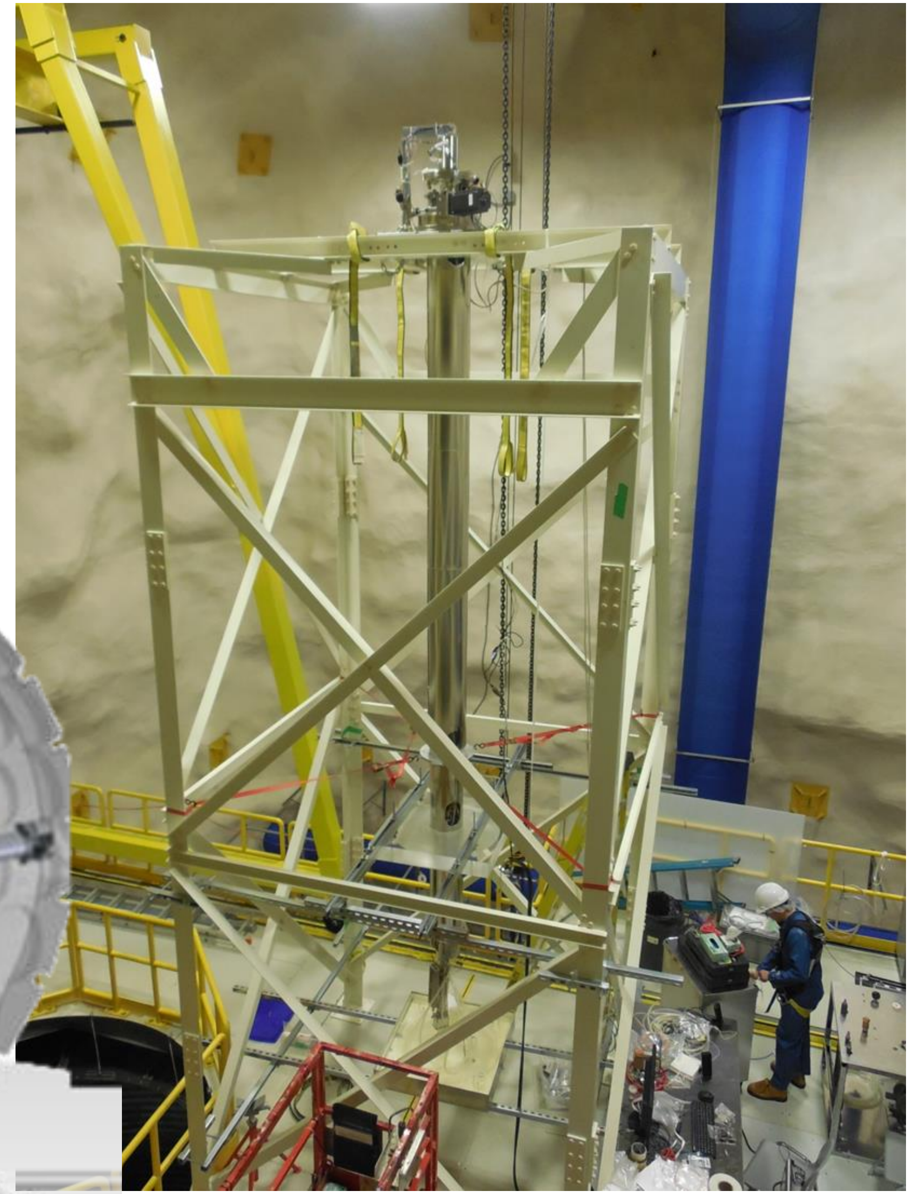
Moving the AV into temporary assembly room

Acrylic Vessel Resurfacer

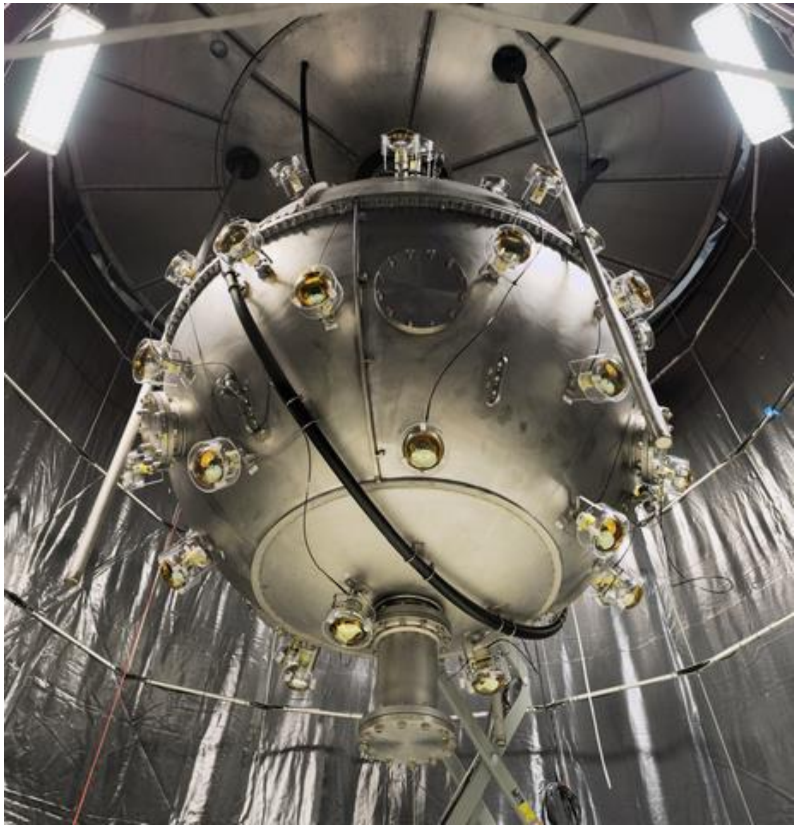
- Mechanical sander to clean inner surface
- Components selected for low radon emanation
- Remove 0.5-mm surface *in situ* with N_2 purge
- Cleans surface to bulk-level impurities







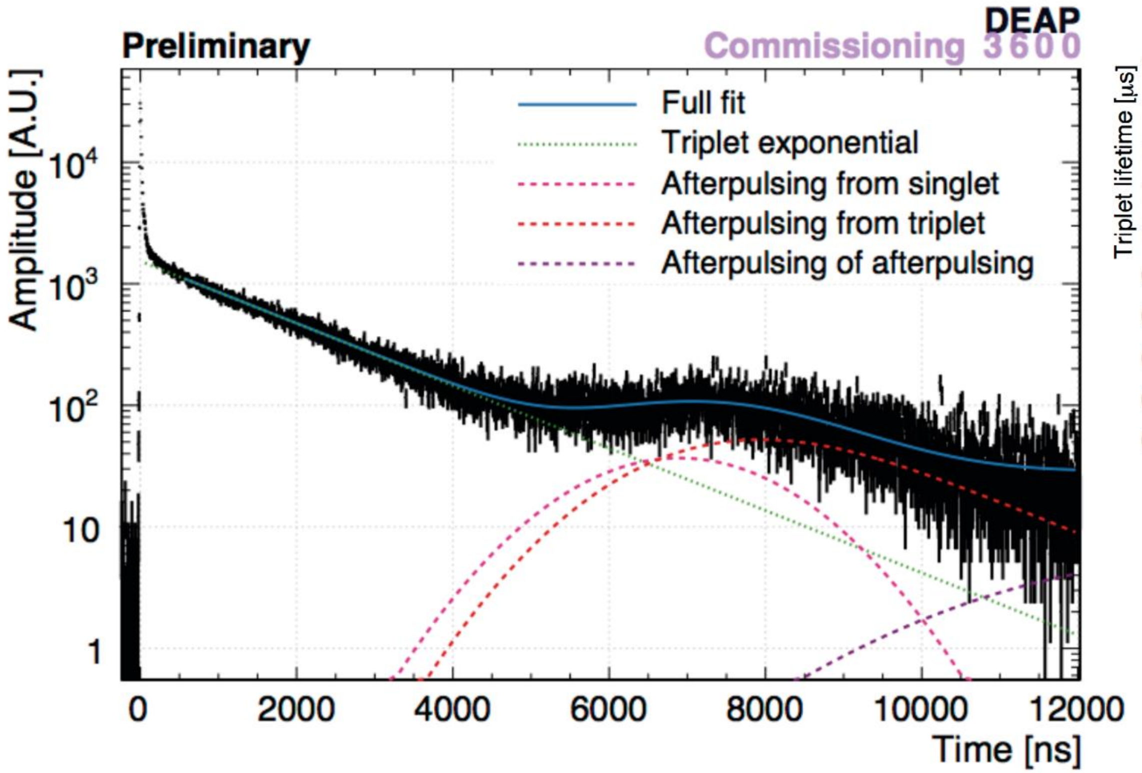
Completed Detector and Shield Tank

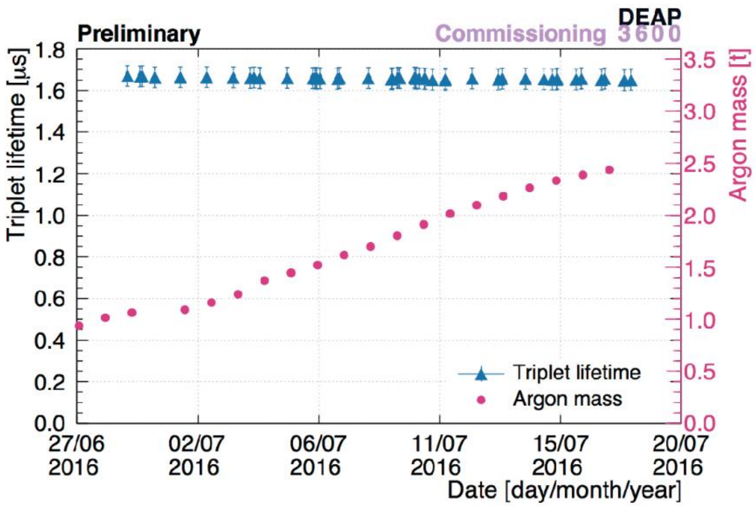


Completed Detector: Steel Shell, calibration tubes, muon veto in Shield Tank (fall 2015)

Shield Tank and emergency vent lines, tank was filled with water Oct 2015, cooldown started Feb 2016

DEAP-3600 argon filling

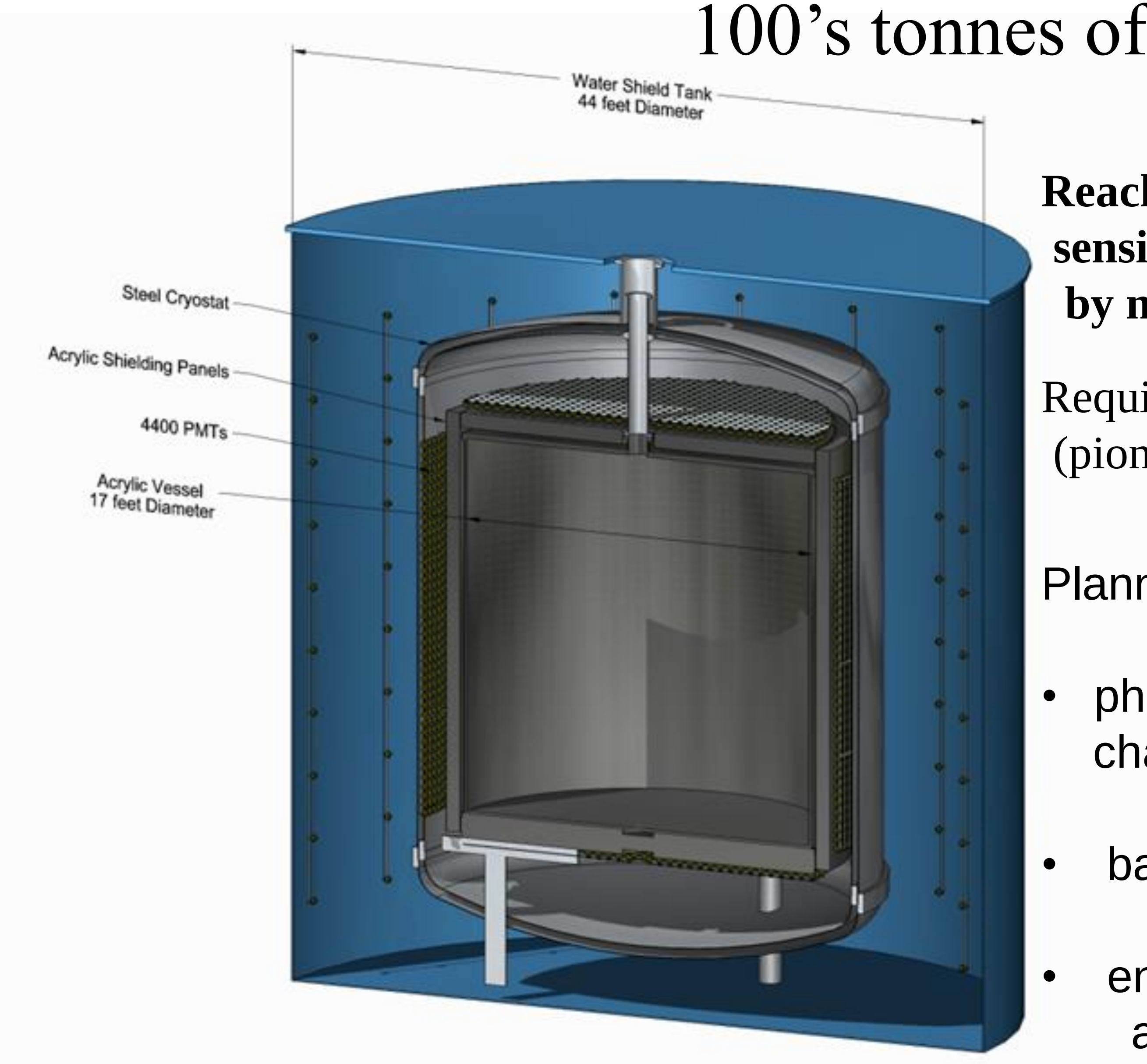




- Continuous filling for the past month.
- The process system can be run in re-circulation model, to further purify the argon.

Argon remains pure during filling, 3600 kg level within 1-2 weeks marks the start of the DM search running (1000 kg-days collected per day)

“Concept for future single phase”: 100’s tonnes of argon



Reaches ultimate DM sensitivity (limited by neutrino backgrounds)

Requires low-radioactivity argon (pioneered by DarkSide)

Planned R&D

- photodetector development, characterization
- background reduction
- engineering design and safety

From the US High Energy Physics Advisory Panel (HEPAP) – Particle Physics Project Prioritization Panel (P5) Strategic Plan (2014)

Dark Matter: Several experiments are needed using multiple target materials to search the available spin-independent and spin-dependent parameter space. This suite of experiments should have substantial cross-section reach, as well as the ability to confirm or refute current anomalous results.

Summary

Many experiments targeting low-mass and high-mass regions, several new ideas in low-mass region. Vibrant field with new ideas and developments, many new supporting and enabling techniques developed. Apologies for omissions, only a v. small fraction has been discussed here.

Large noble liquid detectors exploring high mass region, possibility of seeing "SUSY" from low-energy nuclear recoils underground.

Many exciting new results, including recent limits from LUX and PandaX-II !
Expect new results from XENON-1T and DEAP-3600.

Many projects aiming for sensitivity near neutrino "floor" in the next 5-10 years. Important to develop experimental sensitivity with multiple targets and range of mass sensitivity.

Field has a healthy mix of projects, some with sensitivity right around the corner, some that that will take us into mid-2020s and beyond. Discovery can be anywhere along the way – should use the new measurements to guide the future program, and wherever possible … collaborate!

END