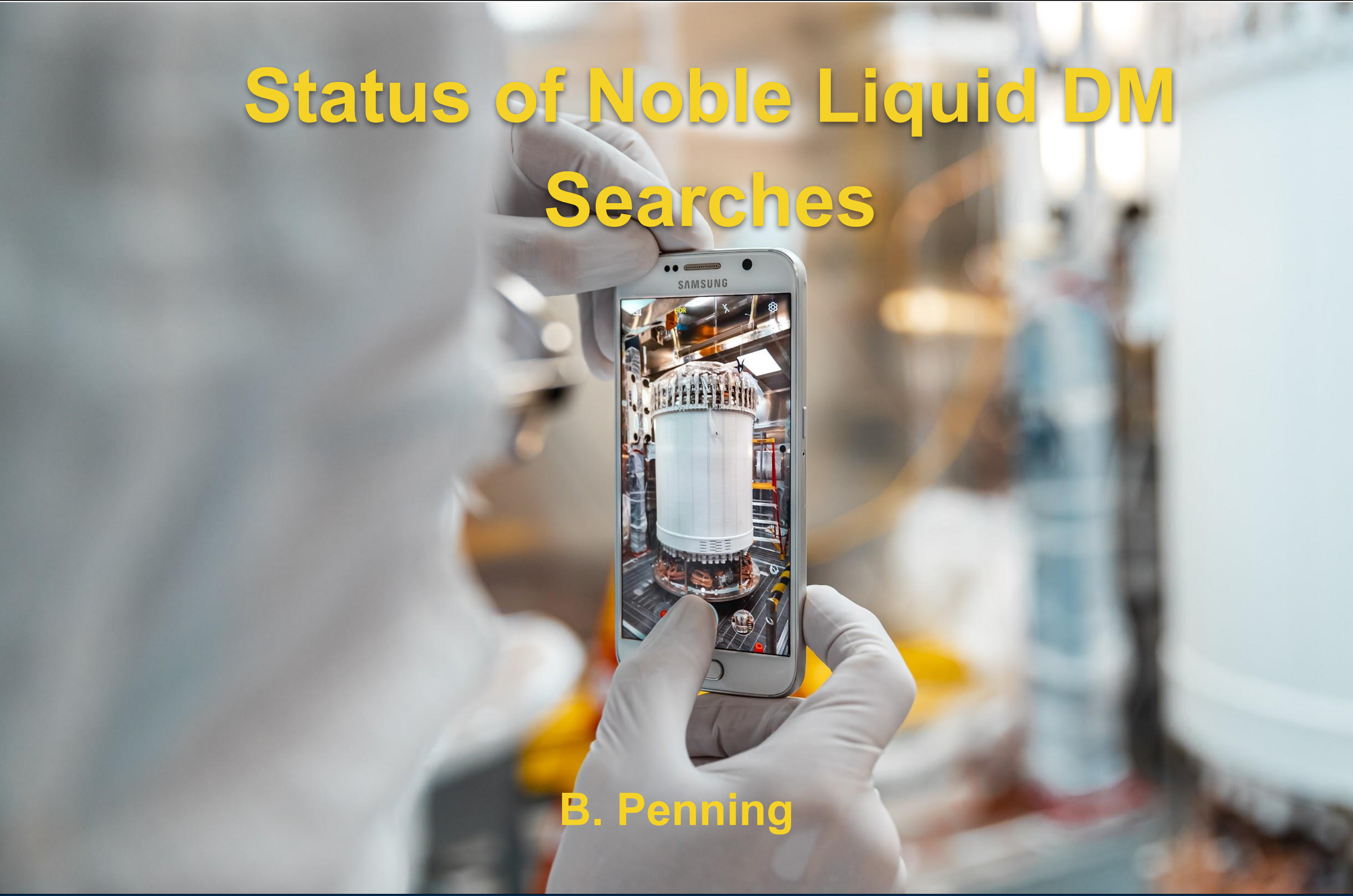
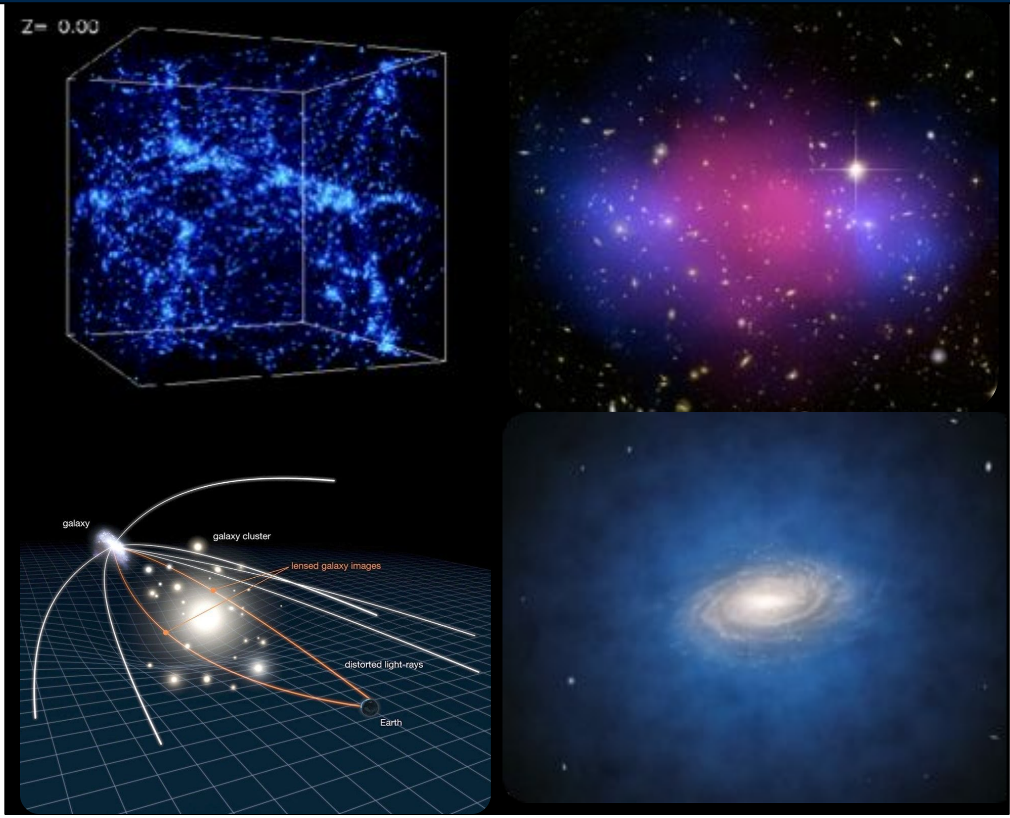
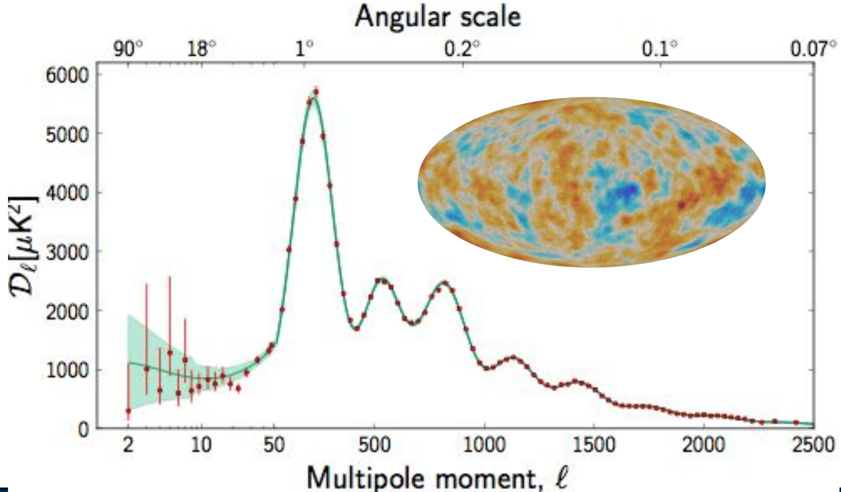
Status of Noble Liquid DM Searches



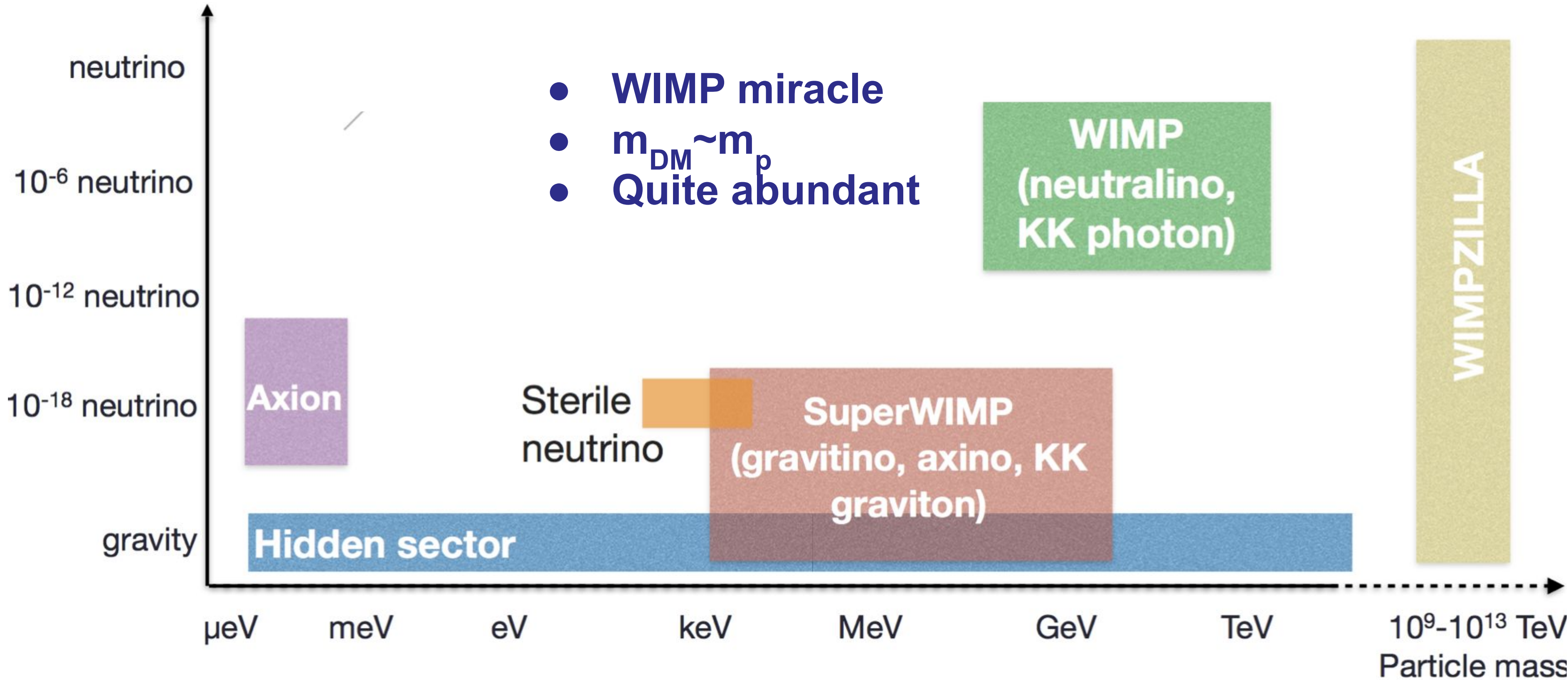
B. Penning

- Dark matter is the **only theory** that can simulate and reproduce **observations on all scales**:
  - Galaxy rotation curves
  - Galaxy clustering
  - Cluster collision
  - Large-scale structures
  - CMB fluctuations
  - Gravitational lensing





- **DM is already discovered**, just not yet identified
- Standard Model of Cosmology, **ΛCDM**: $\Omega_\Lambda \approx 0.68$, $\Omega_{DM} \approx 0.27$, $\Omega_b \approx 0.05$



- Man types of DM and may require a different approach
- **WIMPs still the best motivated model**

Carta Marina

See **A. Vincent's** talk how to sail these treacherous seas

Carta Marina

How to Detect DM?

- Detection means interaction

detector mass

local DM density ~0.3 GeV/cm^3

WIMP velocity

cross section

recoil energy

Nuclear Form Factor

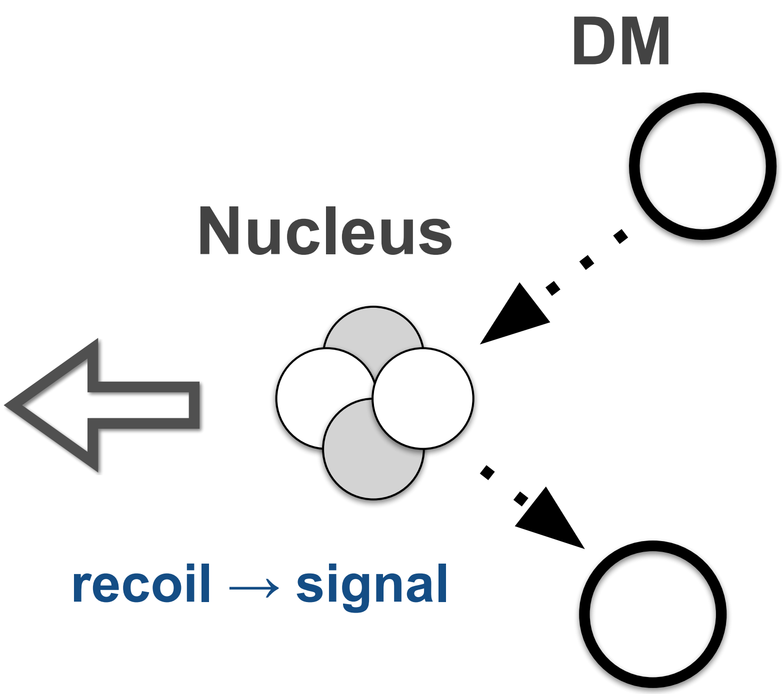
$$\frac{dR}{dE_{\mathrm{nr}}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\min}}^{\infty} v f(v) \frac{d\sigma}{dE_{\mathrm{nr}}} dv \propto \exp\left(-\frac{E_{\mathrm{nr}}}{E_0} \frac{4 m_\chi m_N}{(m_\chi + m_N)^2}\right) F^2(E_{\mathrm{nr}})$$

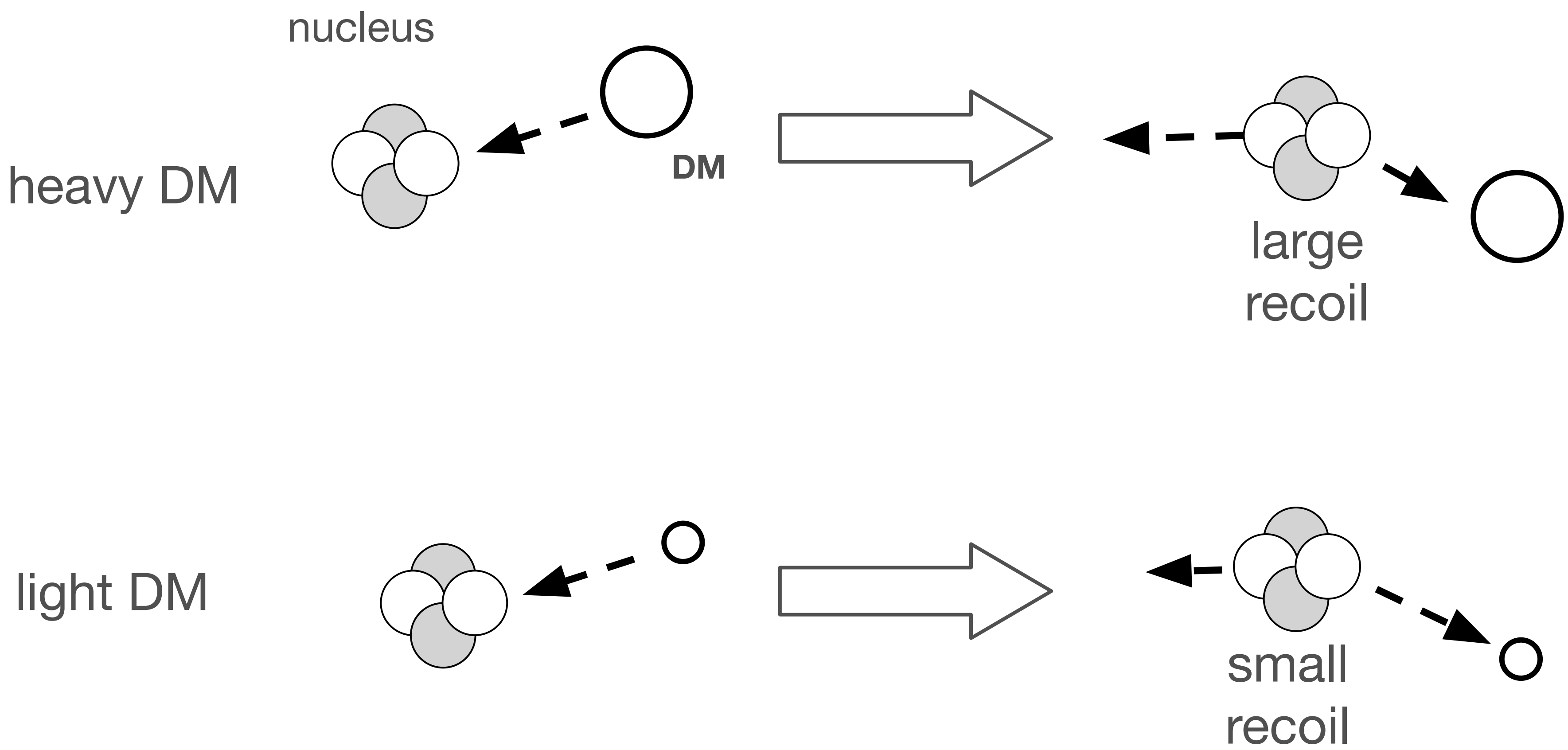
target nucleus & DM mass

WIMP energy

- **Rare events**, we can only influence is detector size & target
- Focus of this talk: Spin-independent (SI) scattering, **scalar or vector** like particle, favors **heavy targets** (A^2 scaling)

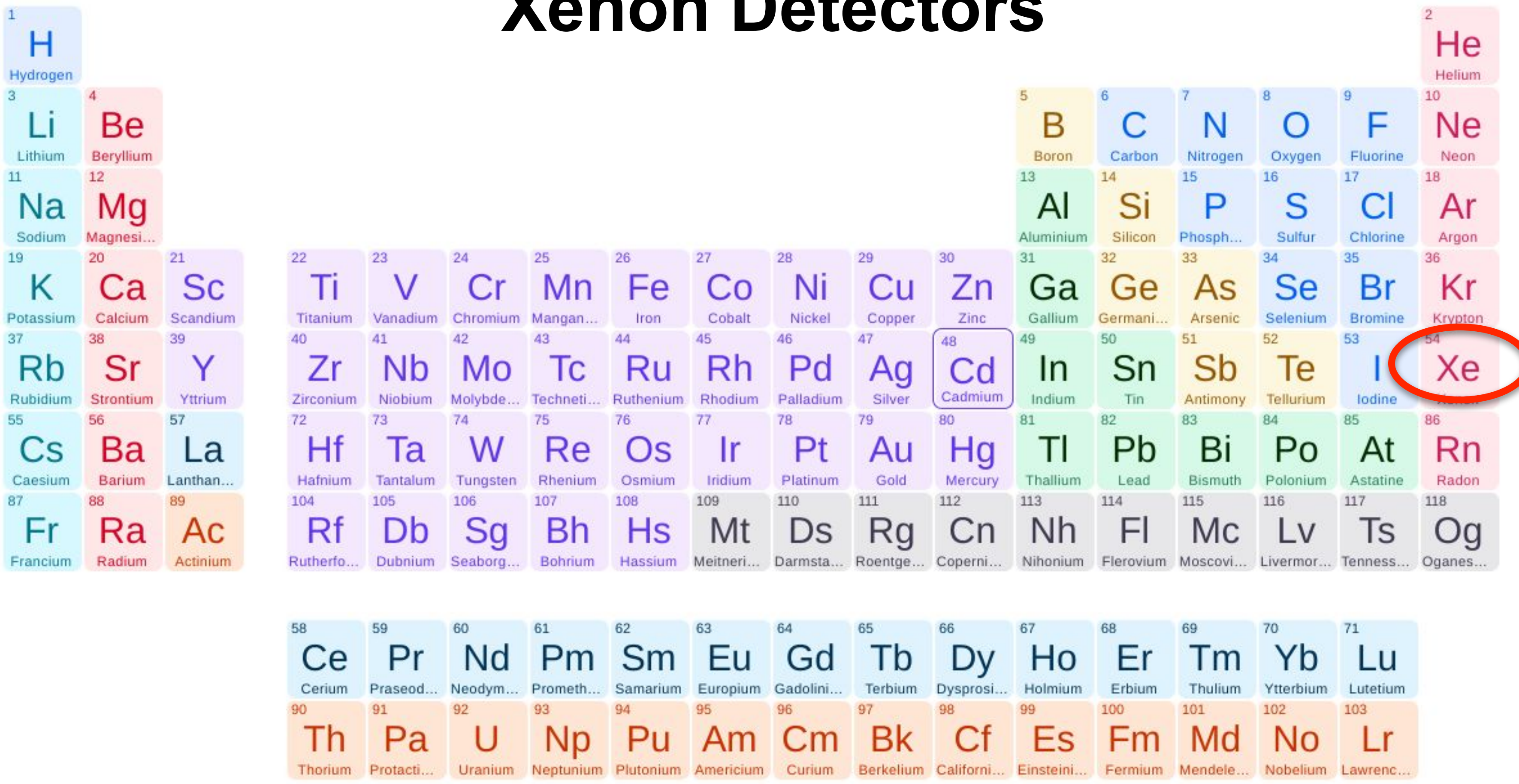
- Detect DM as our solar system passes through the galactic halo
- Typical velocity of Earth: **v~10^{-3} c** →Kinetic energy O(100 keV)
- Very rare interactions O(1/yr/kg)
- This means for our detector:
  - Very **stringent cleanliness** and **background rejection requirements**
  - **Ultra sensitive**
- Noble liquid detectors demonstrated to have best sensitivity





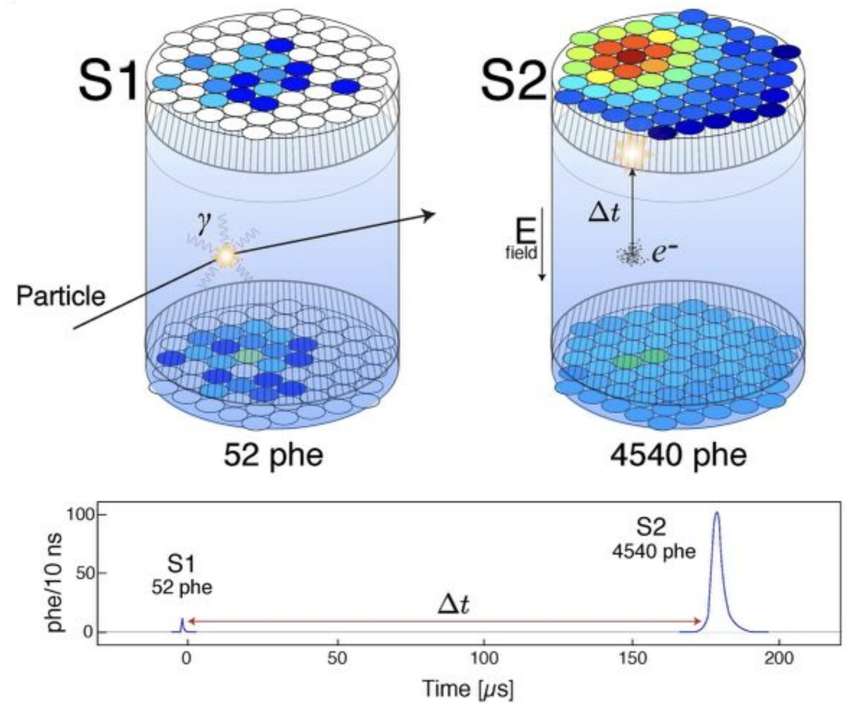
- Purely kinematic process, momentum transfer crucial
- Low mass difficult

Xenon Detectors



I will explain common techniques of **LXe detectors** based on LZ

- Dual phase TPC, **two signals**
  - **Prompt scintillation light** (S1)
  - Prop. **charge signal** amplified in gas (S2)
- Signal ratio allows to discriminate particle
- **Electron** scatter tend to produce **more charge**
- **Neutron** scatter create **more light**
- Depth (z) from time difference between S1/S2 and light pattern (x, y)
- The TPC is surrounded by active veto detectors



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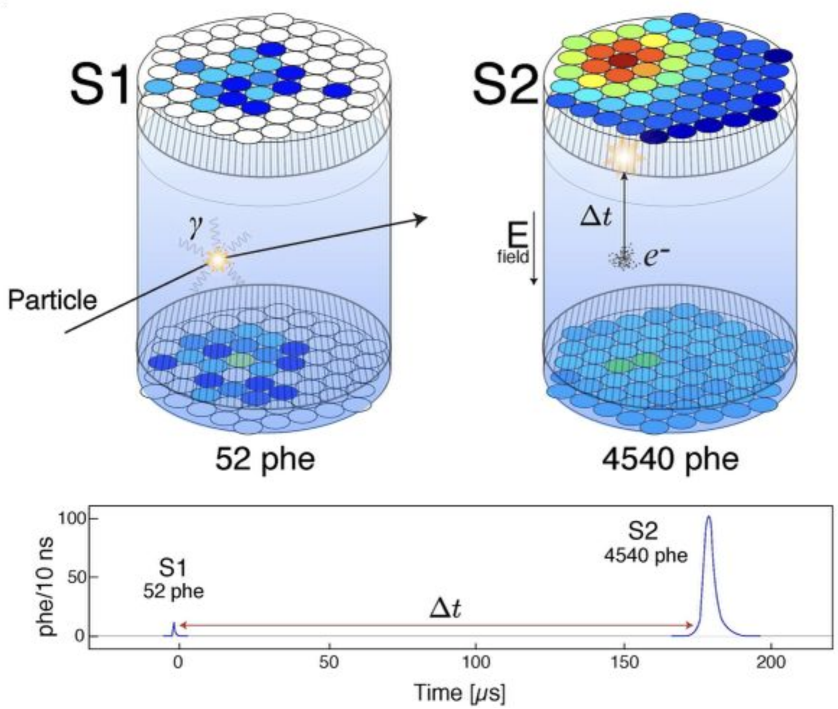
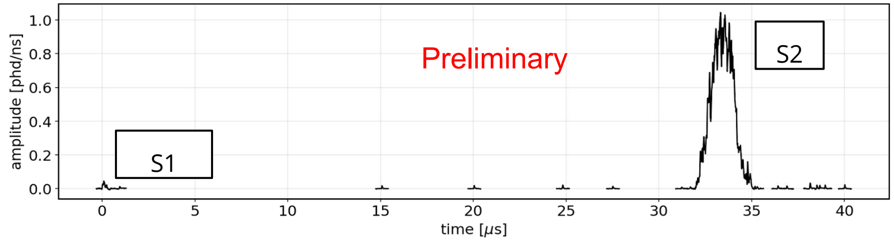
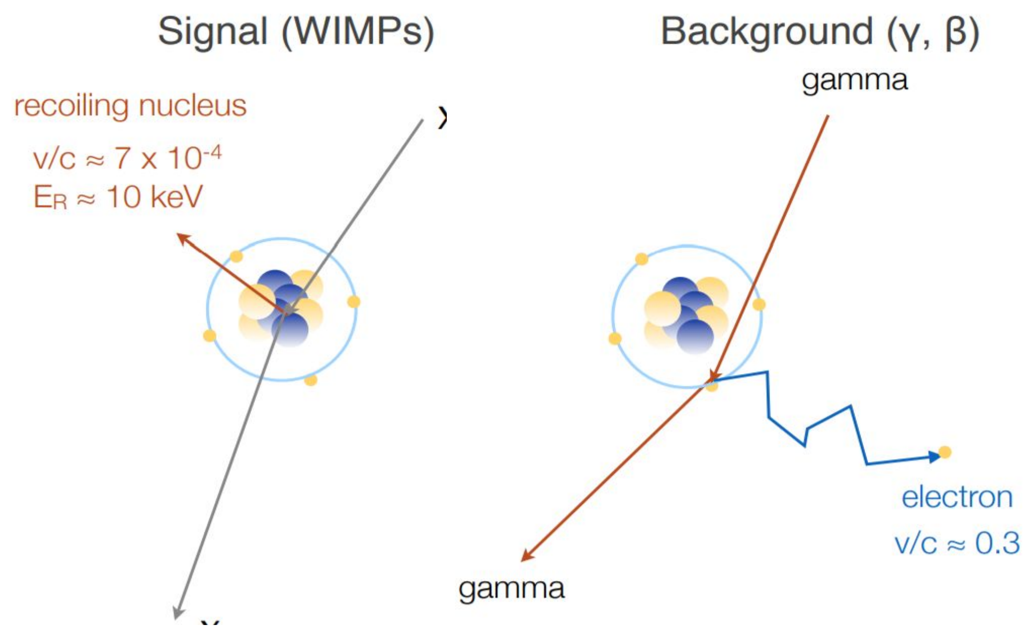
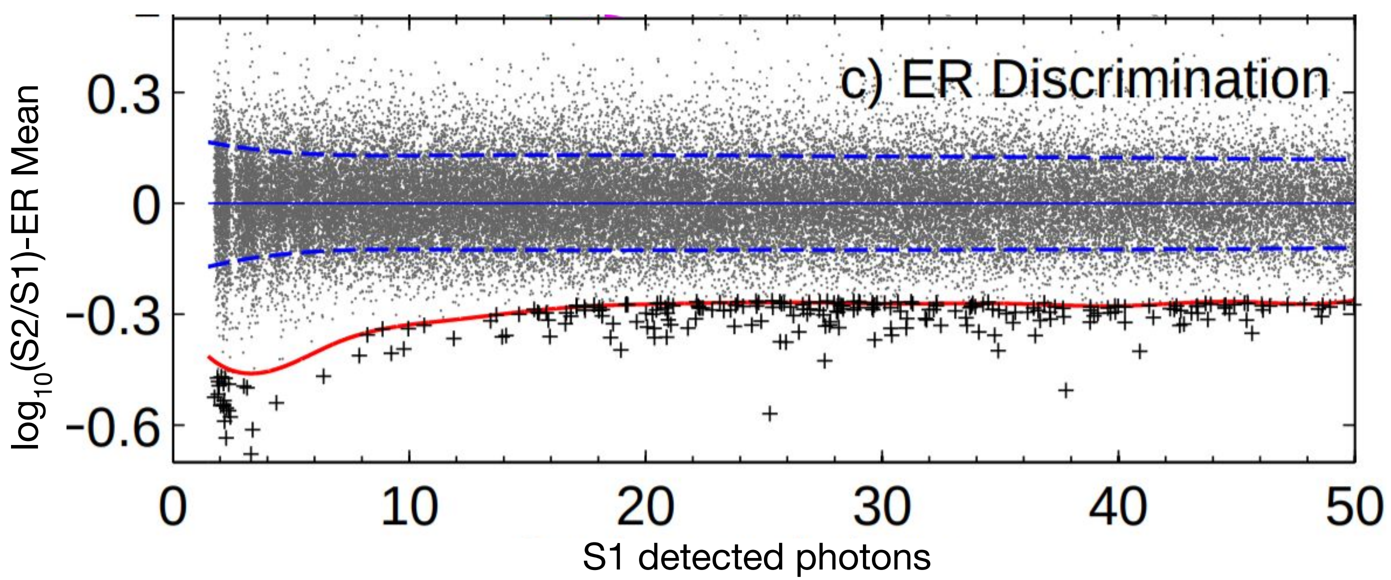
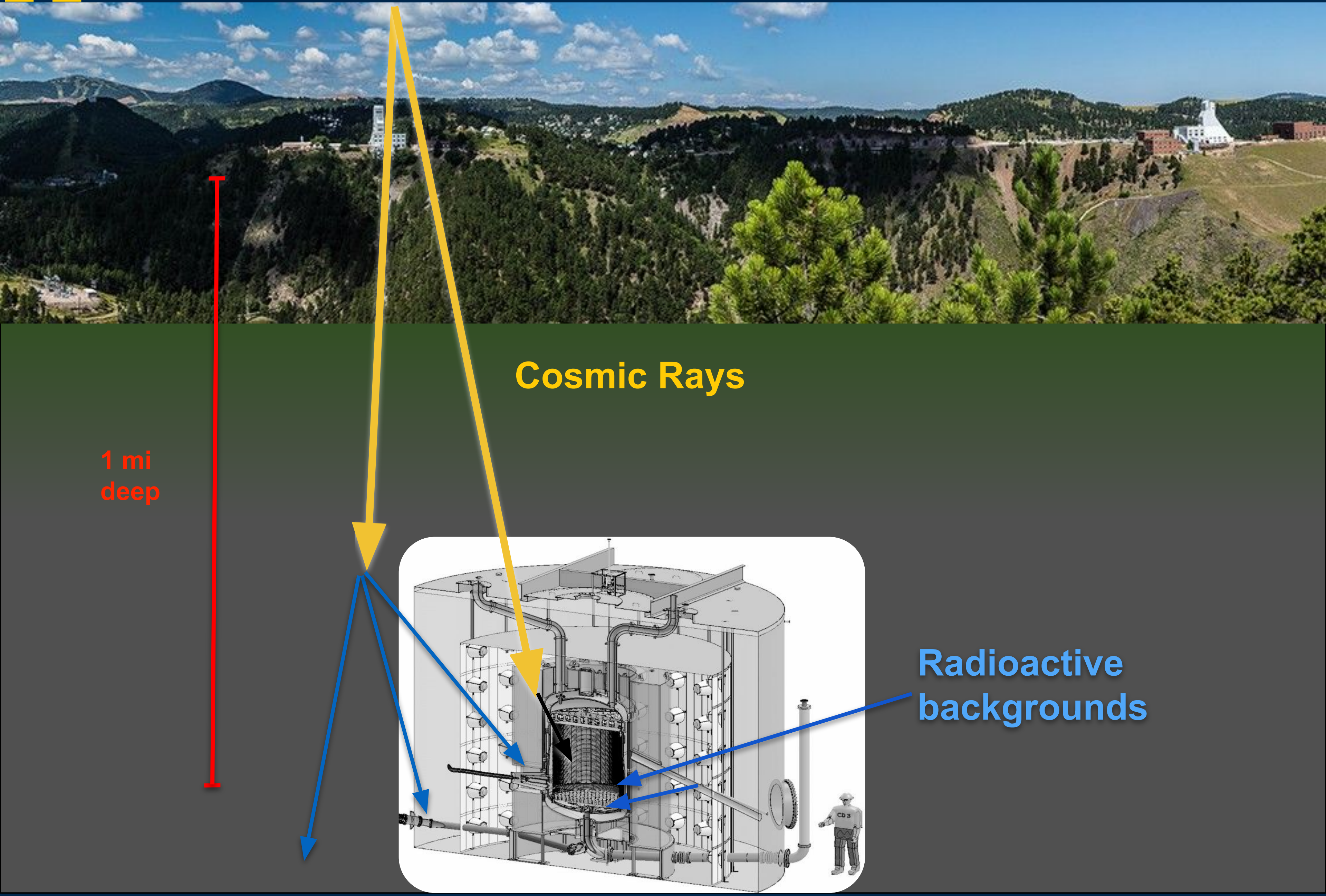




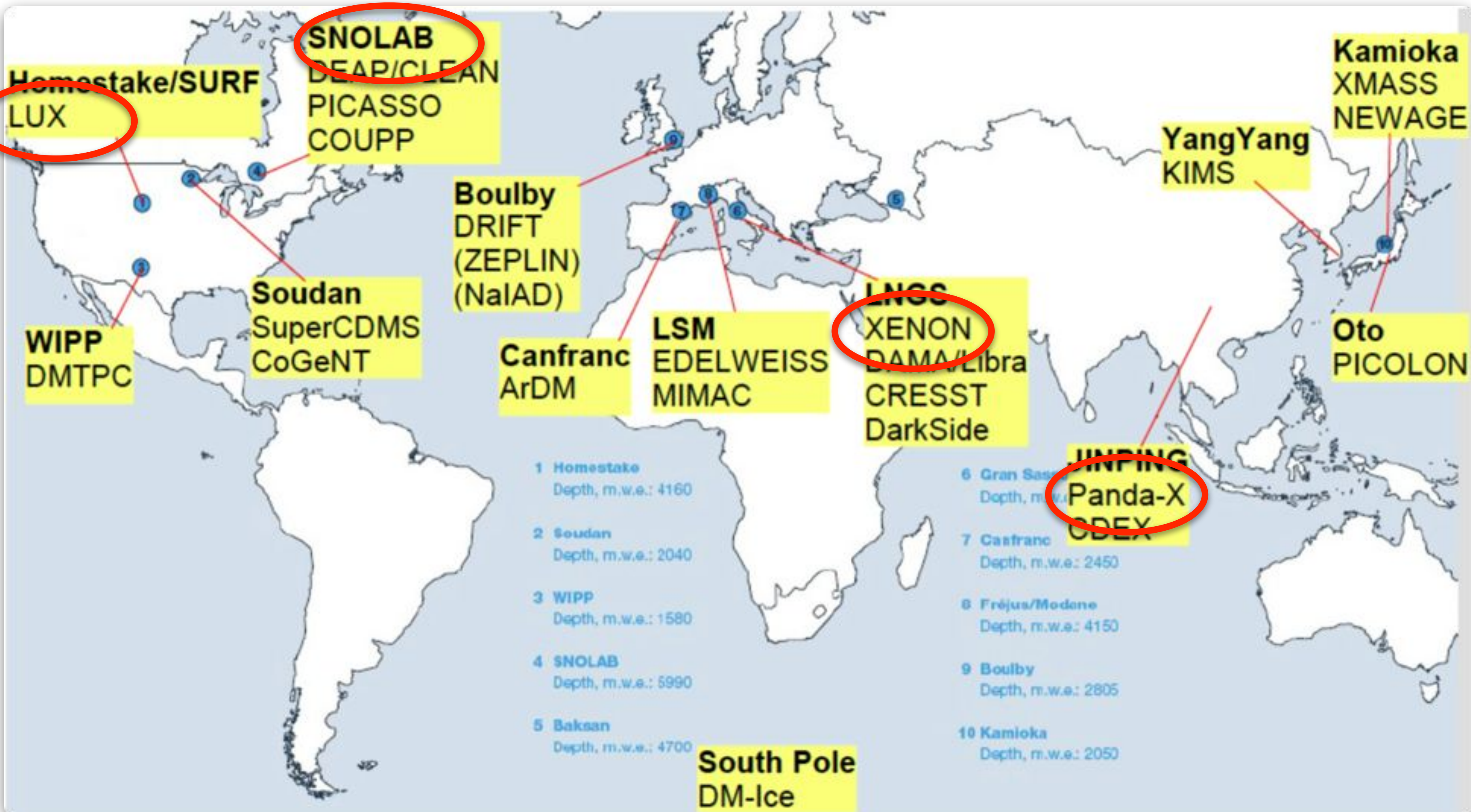


- Ionization/excitation (charge/light) depends on dE/dx
- **Excellent discrimination** of signal (WIMPS → NR) and most backgrounds (γ → ER)
- **99.5% separation** before statistical methods




Cosmic Rays
1 mi
deep
Radioactive
backgrounds

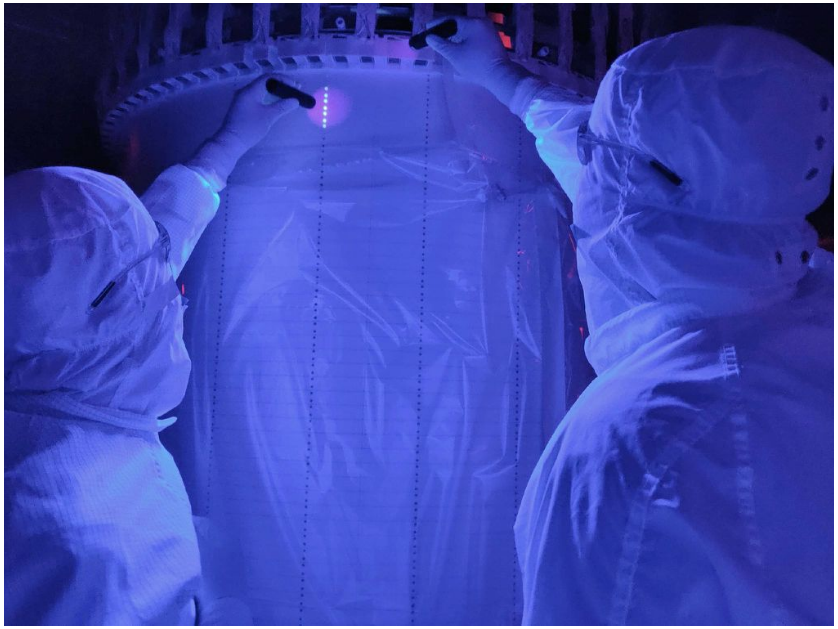
- Cosmogenic backgrounds:
  - Go deep! 1 mile underground (4850 feet)
- Reduces muon flux by 10^7
- Science gem: Sanford Underground Research Facility (SURF) in **South Dakota**
  - Leading DM and neutrino experiments, accelerator, ….

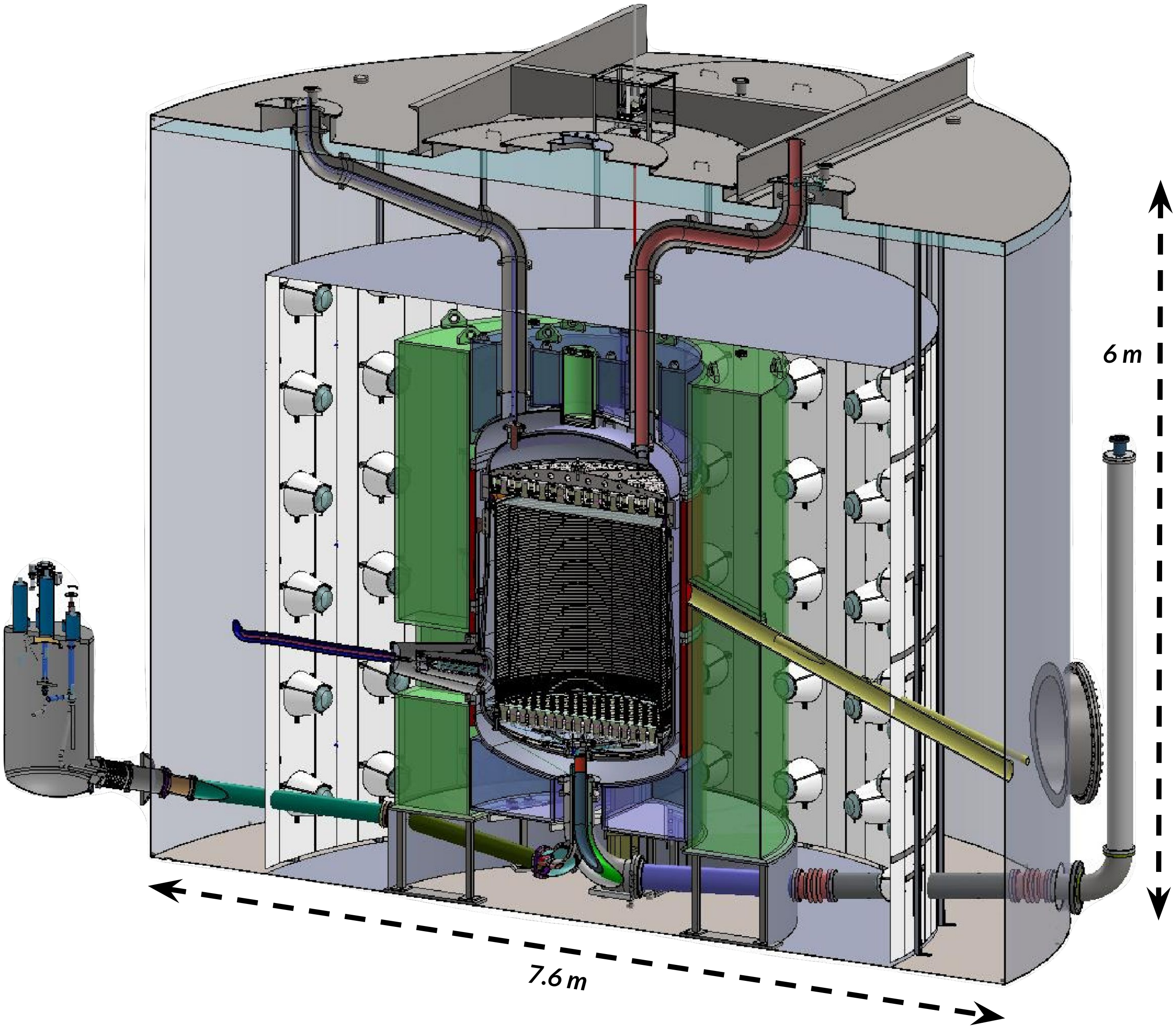

Homestake/SURF
LUX
SNOLAB
DEAP/CLEAN
PICASSO
COUPP
Boulby
DRIFT
(ZEPLIN)
(NaIAD)
Soudan
SuperCDMS
CoGeNT
WIPP
DMTPC
Canfranc
ArDM
LSM
EDELWEISS
MIMAC
LNGS
XENON
DAMA/Libra
CRESST
DarkSide
JINPING
Panda-X
CDEX
YangYang
KIMS
Kamioka
XMASS
NEWAGE
Oto
PICOLON
South Pole
DM-Ice
1 Homestake
Depth, m.w.e.: 4160
2 Soudan
Depth, m.w.e.: 2040
3 WIPP
Depth, m.w.e.: 1580
4 SNOLAB
Depth, m.w.e.: 5990
5 Baksan
Depth, m.w.e.: 4700
7 Canfranc
Depth, m.w.e.: 2450
8 Fréjus/Modane
Depth, m.w.e.: 4150
9 Boulby
Depth, m.w.e.: 2805
10 Kamioka
Depth, m.w.e.: 2050

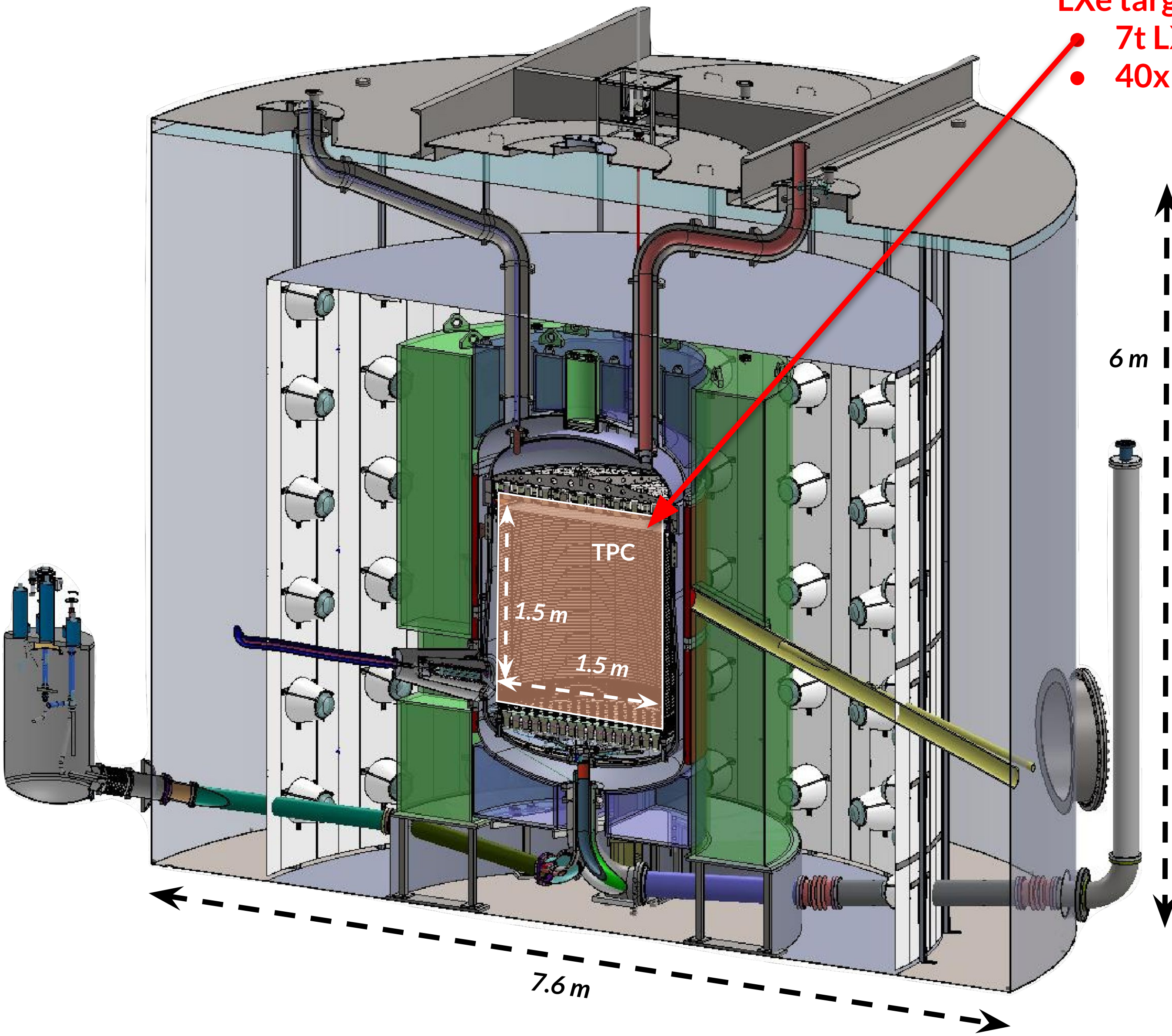
1 Banana = 15 Bq

- **Need also to avoid all type of internal contaminants**
  - Use purest materials obtainable, screen all materials
  - Build everything in clean room, reduce dust on surfaces to O(ng/cm^2)
  - Keep circulating and purifying target material: aim Xenon contaminants to **O(0.015 ppt)**

- Bananas are actually somewhat radioactive due to potassium
  - **15Bq/Banana**
- Our target activity in the Xe: 2 µBq/kg - **1/750,000 Bananas**
- Cleaning, cleaning, cleaning, cleaning!

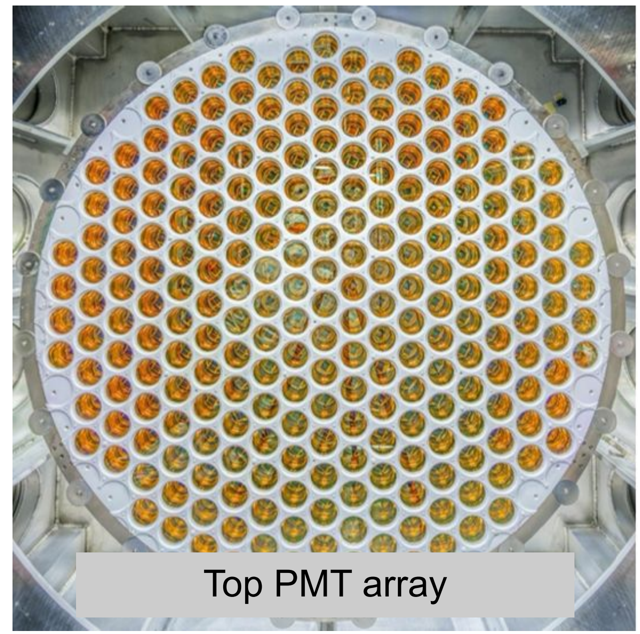


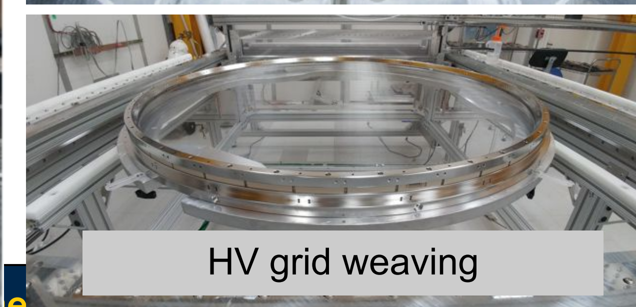

6 m
7.6 m

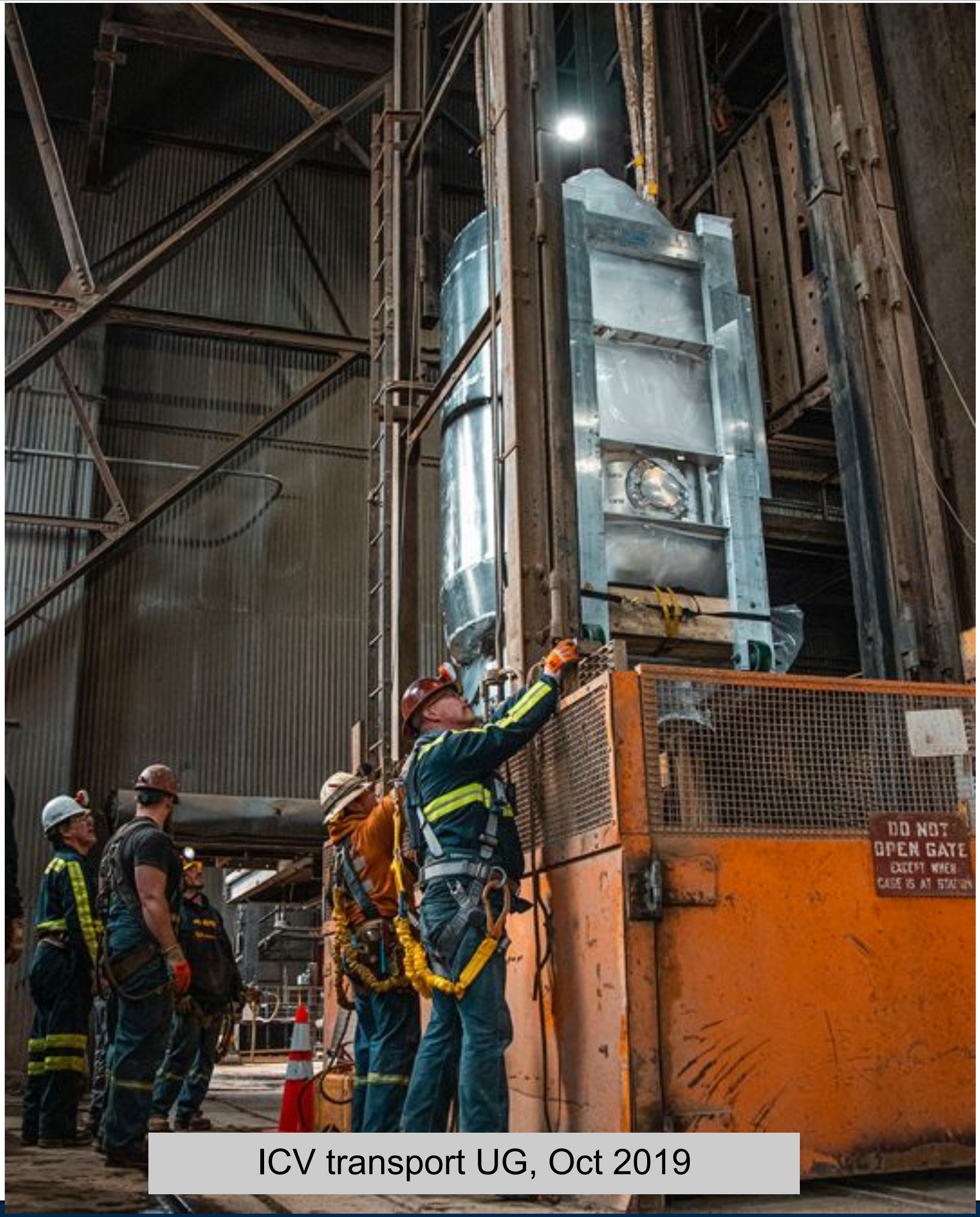

LXe target:
7t LXe TPC
40x LUX
TPC
1.5 m
1.5 m
6 m
7.6 m


Assembled TPC (July 2019)


Bottom PMT array
with field cage


Top PMT array


HV grid weaving



ICV transport UG, Oct 2019

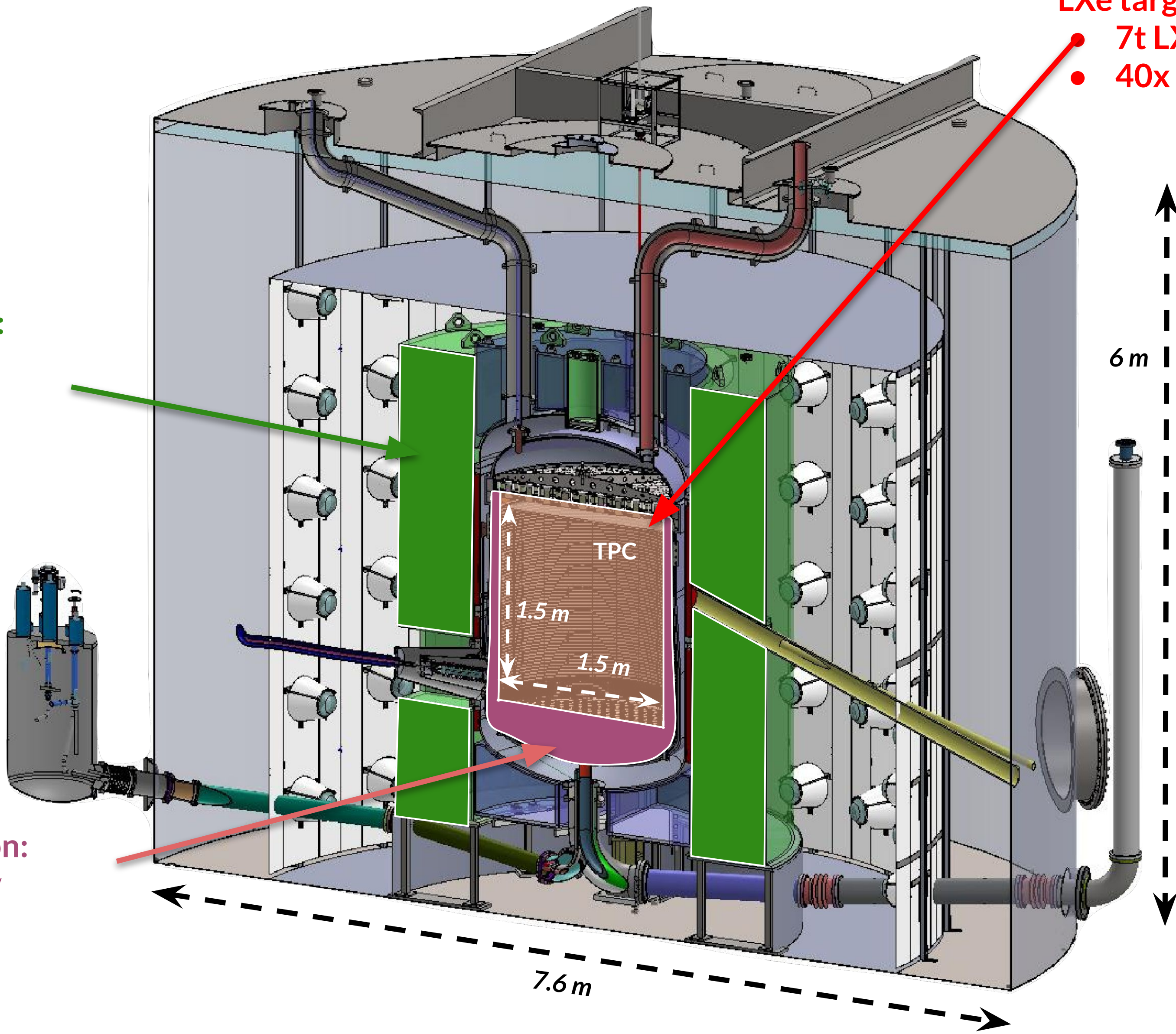
ICV insertion into OCV,
Dec 2019

CHV delivery installation & Cryostat sealed, March 2020

OD installed, Summer 2021

LXe target:
- 7t LXe TPC
- 40x LUX

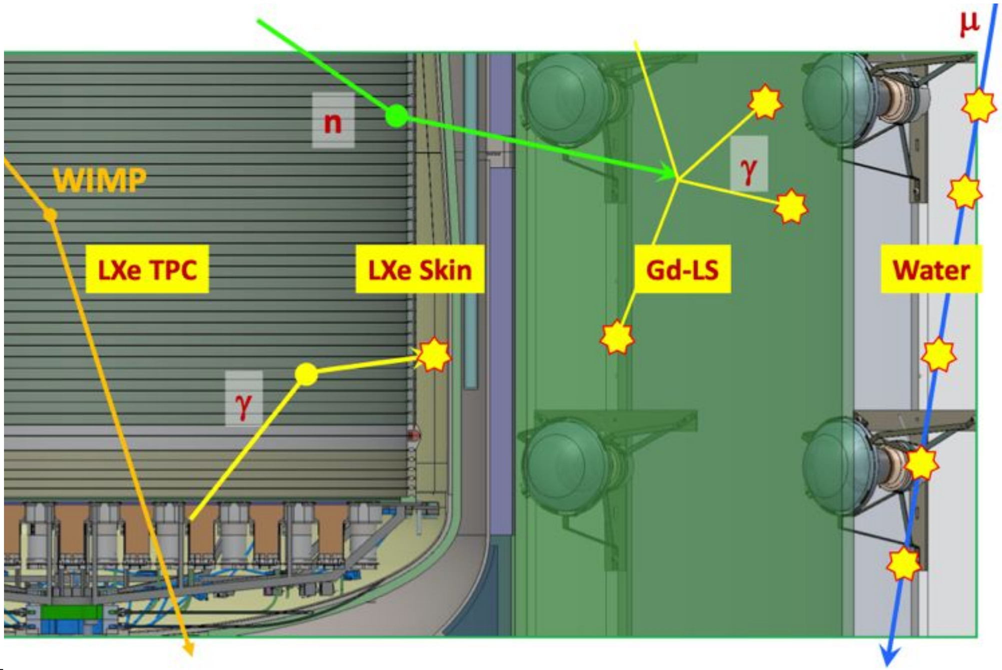
Outer Detector:
- 17 t Gd-LS
- 120 PMTs
- New in LZ



LXe “skin” region:
- Veto MeV γ
- New in LZ

Outer Detector:

- **17 tonnes Gd-loaded liquid scintillato**r in acrylic vessels viewed by 120 8” PMTs
- Anti-coincidence detector for γ-rays and neutrons
- Observe **~8 MeV γ-ray**s from neutron capture



Skin:

- 2 T of LXe surrounding the TPC
- Lined with PTFE to maximize light collection efficiency
- Anti-coincidence detector for MeV level γ-rays

Water shield:
- 230 t DI water
- Instrumented

Outer Detector:
- 17 t Gd-LS
- 120 PMTs
- New in LZ

LXe "skin" region:
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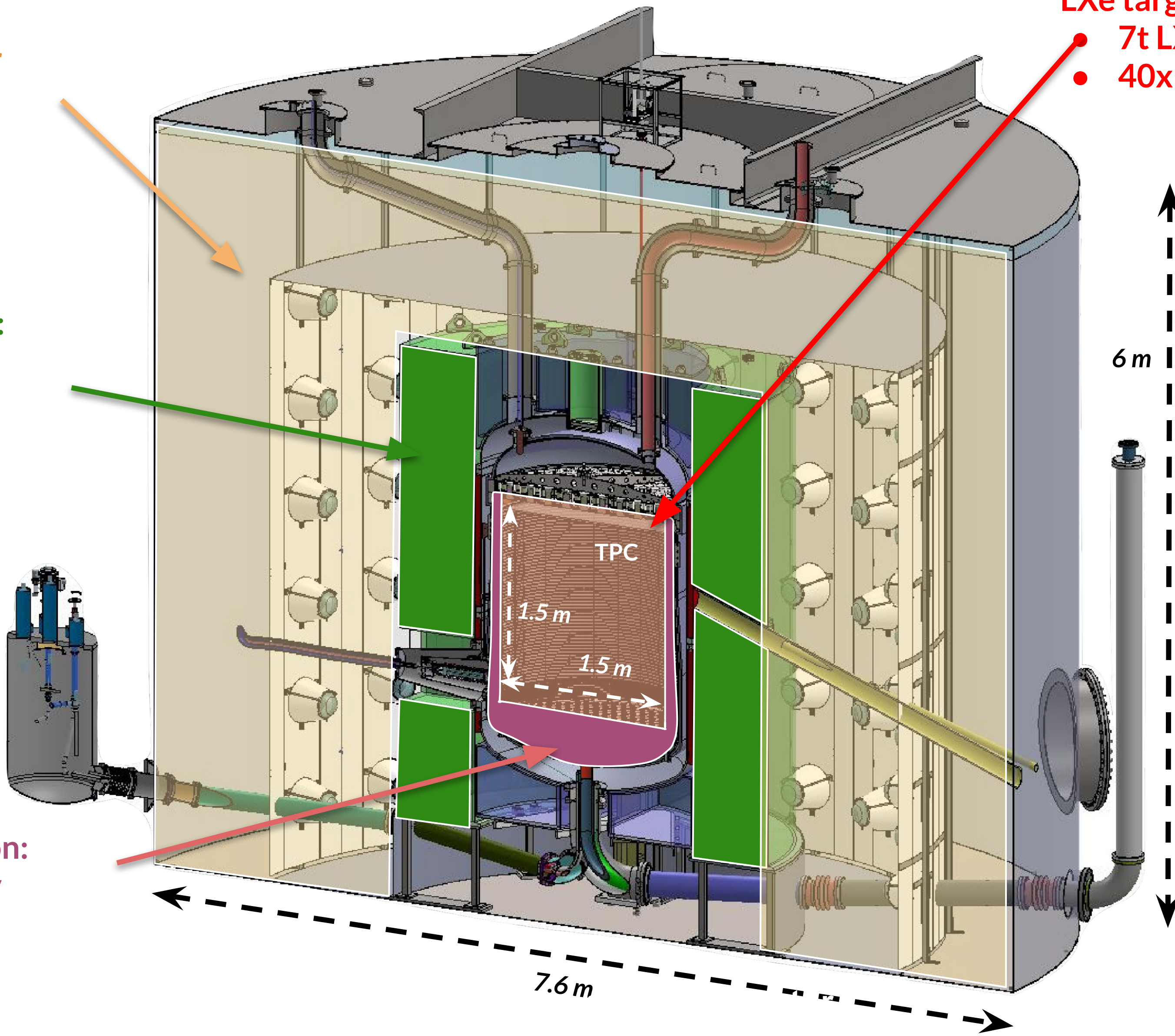
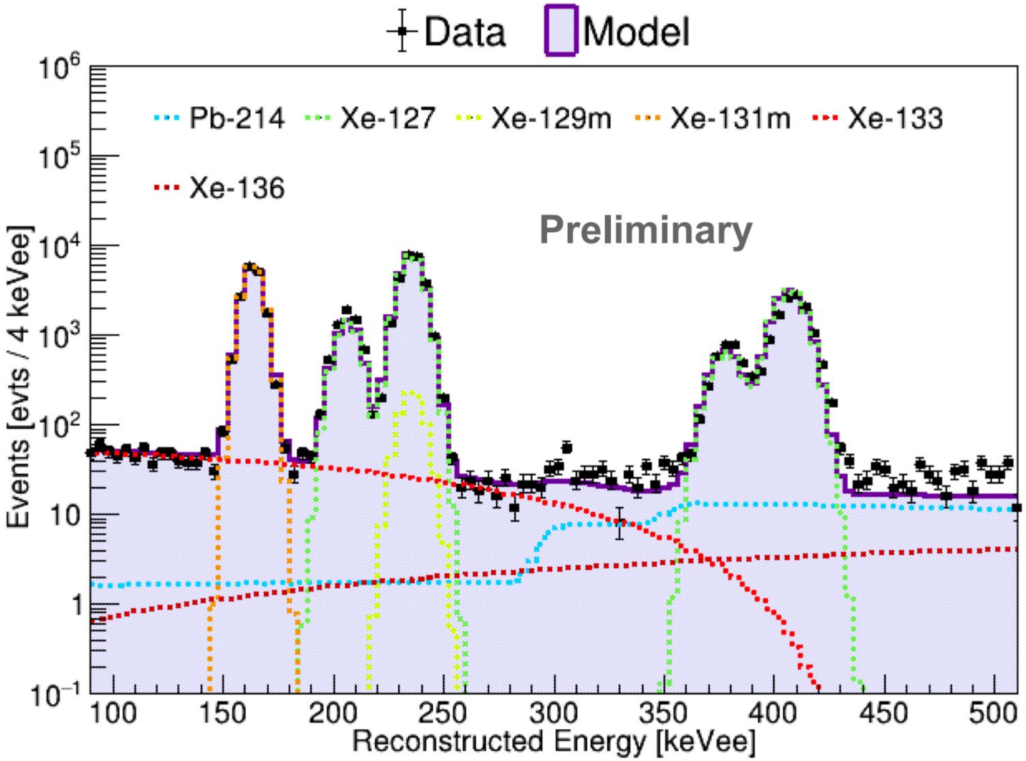
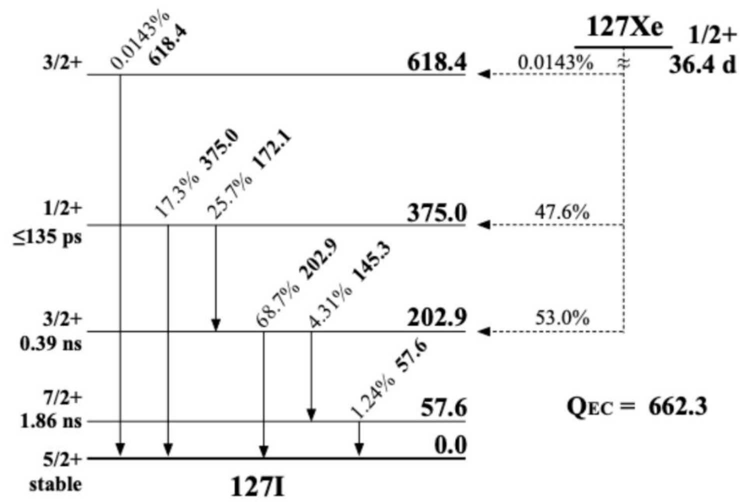


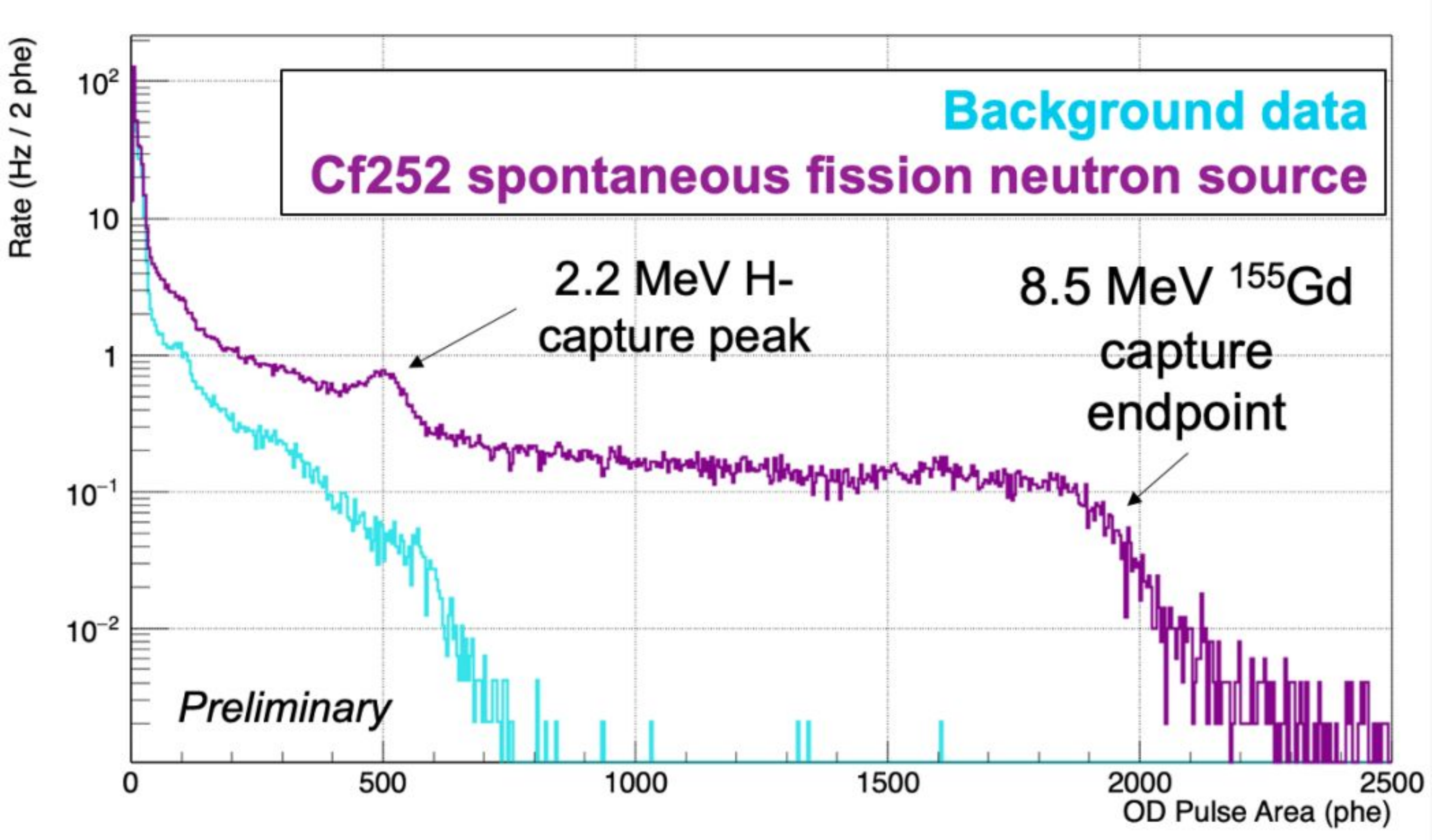
- We have data!
- All hands on deck!

- **Xenon can become activated by cosmogenics** leading to background contributions from Xe-127, Xe-129m, Xe-131m, Xe-133 (other Xe activation products are much shorter lived)

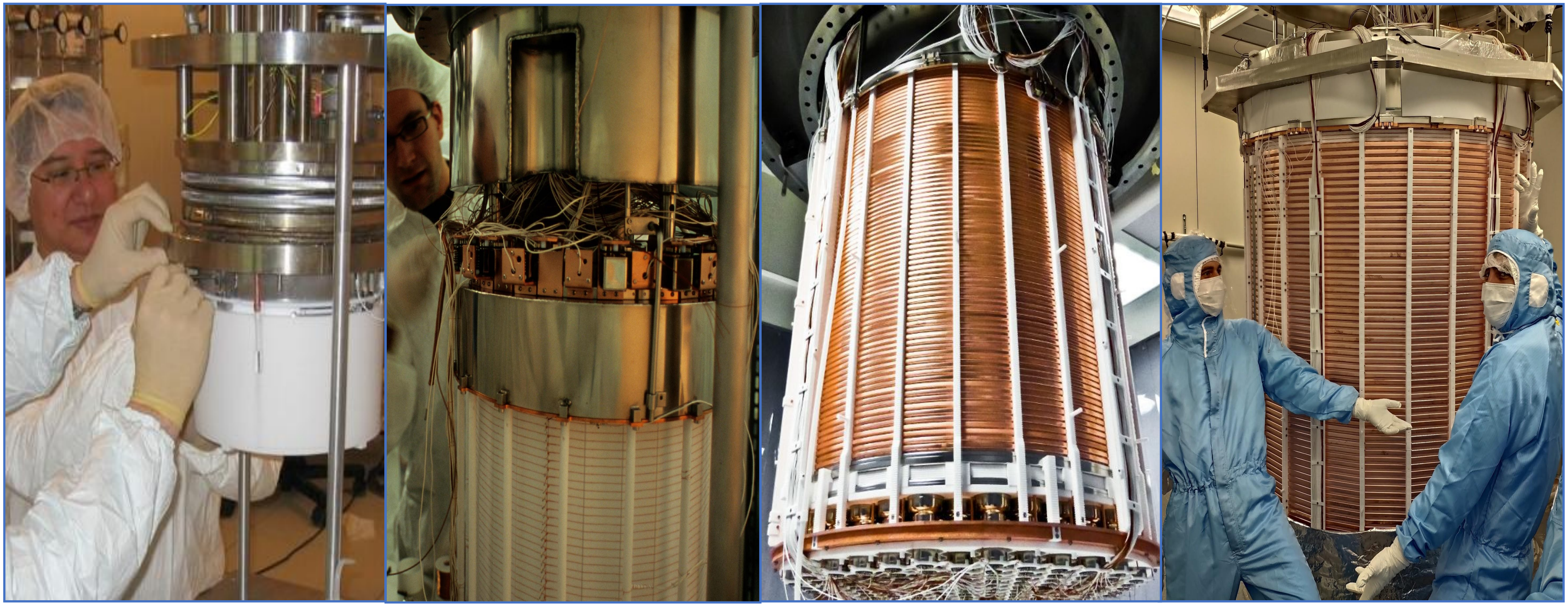


Xe-127 decays by electron capture





- OD backgrounds slightly lower than expected
  - Allows threshold < 200 keV



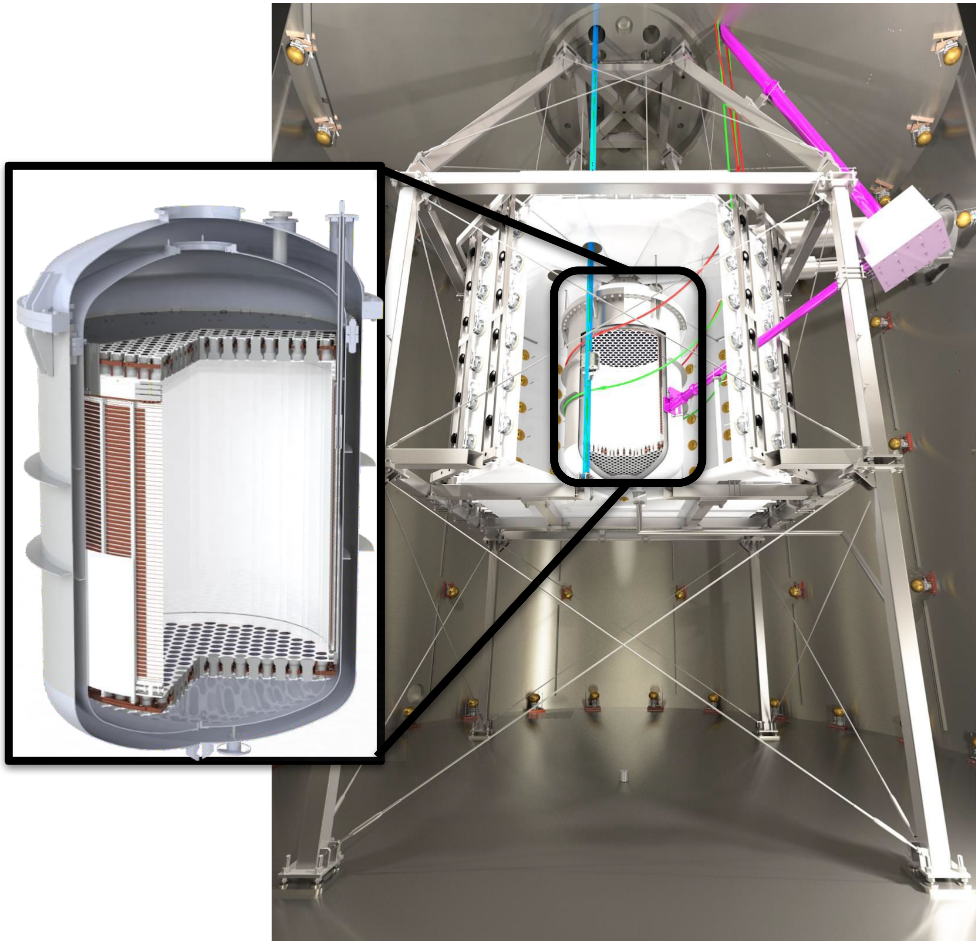
Xenon10	Xenon100	XENON1T	XENONnT
14 kg Xe	62 kg Xe	2 T Xe	5.9 T Xe
2005-2007	2008-2016	2012-2018	2019-2020

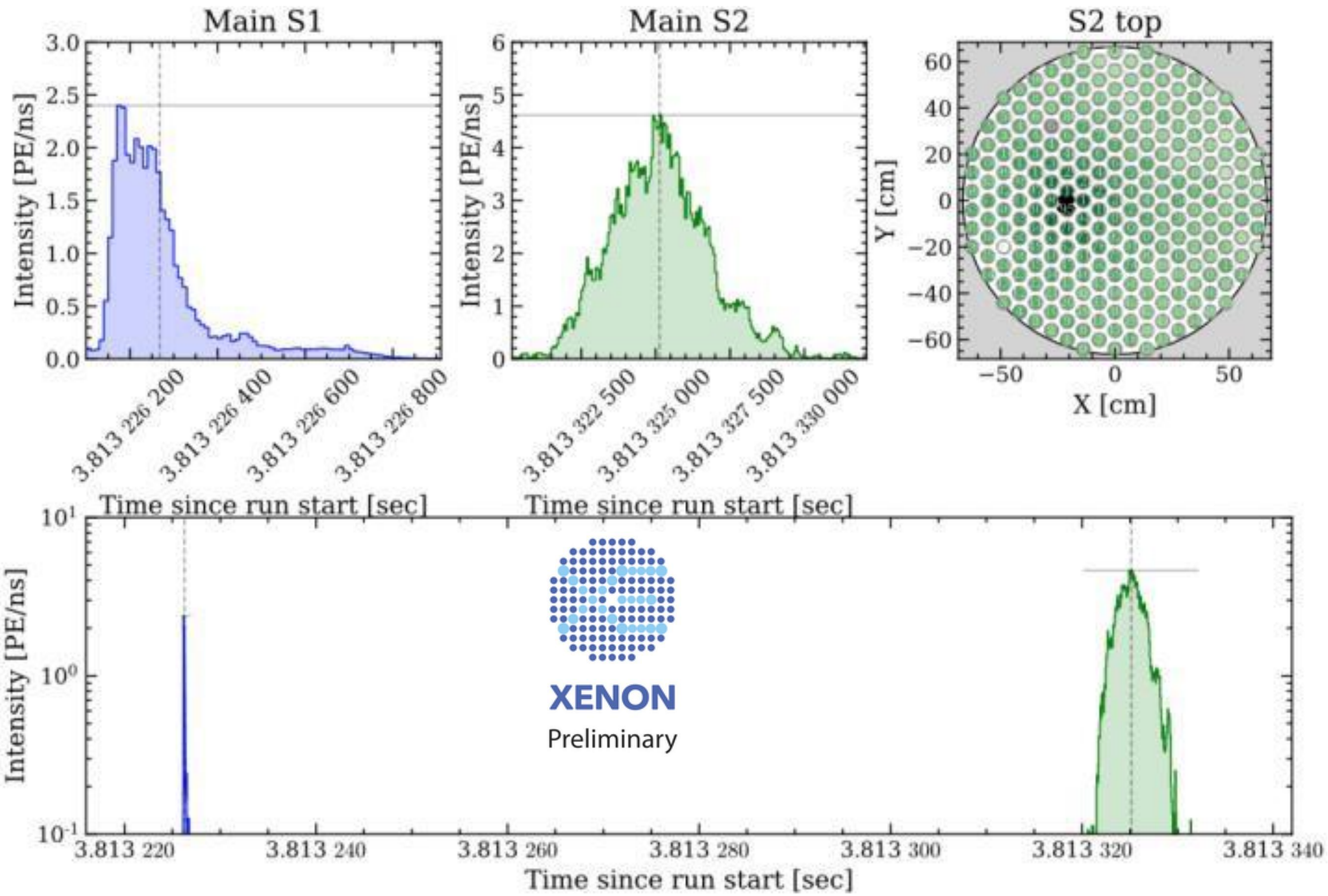
XENON

- Sharing a lot of infrastructure with **Xenon1T**, very fast upgrade cycle
- Notable improvements:
    - **Fiducial volume: 4T**
    - Very low ER background **(1/6 compared to XENON1T**)
    - Low neutrons backgrounds (1 evt/ 20t yr. exposure)

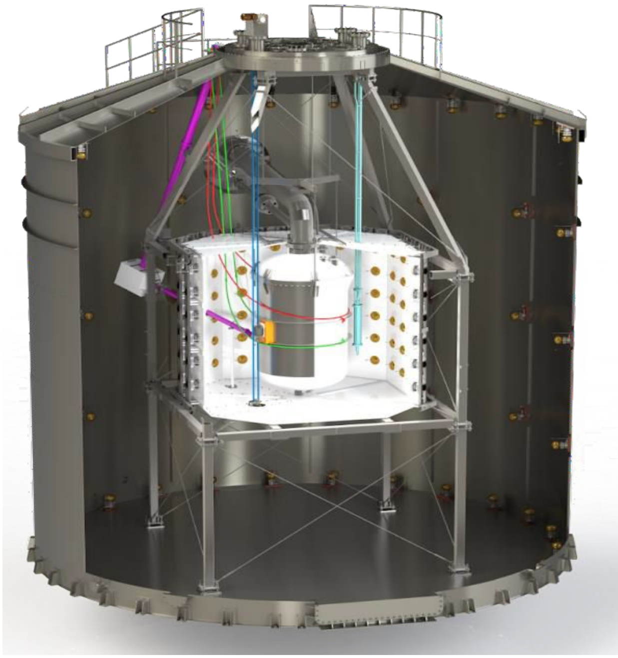
https://arxiv.org/abs/2112.05629

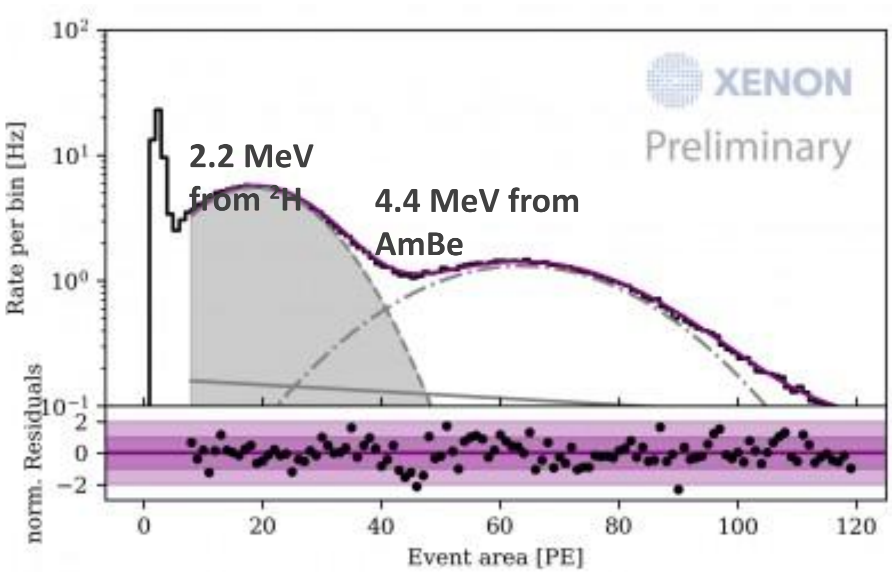
- Larger TPC than XENON1T
  - Active Xe mass **2t** → **5.9t** (3x)
  - Drift length **1m** → **1.5m** (1.5x)
  - PMTs **248** → **494** (2x)
- The larger a detector the higher the purity needs to be
  - Strict radioassay program
  - Rn emanation rate: 4.2 μBq/kg (simulated, **1/3 of XENON1T**)
- Improved **support system**:
  - Calibration system,
  - Neutron & muon vetos





- XENONnT **taking data**
- PMTs have stable gains, average **QE is 34%**
- Good **single-electron** resolution

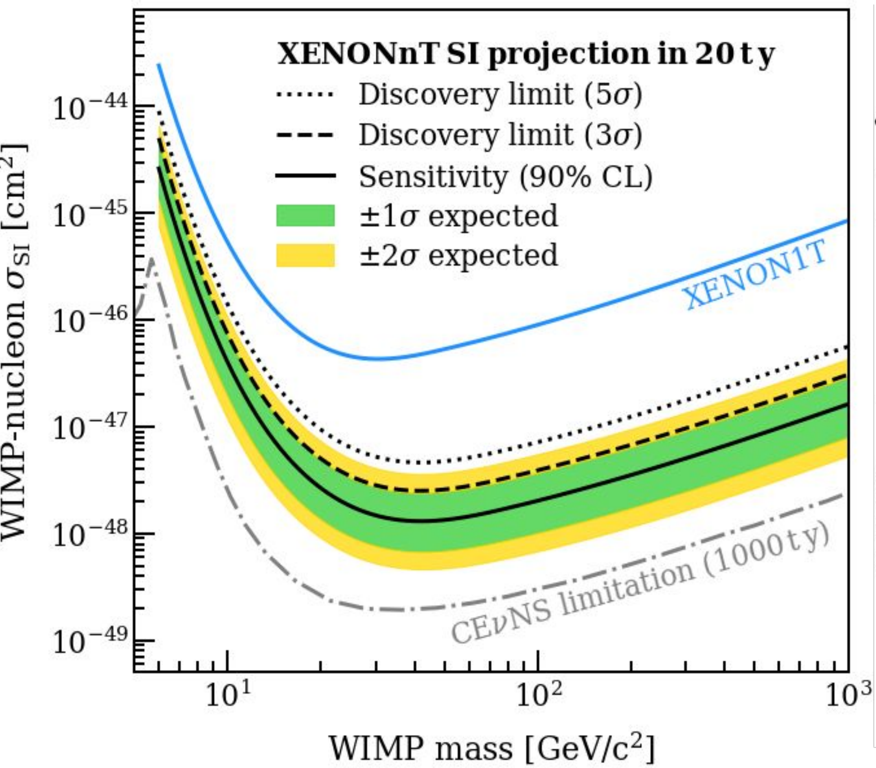


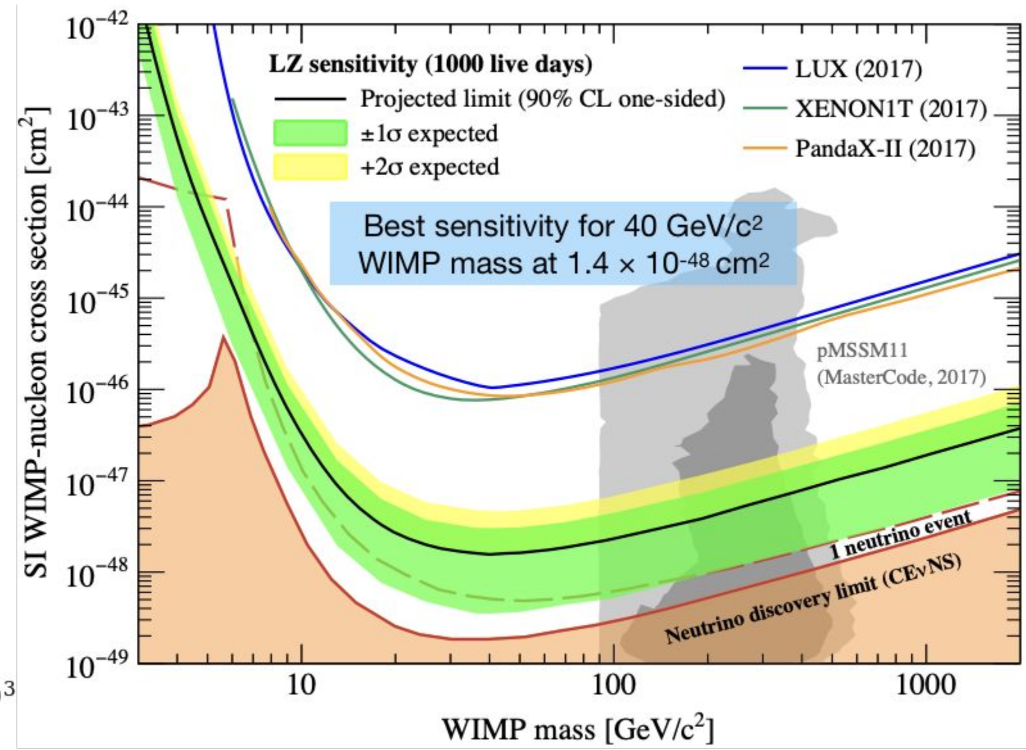


- Gd-Water Cherenkov detector
  - 33m^3, with 120 PMTs inside ePTFE panels
  - **87% expected neutron** tagging efficiency with **Gd-doped water**
  - Trigger on 4.4 MeV AmBe, 90% efficiency in detecting neutron capture with demi-water
- Translate to **65% tagging efficiency with water** (match with sim)
- Goal: <1 evt / (20 t × yr)

XENON

LZ





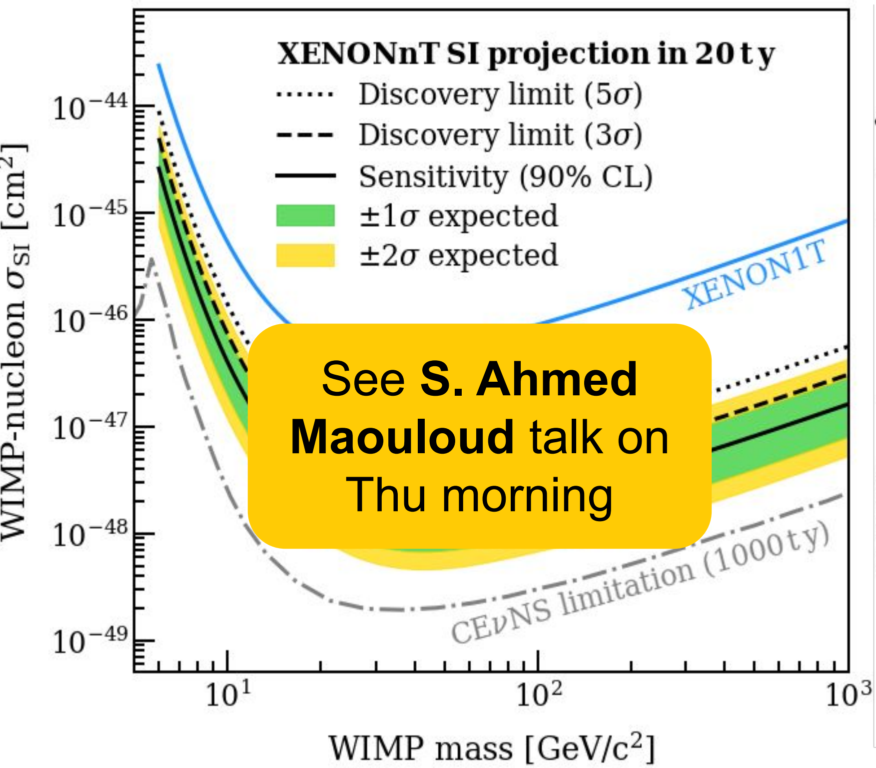
1.4×10^{-48} cm^2 @ 50 GeV/c^2

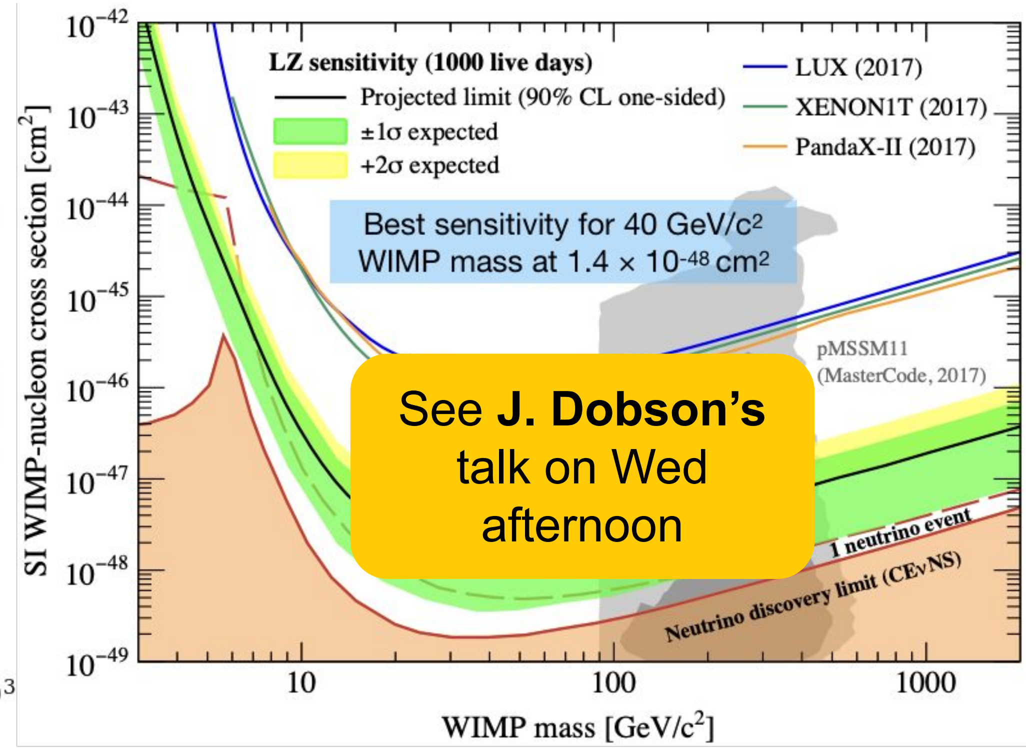
1.4×10^{-48} cm^2 @ 40 GeV/c^2

- Actual ^{222}Rn and neutron rates will be of large impact ultimatively

XENON

LZ





$1.4{\times}10^{-48}$ cm^2 @ 50 GeV/c^2

$1.4{\times}10^{-48}$ cm^2 @ 40 GeV/c^2

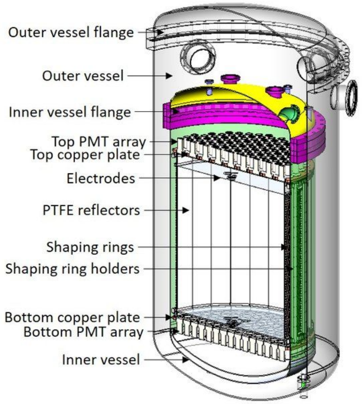
- Actual ^{222}Rn and neutron rates will be of large impact ultimatievely

PandaX = Particle and Astrophysical Xenon Experiments

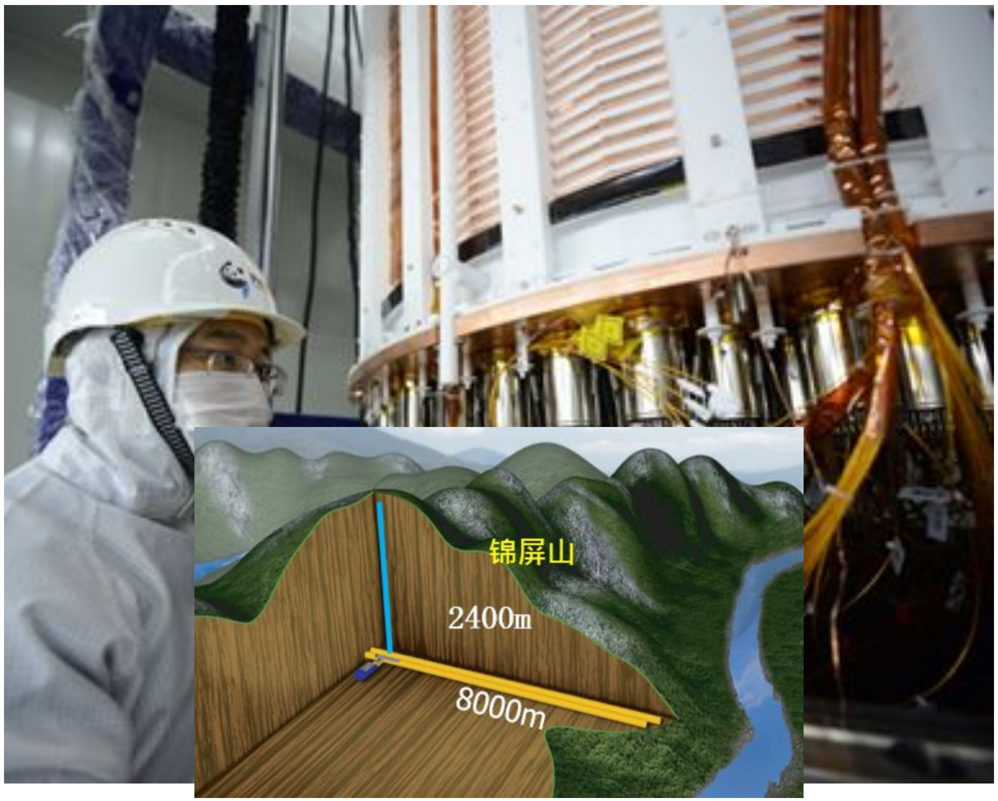
PANDA X

Phase I:
120 kg DM
2009-2014

Phase II:
500 kg DM
2014-2017

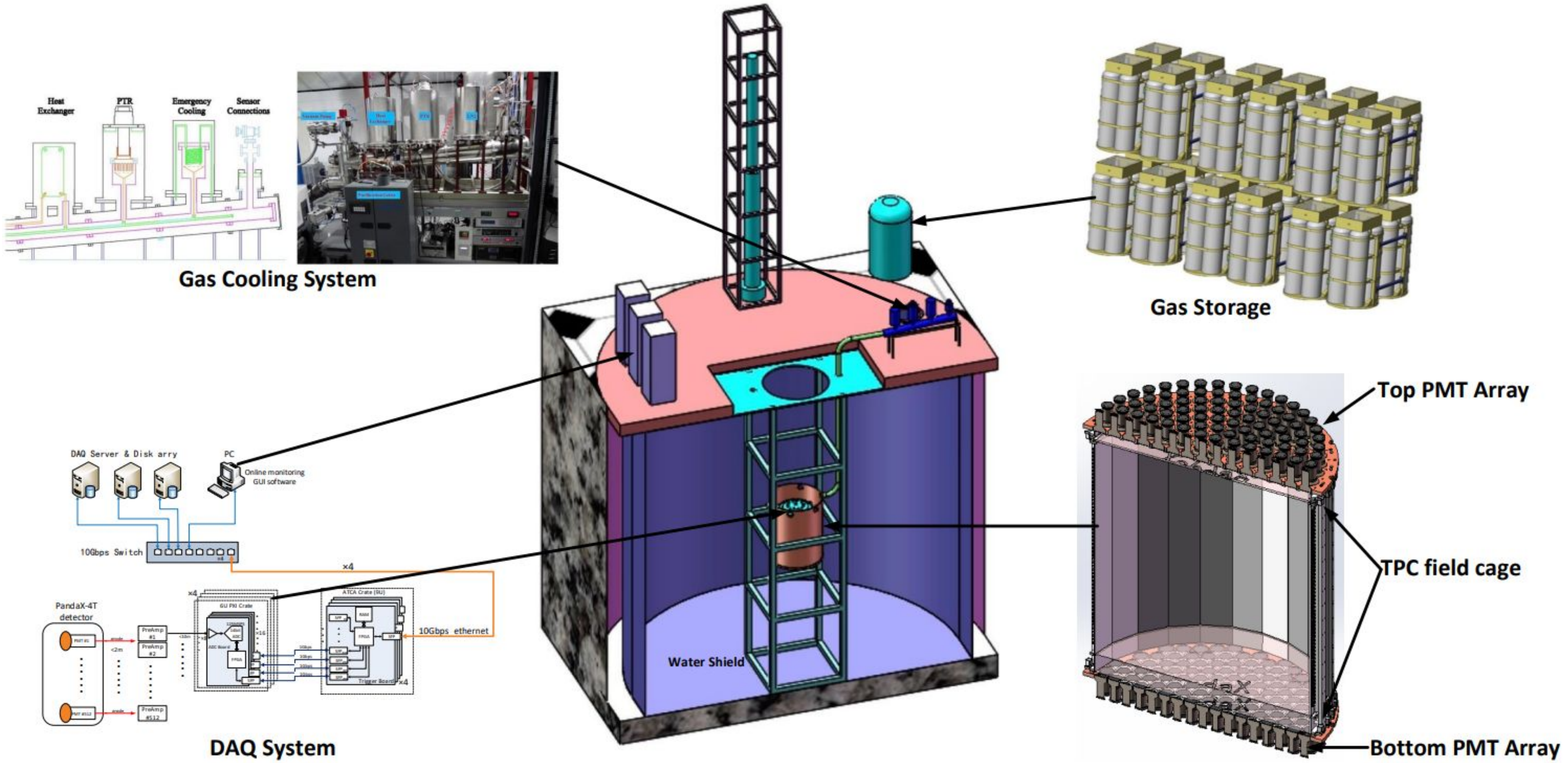


PandaX-4T:
multi-ton DM
2020-

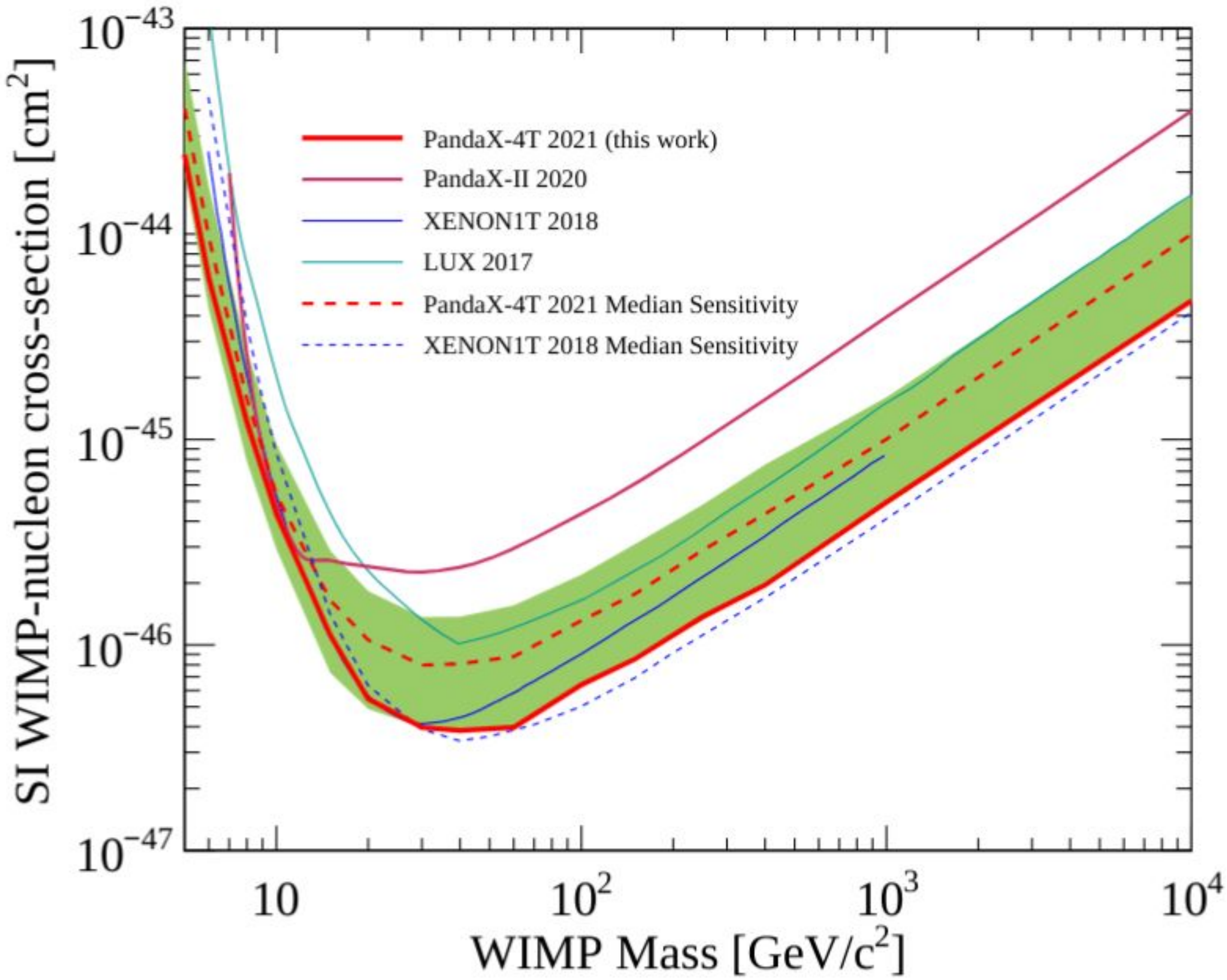


https://arxiv.org/abs/2107.13438

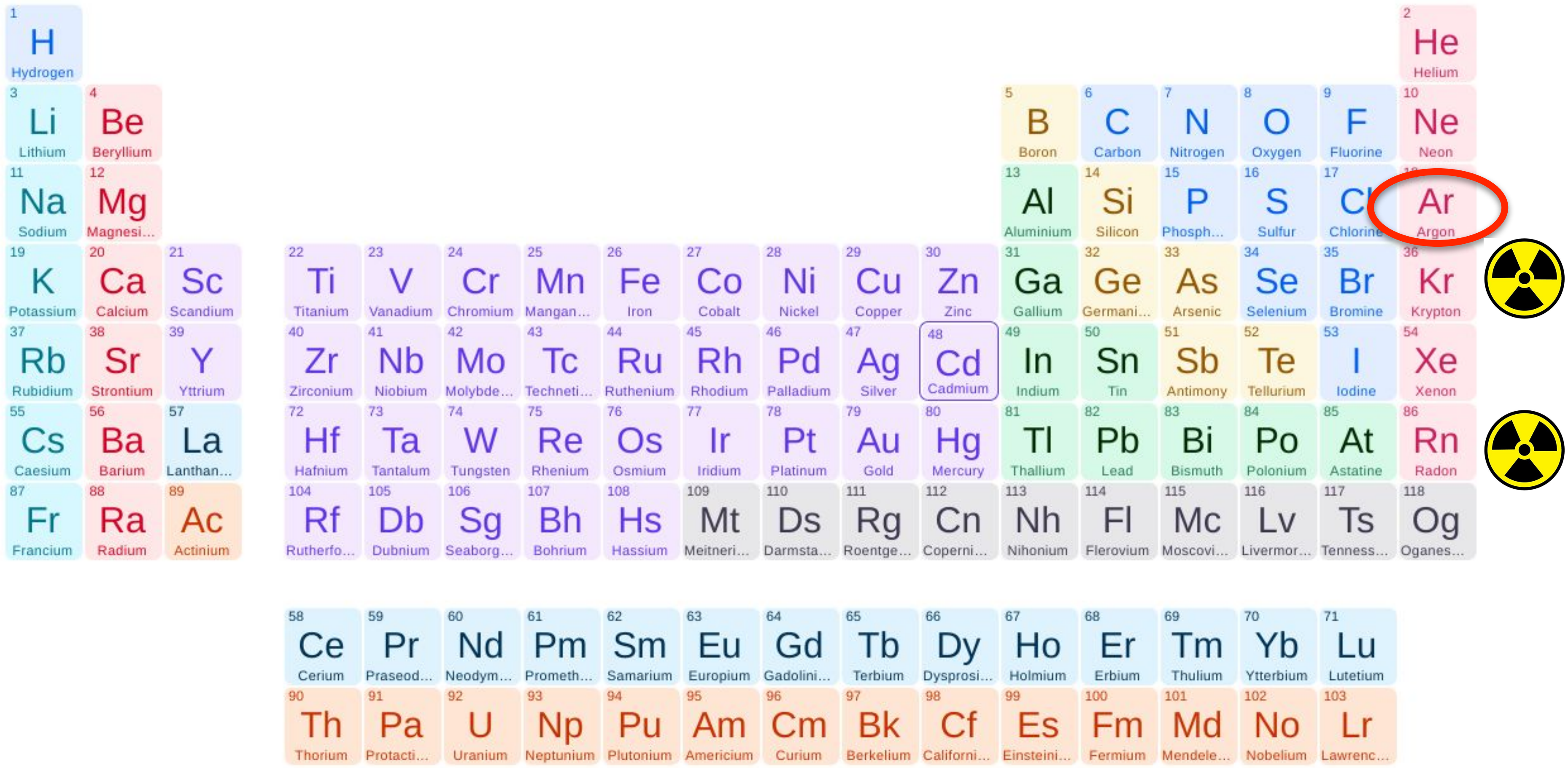
- Located in the China Jinping Underground Laboratory (CJPL)
- 5.7T of Xe, **Fiducial: 3.7T**
- DI **water shield**
- PMTs:
  - 368 3-inch PMT
  - 144 1-inch veto PMT (in Xe)
- DAQ system: Realtime data suppression and triggerless data taking
- **Commissioning** run: 11/2020 - 04/2021

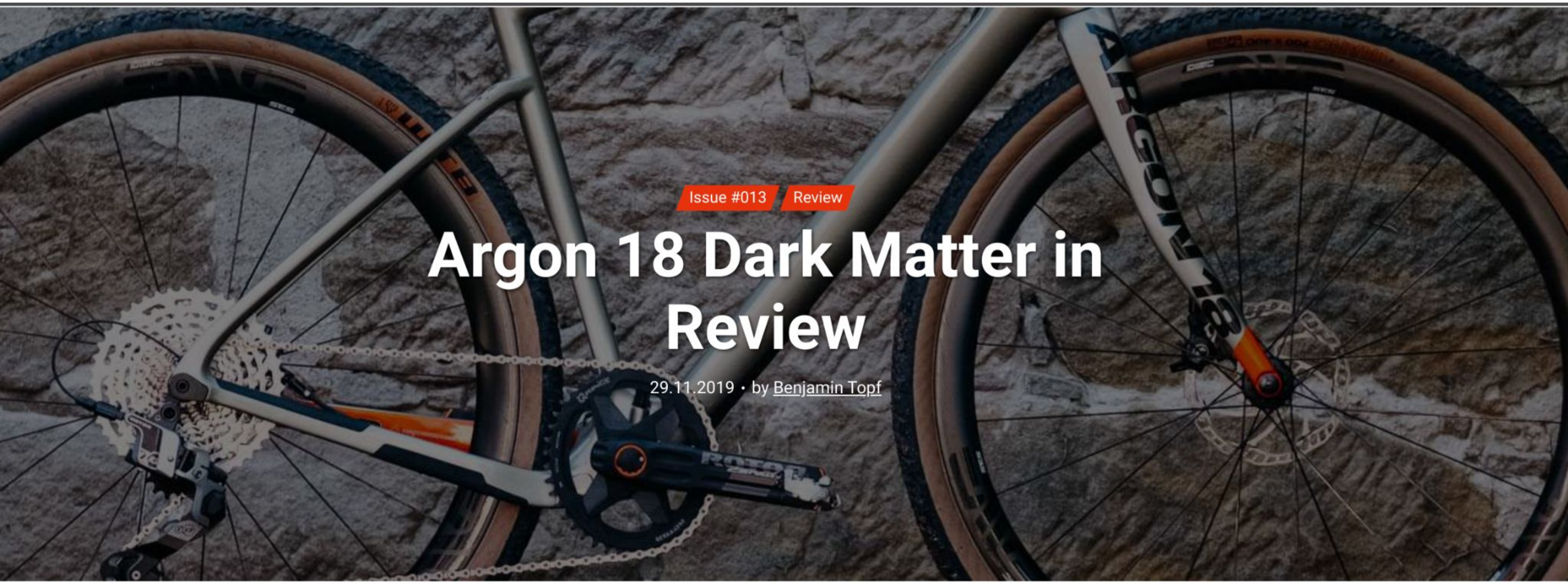


- PandaX-4T impressive performance
- Fast construction/operations with a relatively small team


PandaX-4T 2021 (this work)
PandaX-II 2020
XENON1T 2018
LUX 2017
PandaX-4T 2021 Median Sensitivity
XENON1T 2018 Median Sensitivity
SI WIMP-nucleon cross-section [cm^2]
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10
10^2
10^3
10^4
WIMP Mass [GeV/c^2]

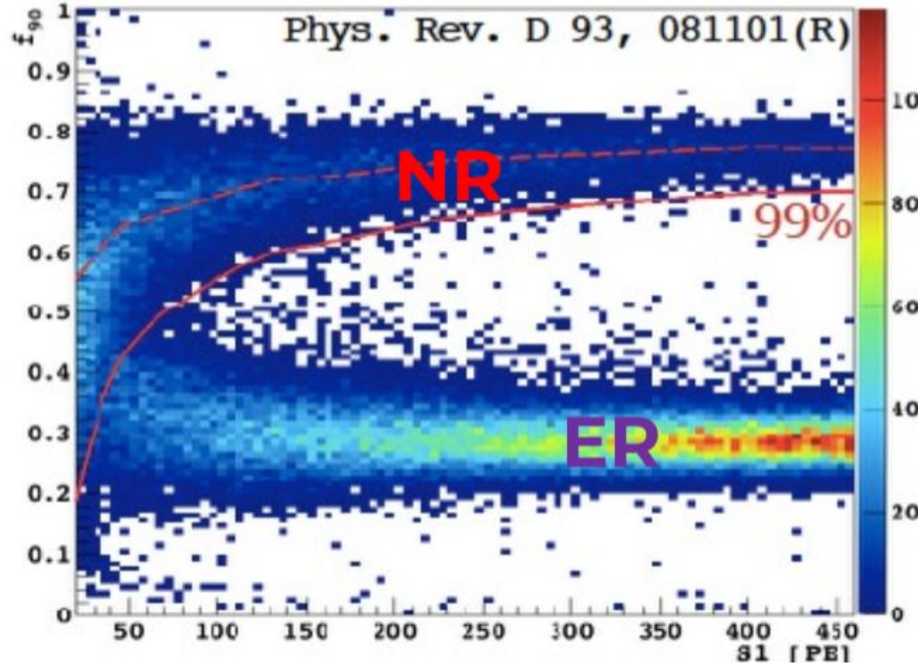
Argon Detectors

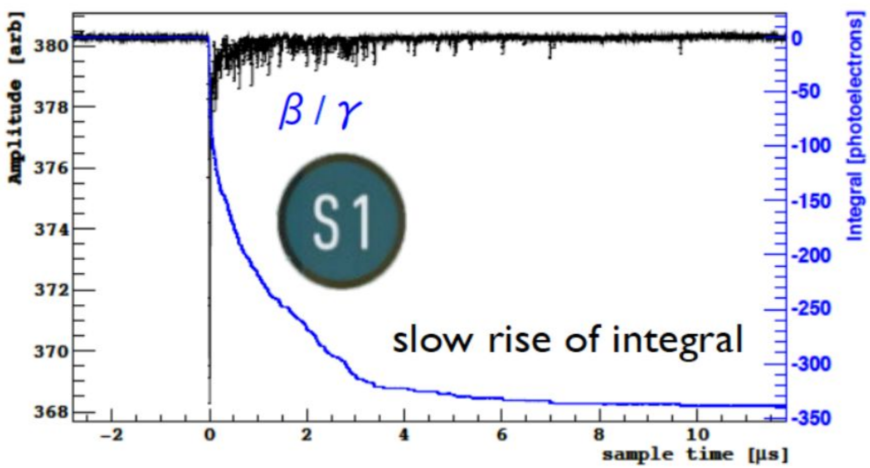


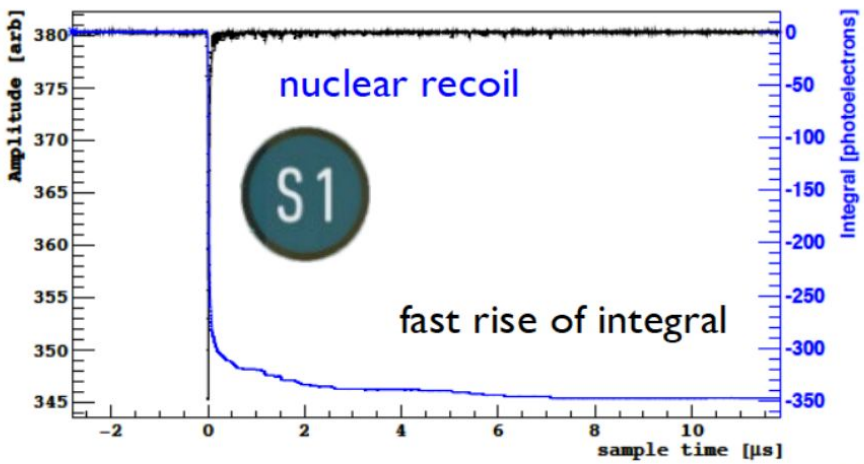


The Argon 18 Dark Matter gravel bike equipped with a 1×13 Rotor groupset is the Canadian brand's candidate for the group test. Does its concept work and how does the hydraulic drivetrain perform? Read on to find out more.

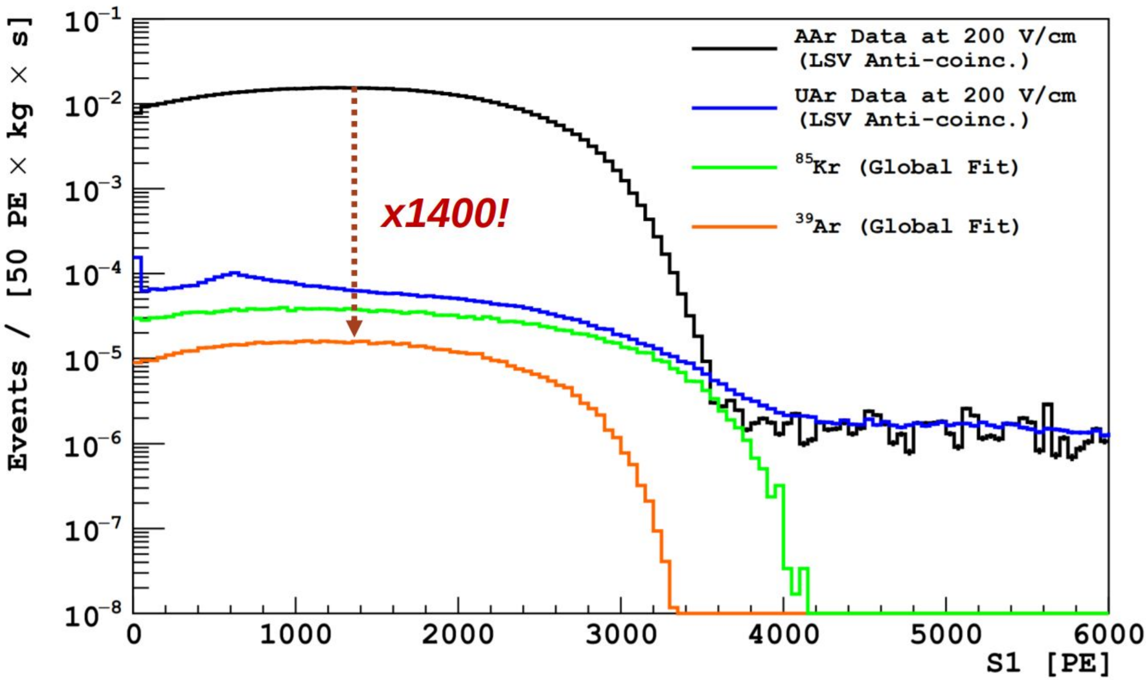
- At has different decay times: singlet (~7ns) vs. triplet (~1.6μs) state.
  - **ER** cause relatively **more triplet**
  - **NR** cause relatively **more singlets**
- Use **pulse shape discrimiation**



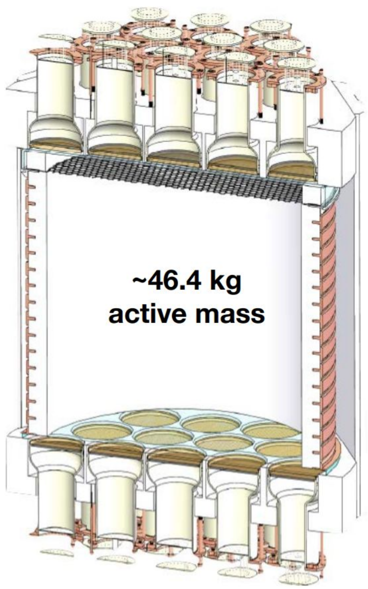


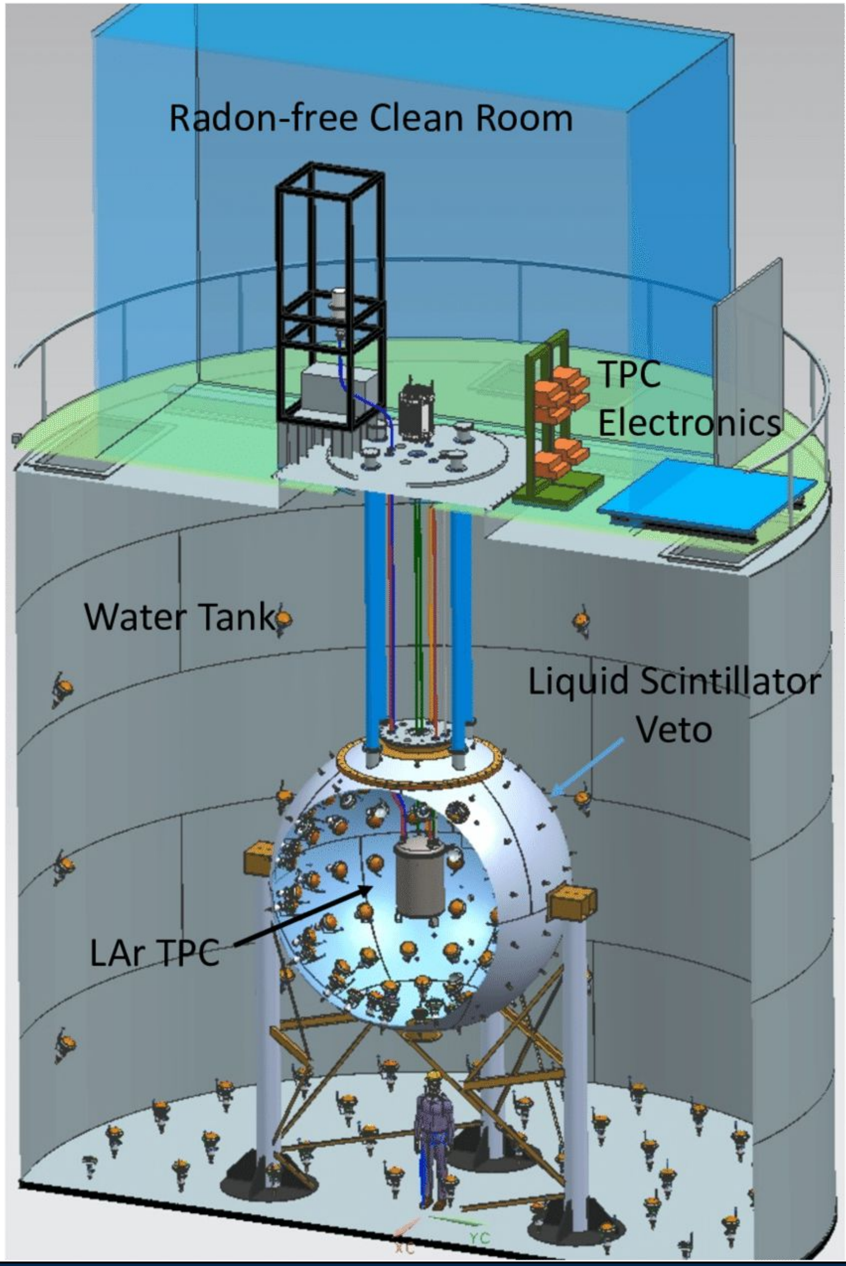


- **Ar** is the **most abundant noble gas** in the atmosphere,
- Much less expensive than Xe plus PSD
  - However, **cosmogenic ^{39}Ar production** limits the size of detectors due to pile-up
    - 10^{-15}g/g → ^{nat}Ar ~ 1Bq/kg, 269 yr half-life
- **Solution**: Source underground Ar depleted in ^{39}Ar, further purify via cryogenic distillation

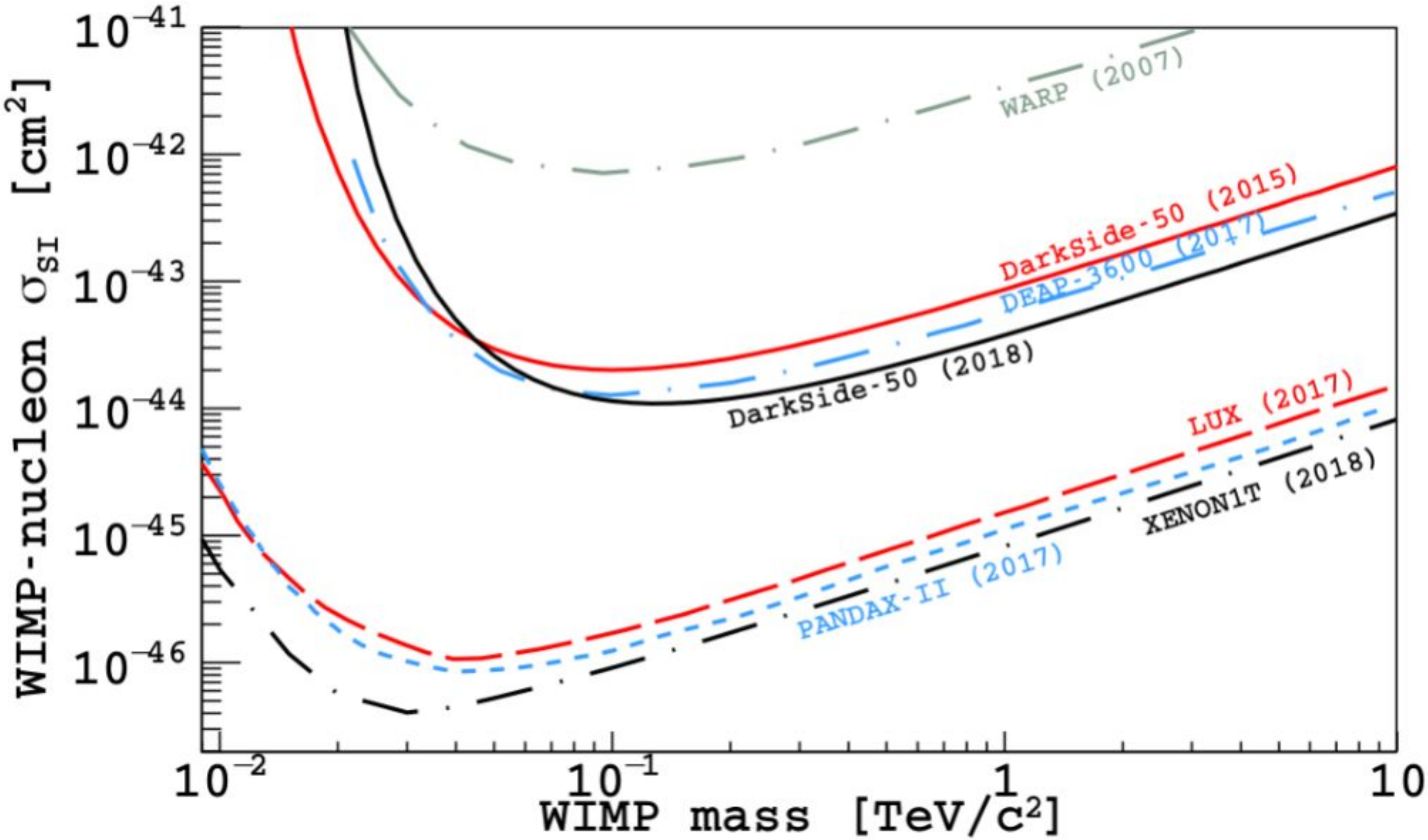


- Data taking: 2014 – 2020
- **Argon DM TPC** using 46 kg LAr underground Argon
- **Active γ/n veto**: 30t of $_{10}$B-loaded liquid scintillator
- 1kT of ultra-pure **water shield** & **active veto for muons**



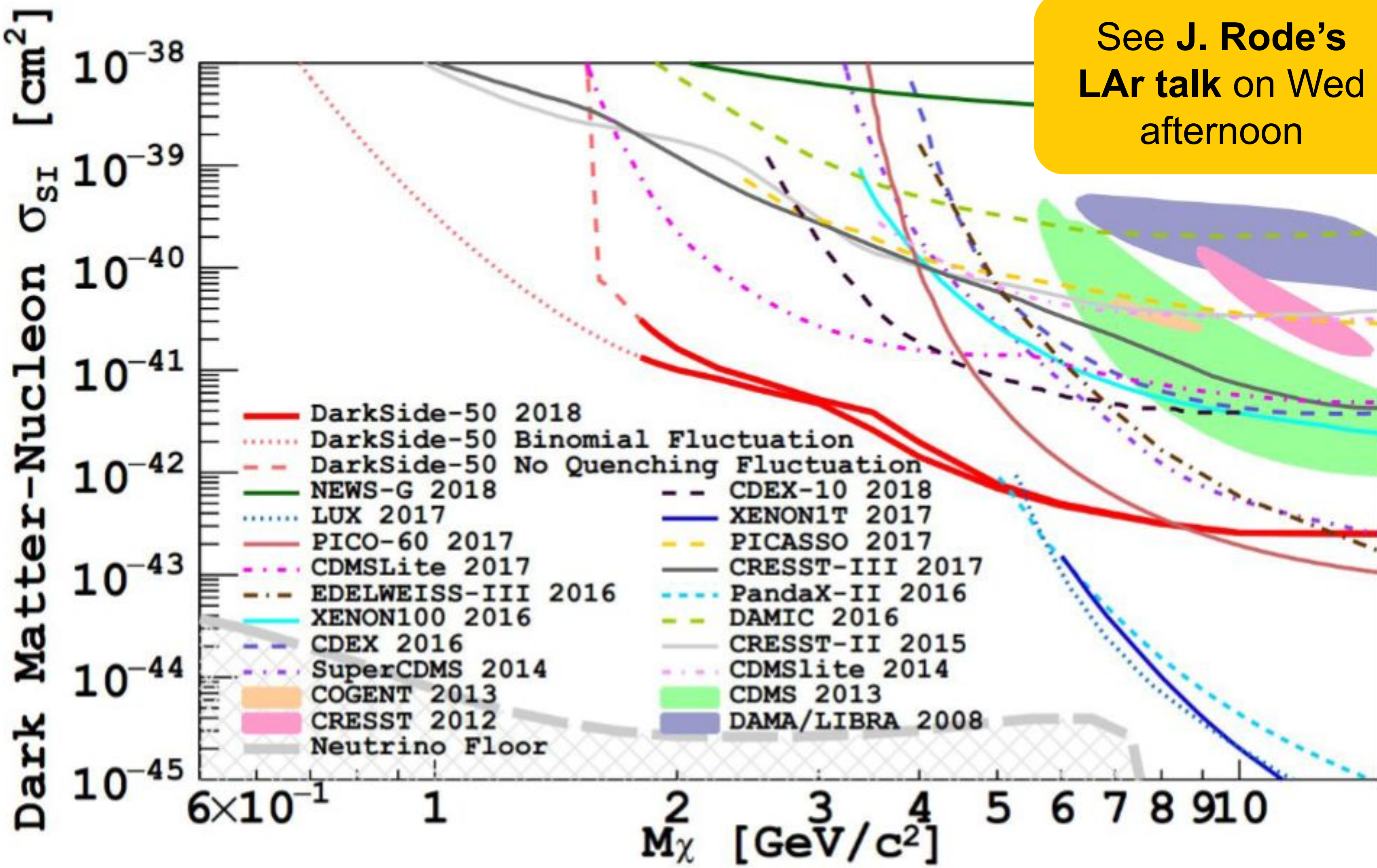


arxiv:1802.07198



- High Mass DM exclusion σ_{xN} > 1.1 x 10 $^{-44}$ cm^2 @100 GeV/c 2

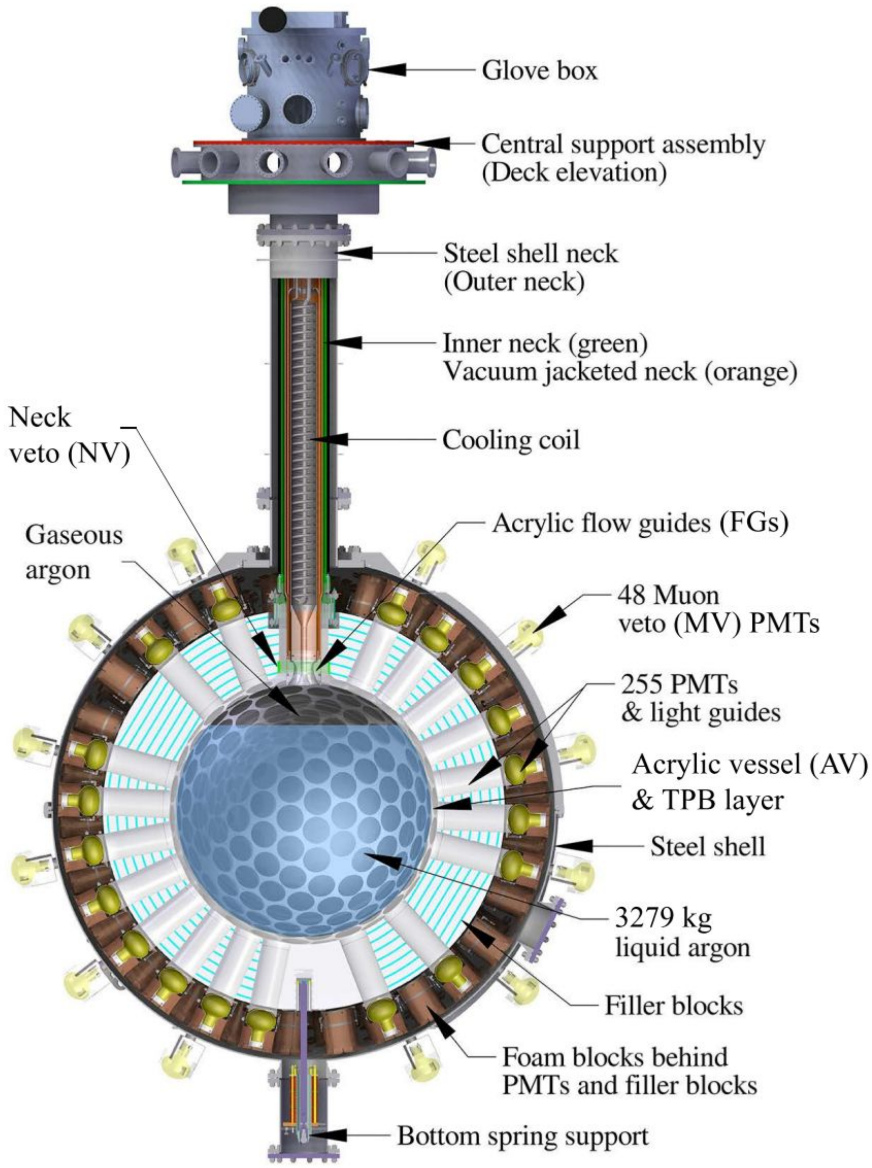
arxiv:1802.06994



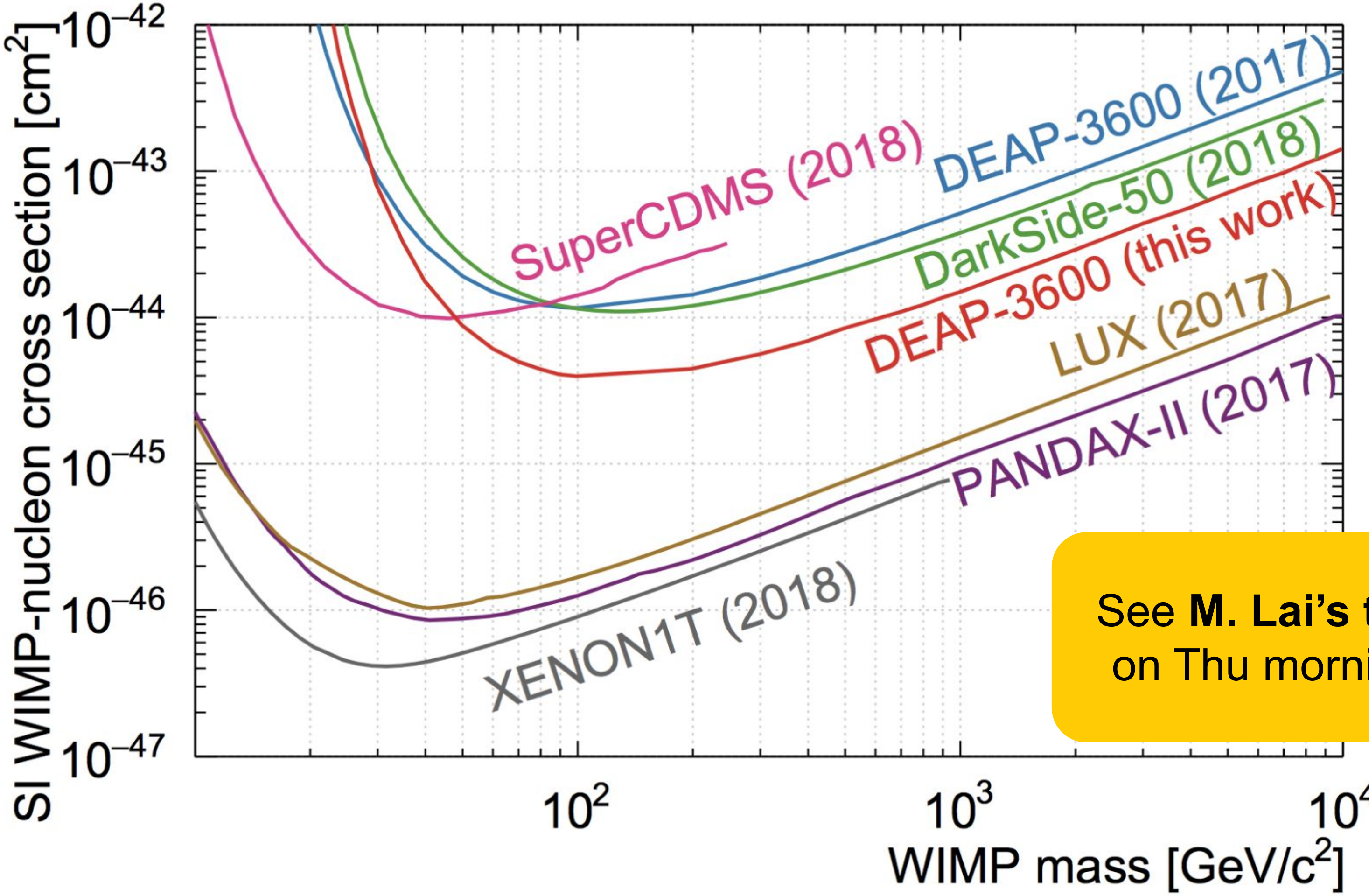
See **J. Rode's LAr talk** on Wed afternoon

- DarkSide-20k performed leading **low mass analysis** (**S2 only**)

- **Single-phase** LAr detector
- ~2 km underground at **SNOLAB** (Canada).
- Searches for **nuclear recoils (10 - 100 keV)**, electron recoils are rejected.
- **3279 kg of LAr** in acrylic spherical vessel
- Demonstration of the **power of PSD**
- Presently **upgrading** due to achieve design performance due to backgrounds around 'neck'



https://arxiv.org/abs/1902.04048

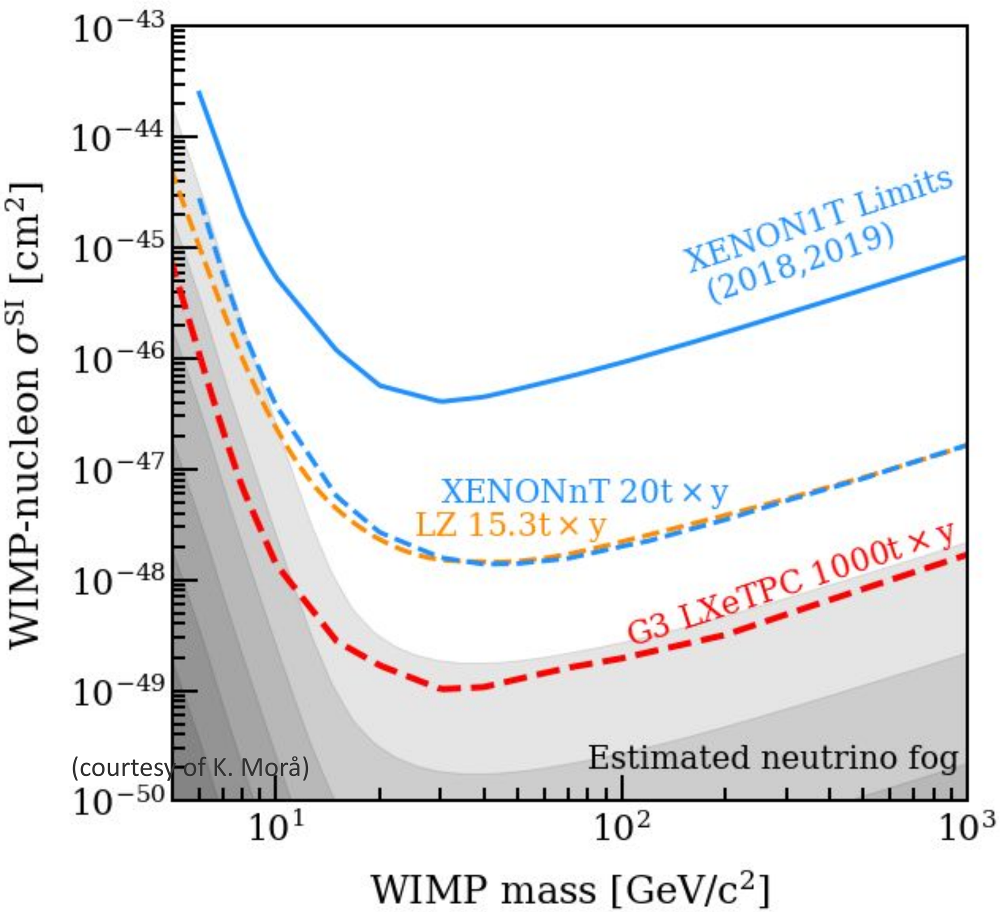


See **M. Lai's talk** on Thu morning

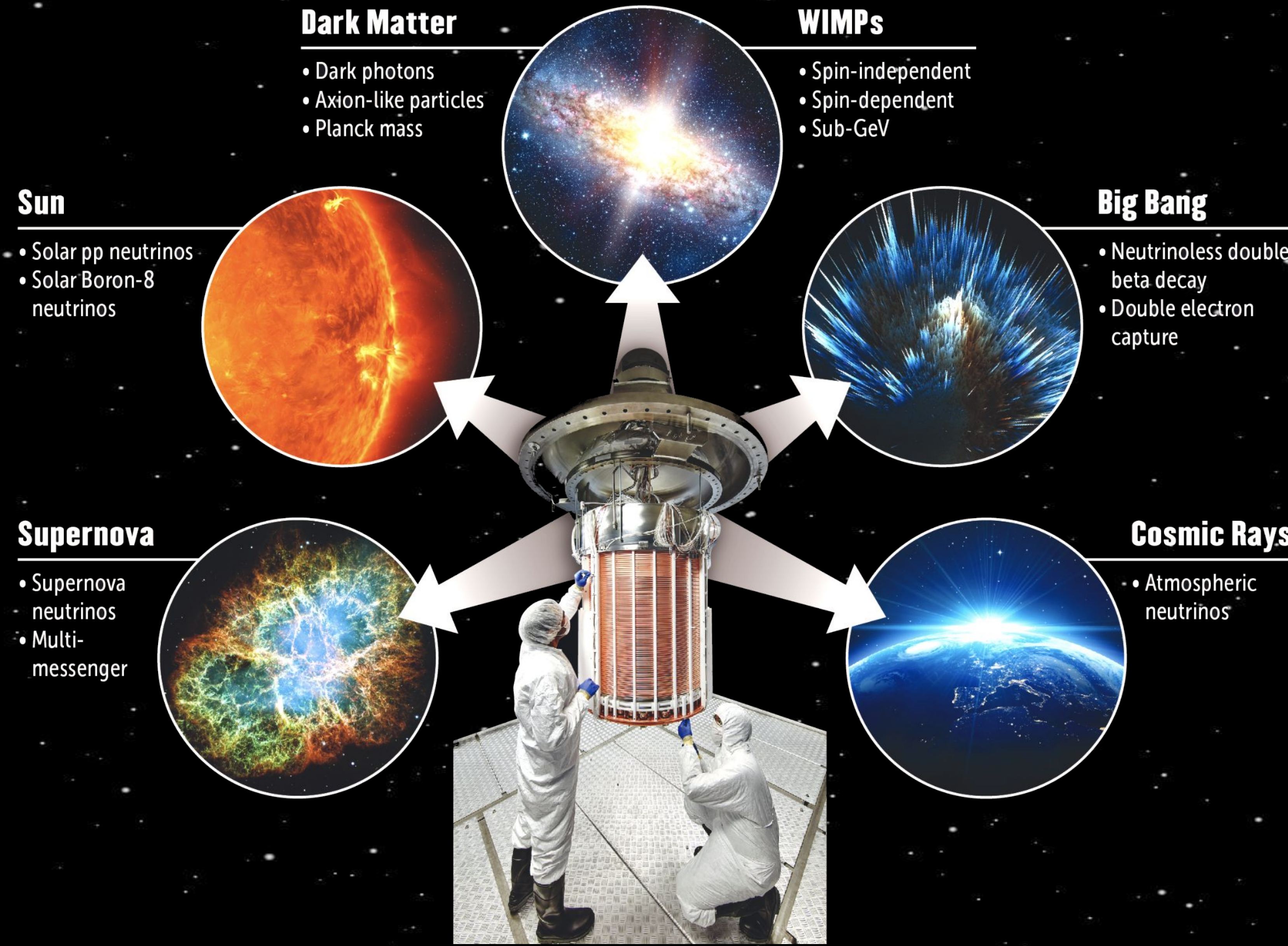
- Limit off **σ_{xN} =3.9 x 10^{-45} cm^2** for a 100 GeV WIMP at 90% C.L,
- Leading **exclusion curve for argon detector**.

The Future

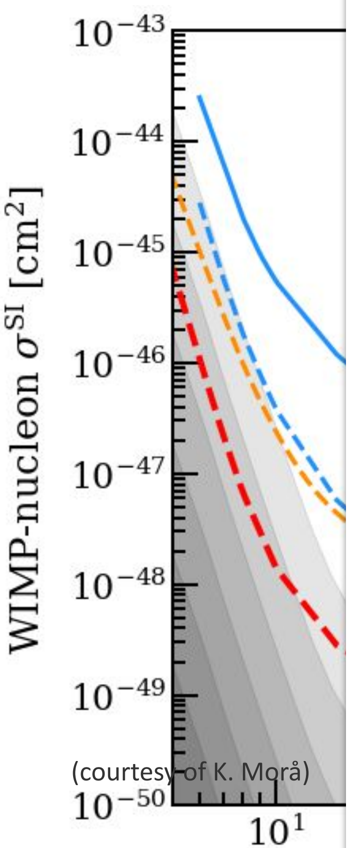
2203.02309



- WIMPs remain the most compelling DM models
  - The “neutrino fog” is still far away
- Lots of other interesting physics other than simply DM (0νββ, nuclear, neutrino, astro)
- **Generation-3 LXe** TPC will be the ultimate multi-purpose observatory to advance new physics
- **LZ & XENON are joining forces**
- Great challenges ahead


Dark Matter
• Dark photons
• Axion-like particles
• Planck mass
WIMPs
• Spin-independent
• Spin-dependent
• Sub-GeV
Sun
• Solar pp neutrinos
• Solar Boron-8 neutrinos
Big Bang
• Neutrinoless double beta decay
• Double electron capture
Supernova
• Supernova neutrinos
• Multi-messenger
Cosmic Rays
• Atmospheric neutrinos

2203.02309



CONTENTS

G3 whitepaper
arXiv:2203.02309
500+ authors

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PC will be
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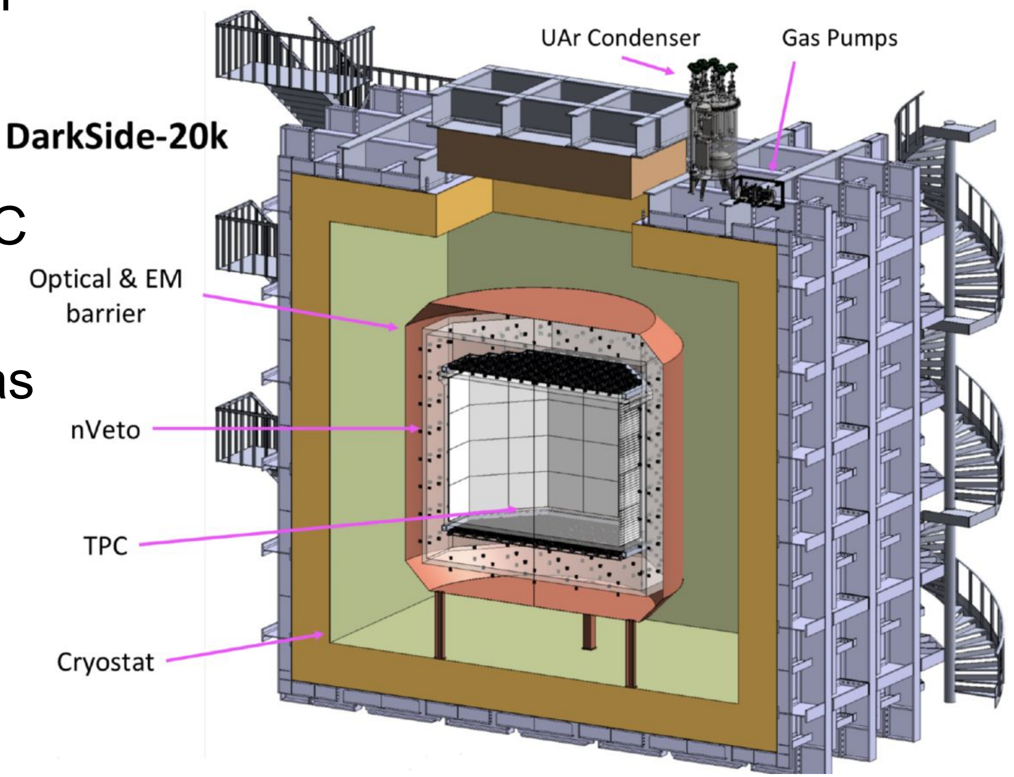
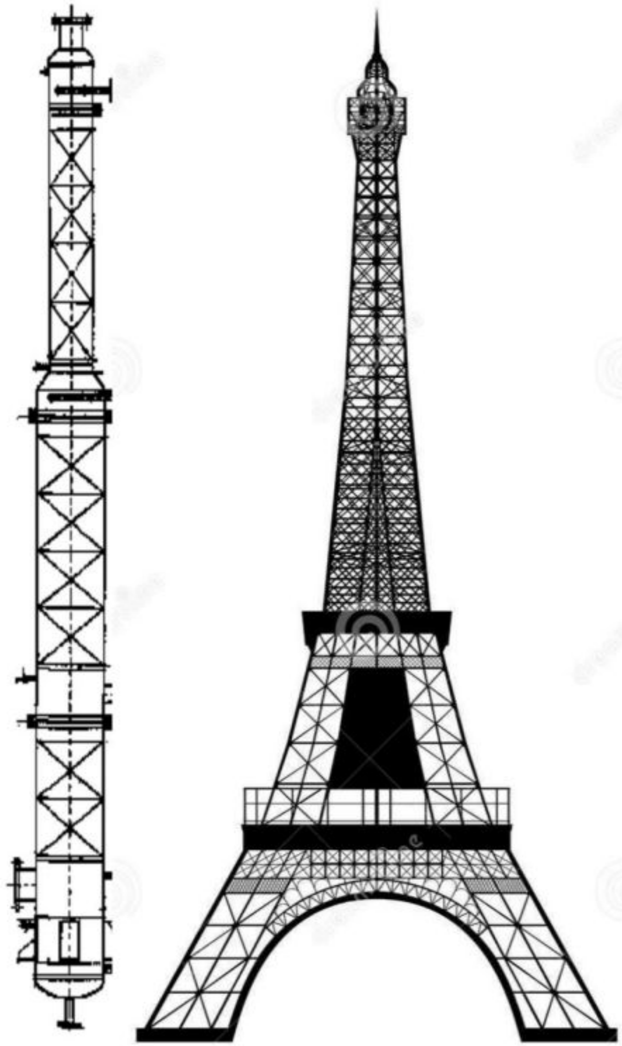
- **Global Argon Dark Matter Collaboration** (GADMC), merger of DEAP-3600, MiniCLEAN, ArDM & DarkSide-50
- **DarkSide-20k**
  - Sealed acrylic dual phase TPC filled with ~ 50 tonnes UAr
  - 2% Gd doped acrylic panels as neutron veto detector
  - Membrane cryostat filled with ~700 tonnes Atmospheric Argon (AAr);
  - SiPMs as photosensors:
    - 8280 channels for TPC
    - ~3000 channels for Veto;

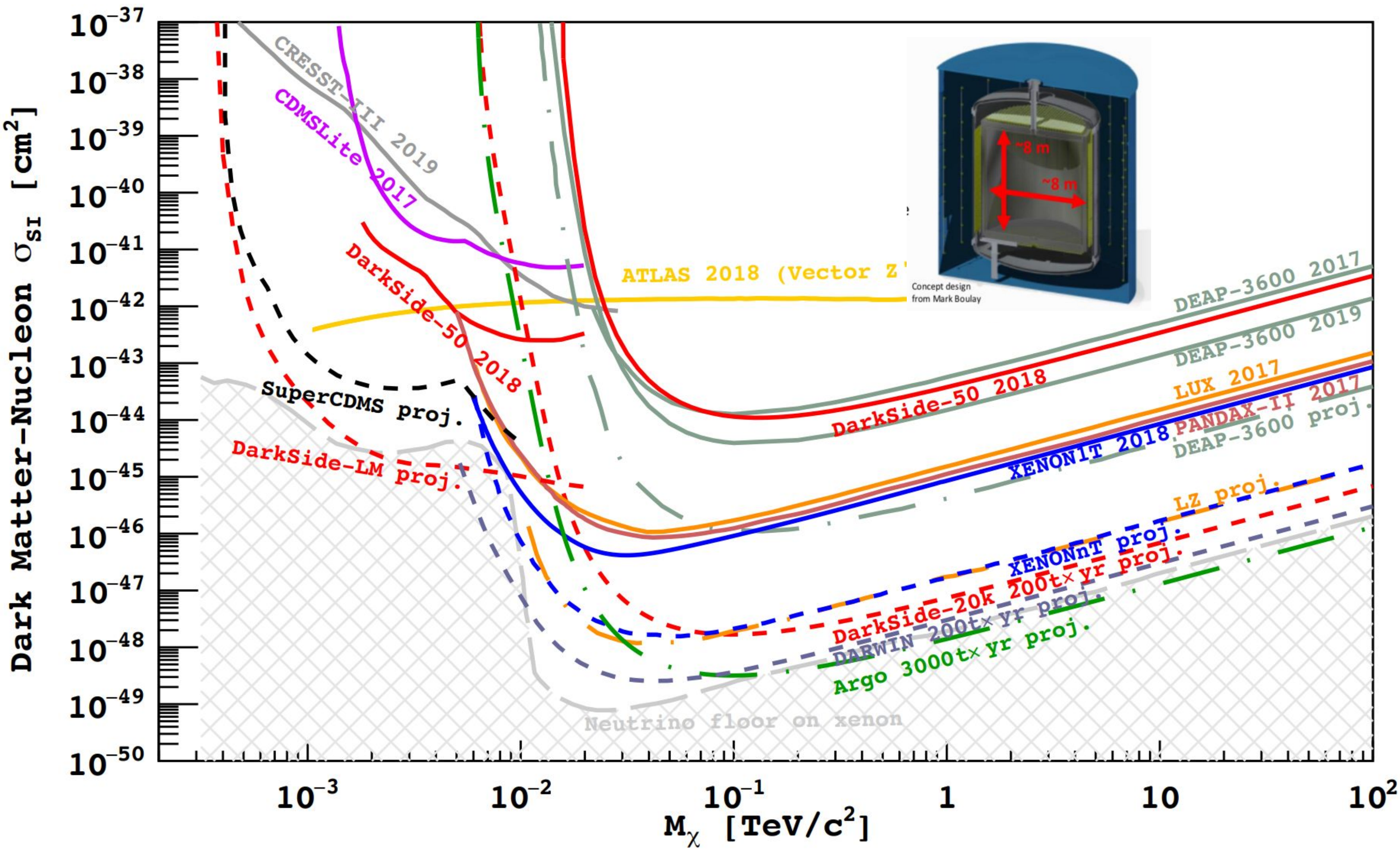


DarkSide-20k
50 T LAr



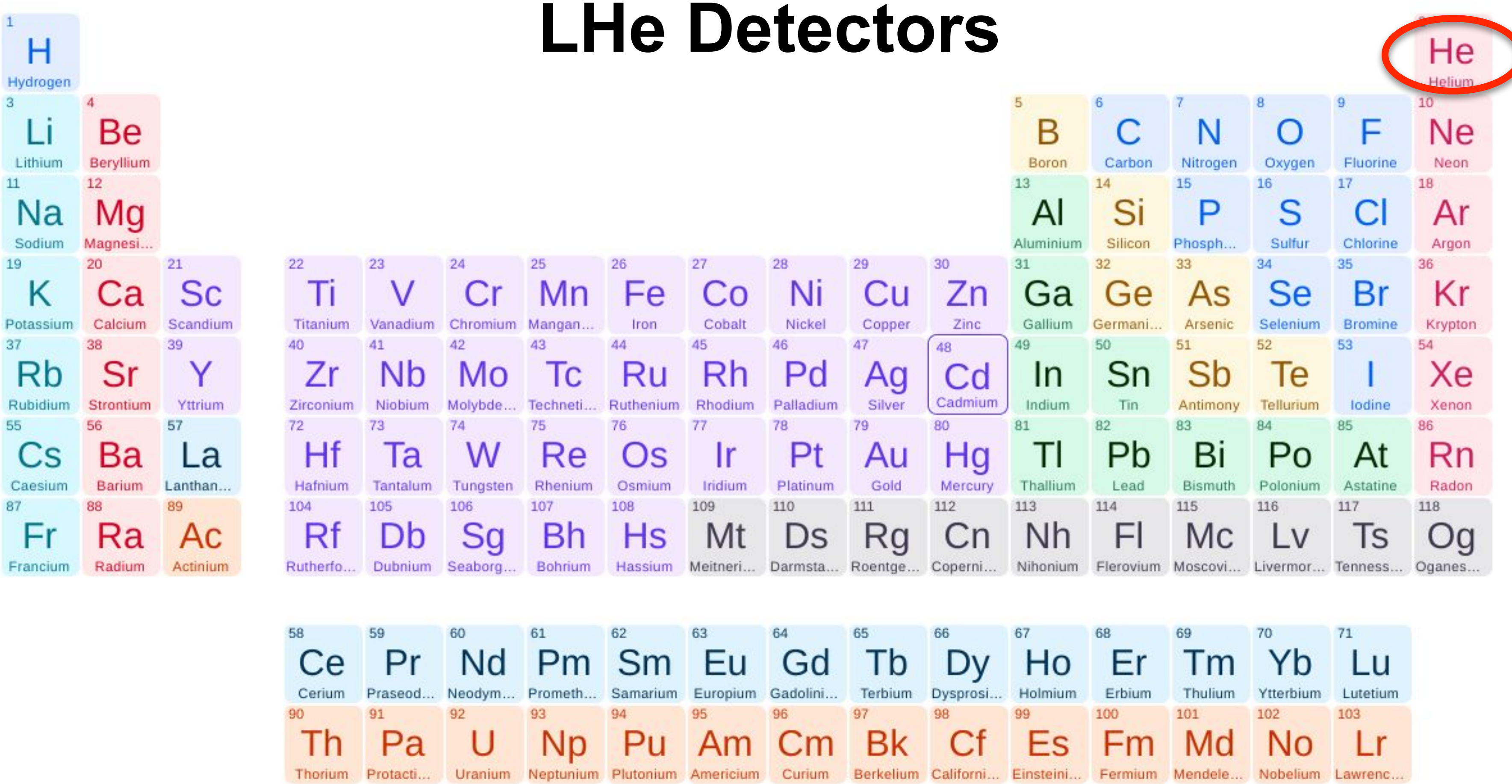
- **Urania:** UA extraction plant in CO, USA. Same source as DS-50
- **Aria**: Huge cryogenic distillation column in Sardinia, Italy
- Final chemical purification of the UAr
    - Process O (1 t/day) with **10^3 reduction** of all chemical impurities
    - Isotopically separate ^{39}Ar from ^{40}Ar

https://arxiv.org/pdf/2101.08686.pdf

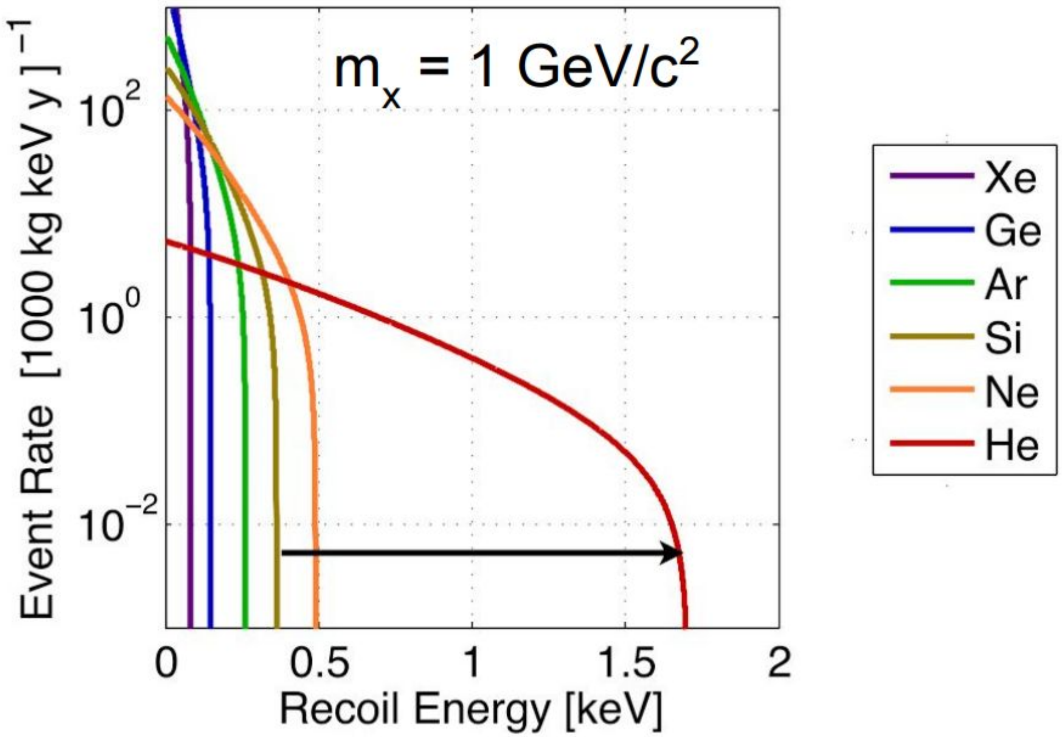


- Long term goal for 300T (!) detector: **ARGO**

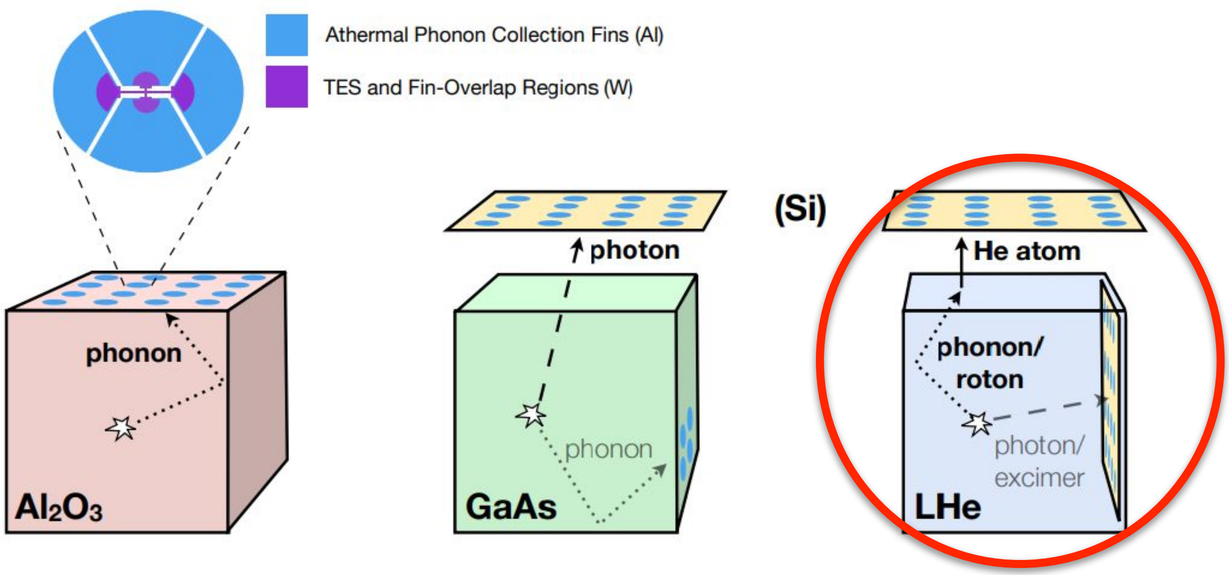
LHe Detectors



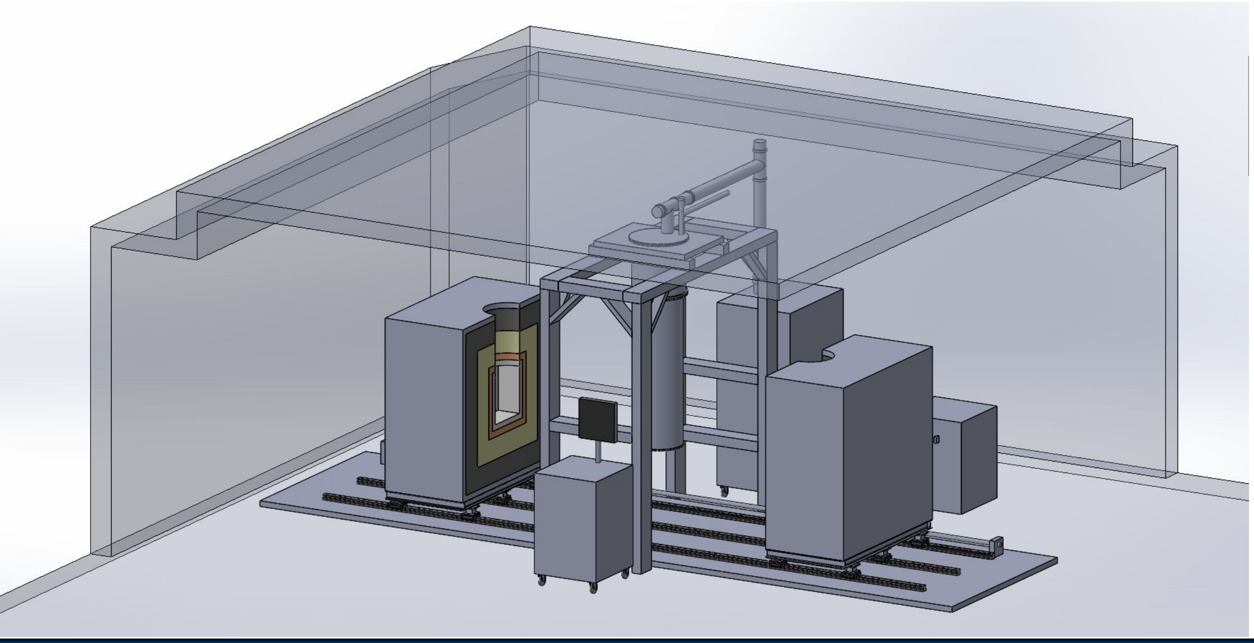
- With sufficiently low threshold and/or a light target, lower dark matter masses may be probed
- He^4 is fairly **cheap**, **radiopure**, **scalable**
- **Novel signal channels** reach sensitivities that can not be realized using only ionization or scintillation signals **(rotons, phonons, scintillation, triplet excimers)**

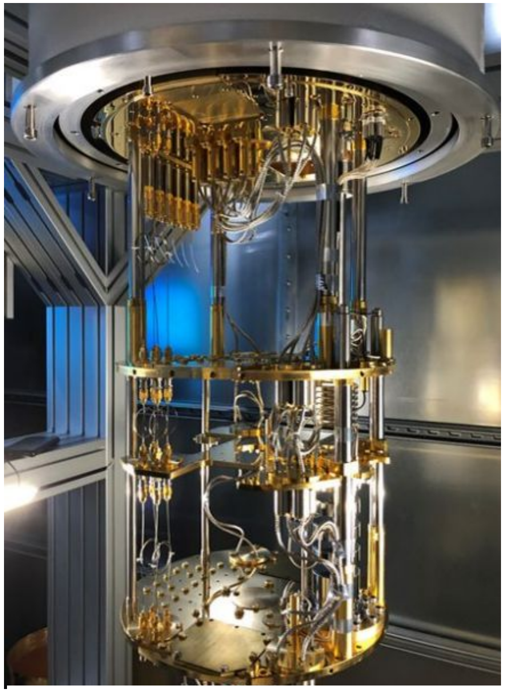


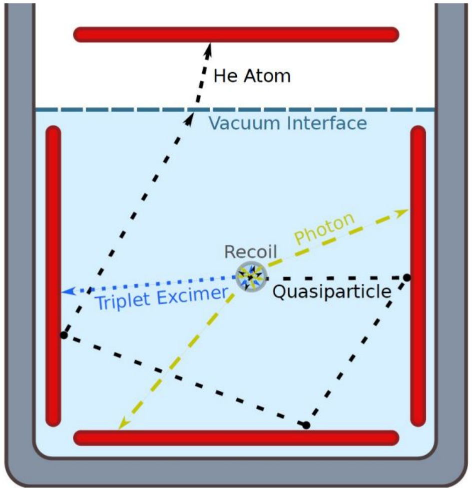
- One experimental design with **different targets for complementary sensitivity**
- 8 institutions, about 30 people
- All targets use small masses, a TES redouts at cryogenic temperatures and require a well shielded detector



- Heart of the experiment is a **dilution fridge (DR) in a multilayer shielding**
  - Swappable payload
  - SPICE (polar crystals) & **HeRALD (superfluid helium)**
- Shielding design has converged on a **compact lead/polyethylene approach** with **TI cryostat**

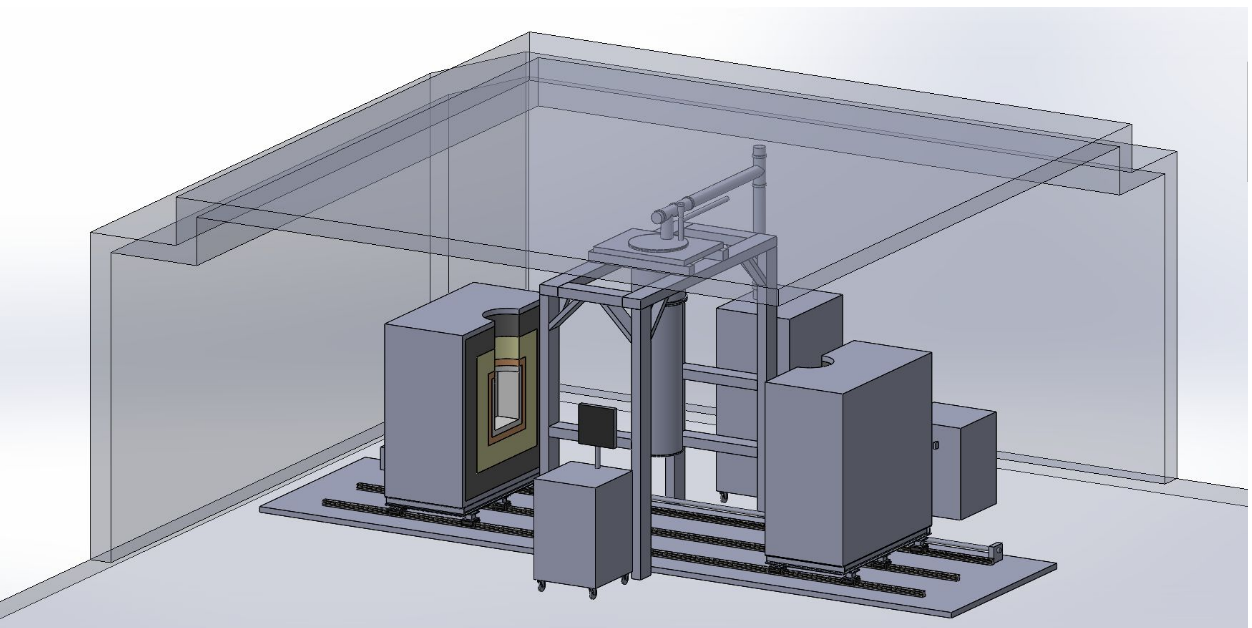


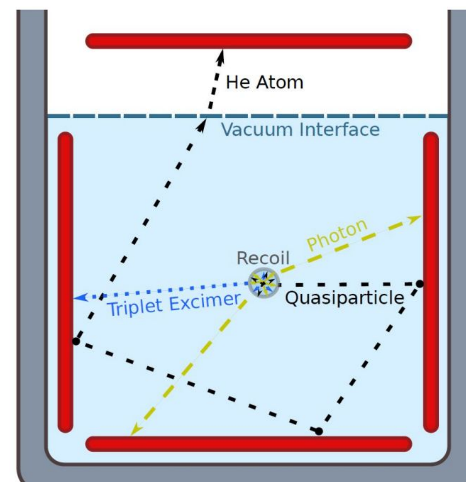




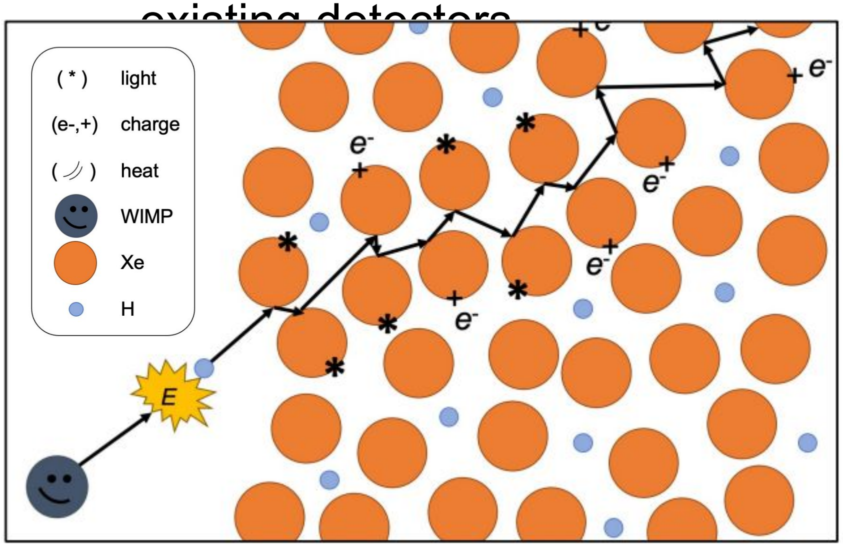
- Heart of the experiment is a **dilution fridg** **a multilayer shielding**
  - Swappable payload
  - SPICE (polar crystals) & **HeRALD (** **helium)**
- Shielding design has converged on a **compact lead/polyethylene approach** with **TI cryostat**

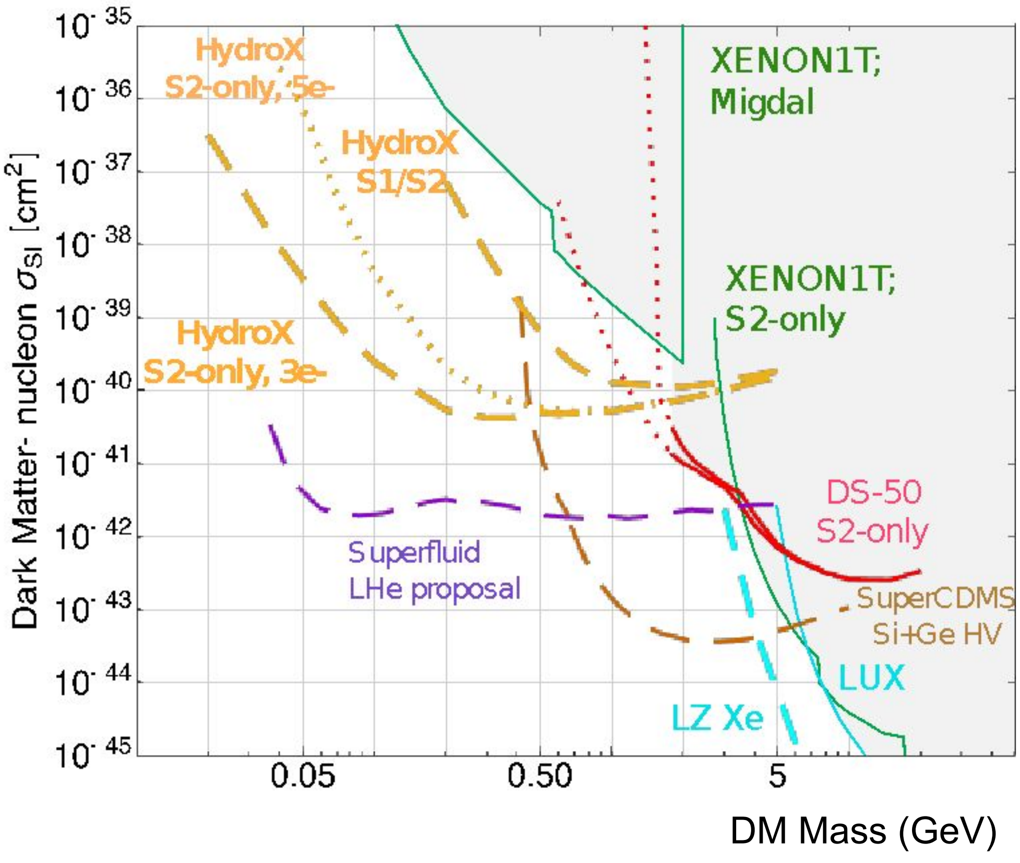
See **D. McKinsey's** Wed talk details on Tesseract





- **Hydrogen** dissolved in **Xe**:
  - Better kinematic match to low mass DM
  - Transfer more energy to visible electronic excitations
- Could imagine program using **deuterium for SD** sensitivity
- **Potential upgrade path** for existing detectors





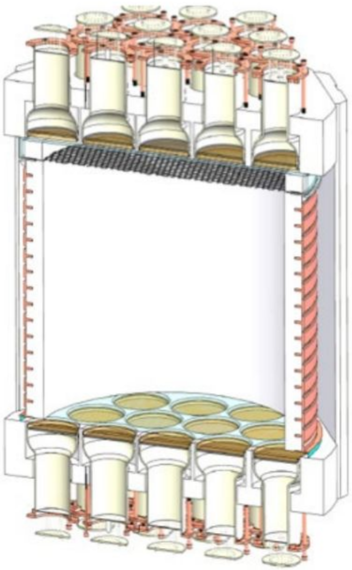
Credit: A. Monte, H. Lippincott

- **DM is out there** and will transform our understanding of the Universe
- WIMP's reman the best motivated candidate yet and we have **discovery experiments that just started running**
- **Tremendous progress** in the last 20 years going from **kg to T scale**

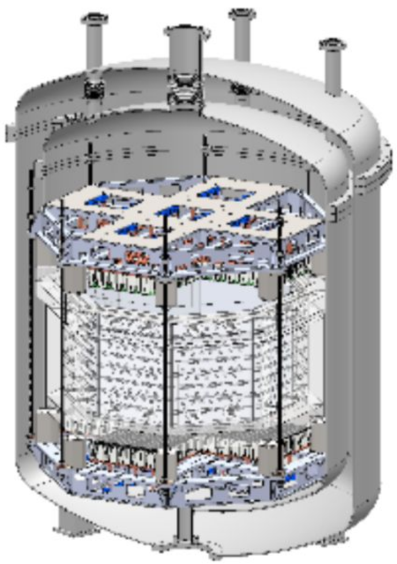
- In the coming decade we will see **another order of magnitude** improvement to the **neutrino fog**
- New experiments **broaden the types of DM and mass range** that **we are probing**
- LXe so far most sensitive, but there are **many other interesting approaches** and we don't know yet what DM is

Backup

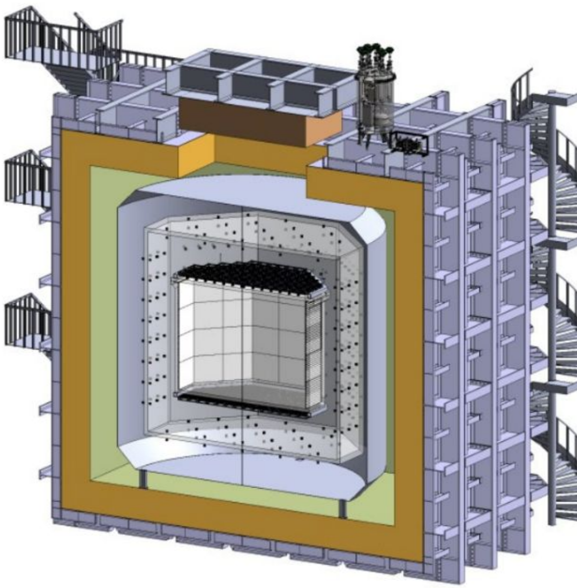
- DarkSide: Multi-stage DM program searching using LAr TPCs at Gran Sassos



DS-50
50Kg LAr



DS-proto-1t
175Kg LAr

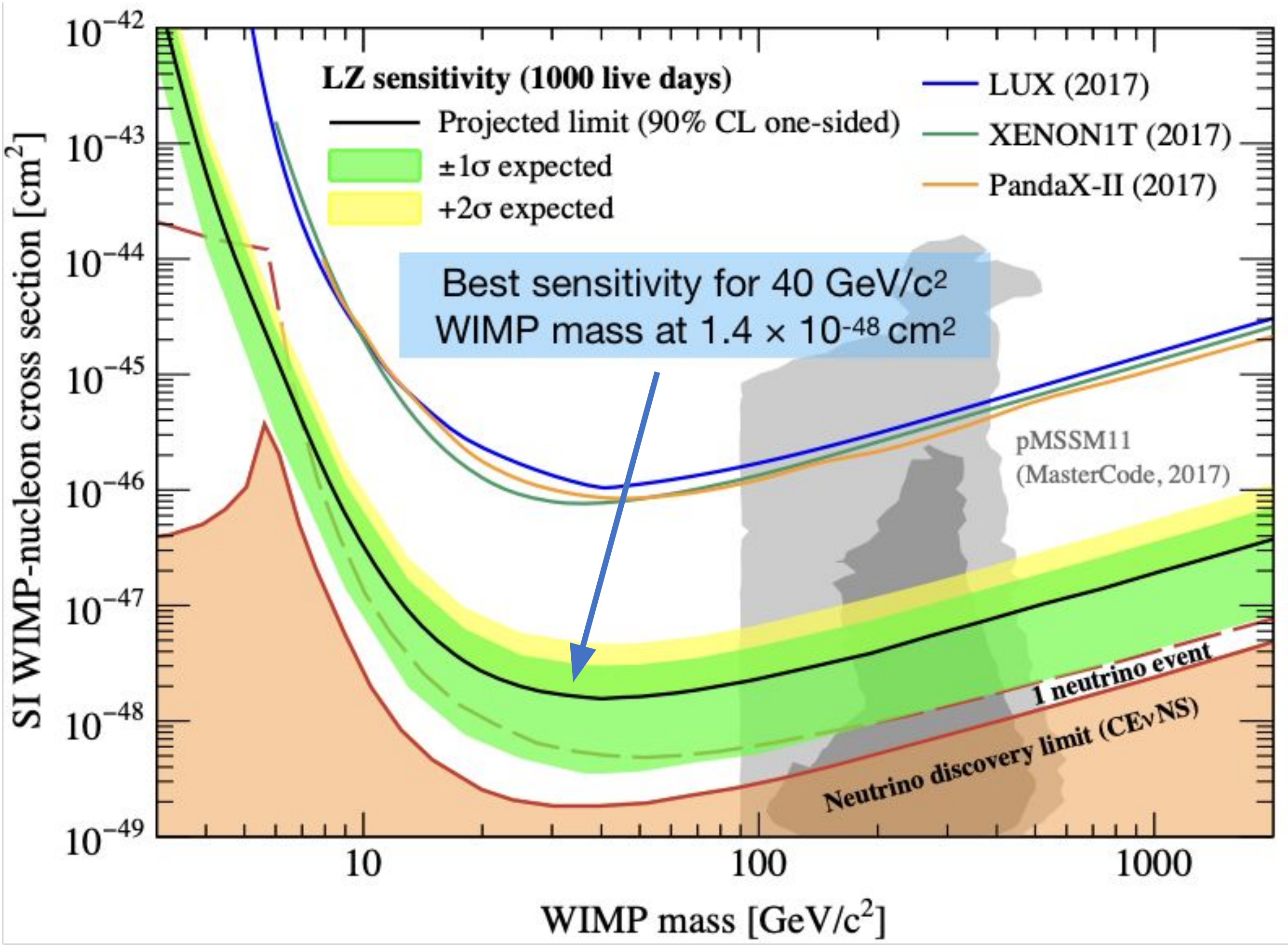


DS-20k
50ton LAr

- Part of the Global Argon Dark Matter Collaboration (GADMC), a combination of past and present experiments (DEAP-3600, MiniCLEAN, ArDM and DarkSide-50)

Standard WIMP Searches

PRD 101, 052002 (2020)

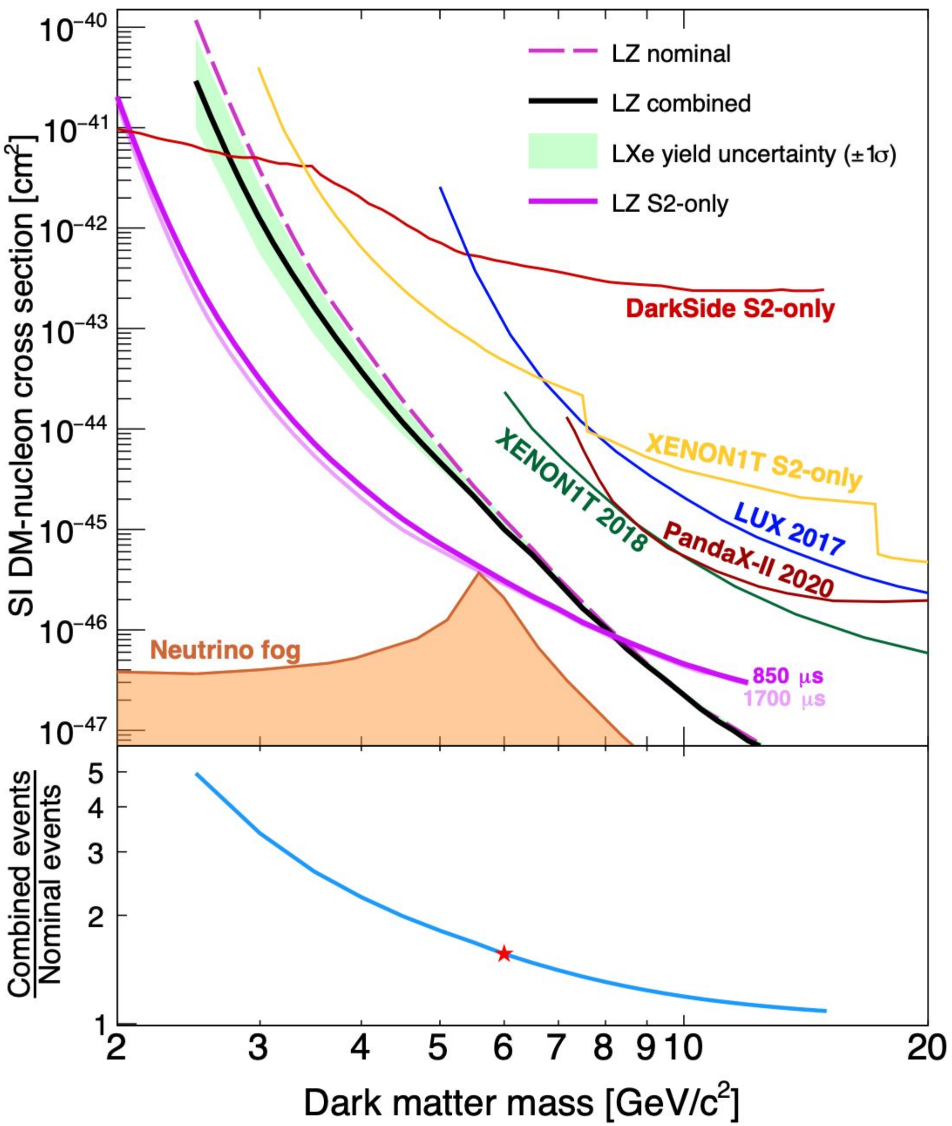


Source	ER [cts]	NR [cts]
Total	1131	1.03
99.5% ER discr., 50% NR eff.	5.66	0.52

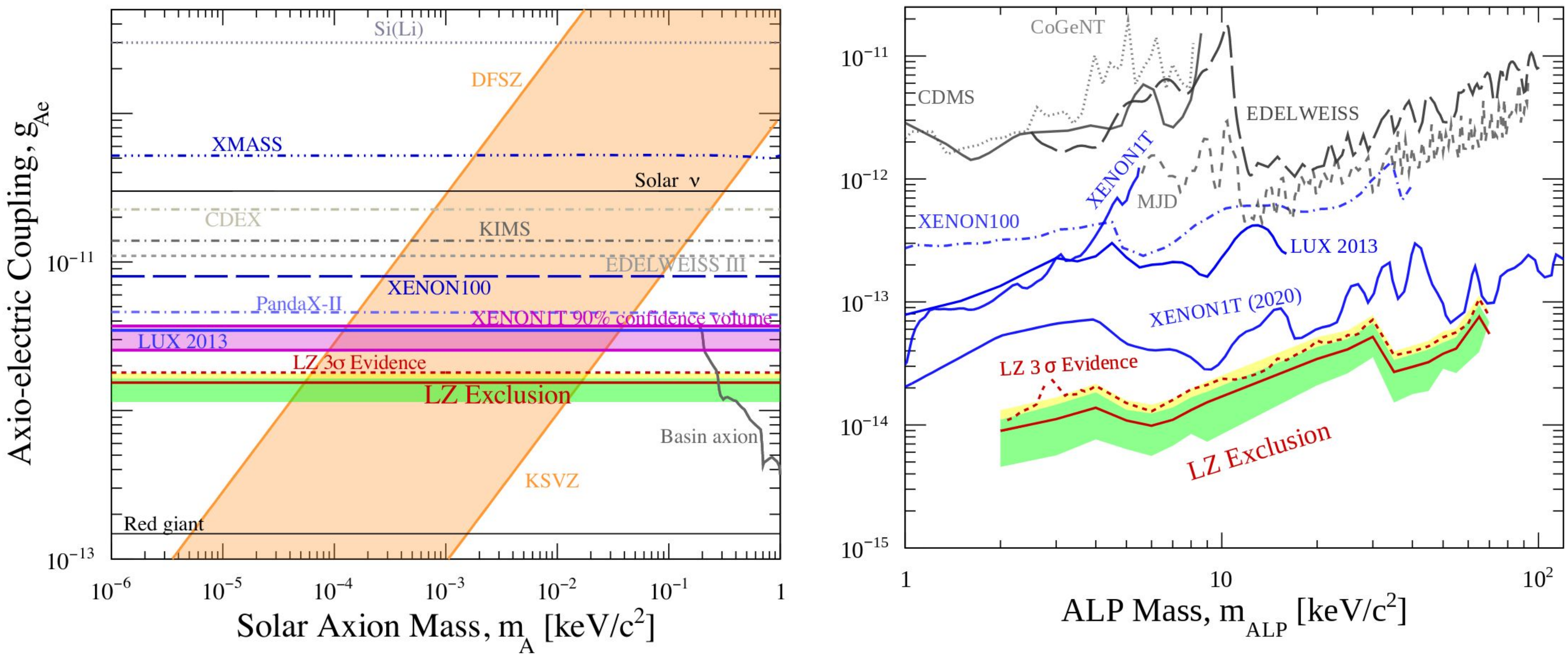
Radon comprises almost half our expected backgrounds

- Non-vetoed single scatters of 1.5-6.5 keV_{ee} (6-30 keV_{nr}) in 5.6 t fiducial volume: 6.18 background counts after 1000 live days arXiv: 2101.08753

- Lower the energy threshold
  - Reduce S1 coincidence requirement from 3 to 2 (exploiting PMT double photoelectric effect)
    - About 4 x improvement at 2.5 GeV/c^2
  - Conduct an S2-only search
    - Greater challenge for background discrimination
    - Employ pulse width
    - Two orders of magnitude improvement
- Sub-GeV masses accessible via Migdal effect

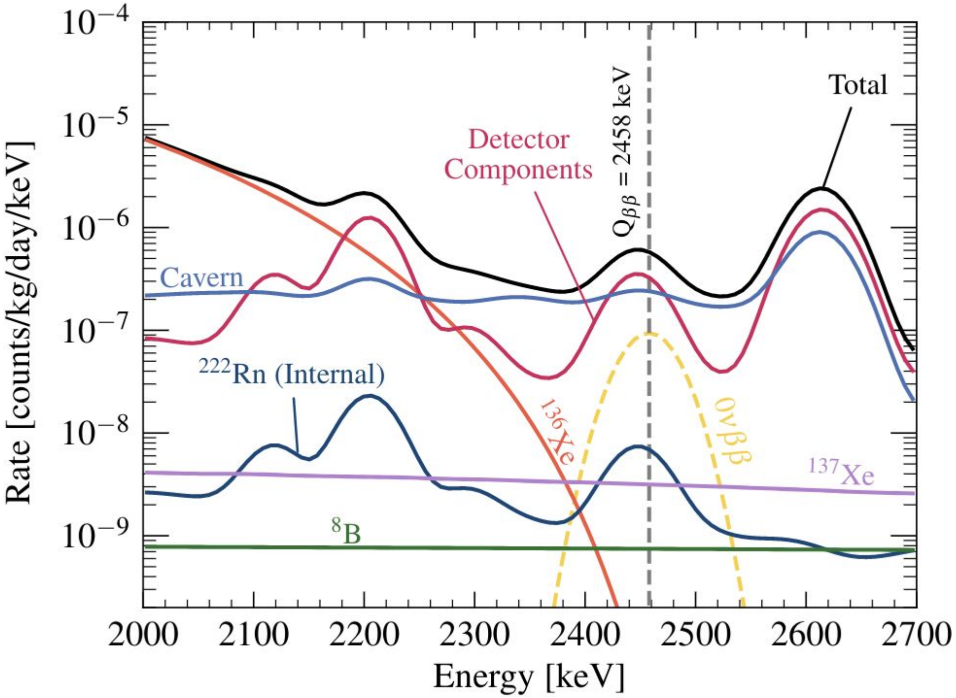


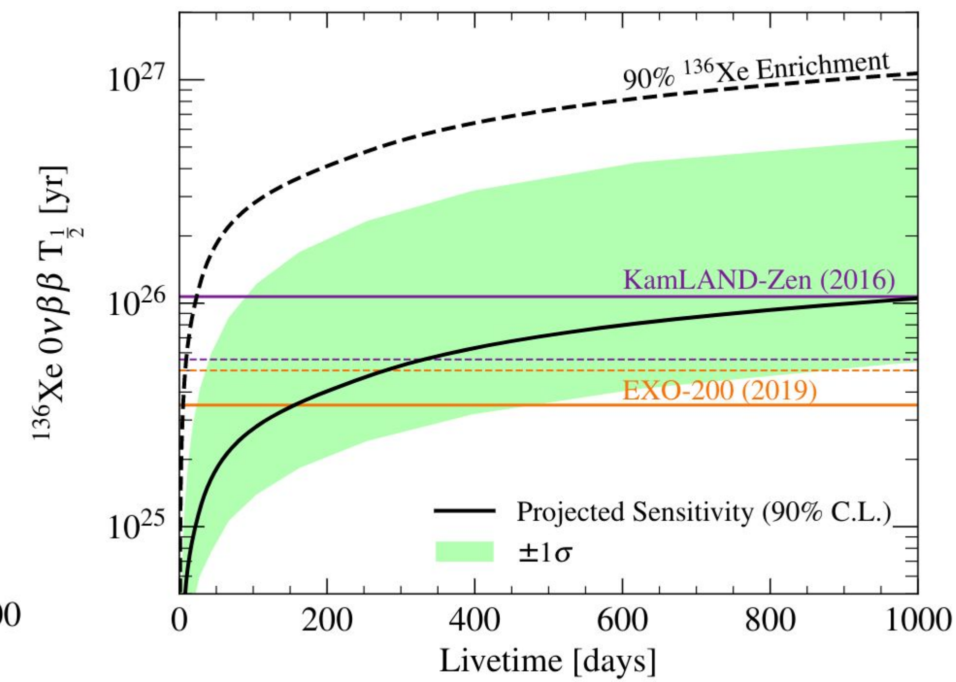
arXiv:2102.11740



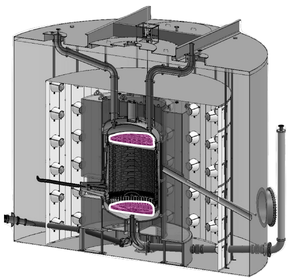
- Explore range of novel model accessible via pure electron recoils
- Backgrounds dominated by ^{222}Rn and ^{124}Xe ννββ
- Studies seven model, amon gothers: Solar axions, axion-like dark matter, neutrino magnetic moment etc
- In all LZ is able to reach world leading sensitivities

Phys. Rev. C 102, 014602 (2020)

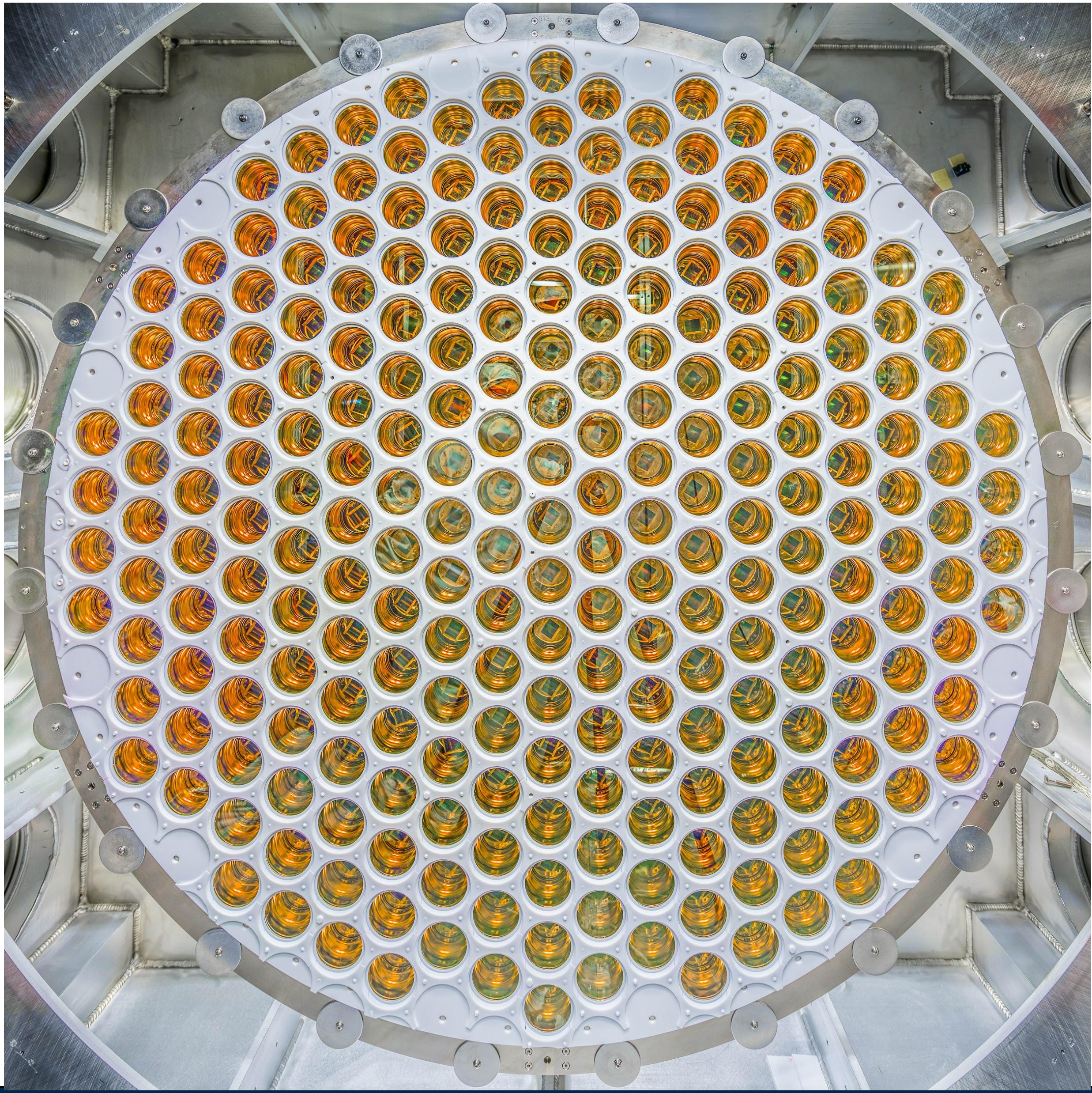




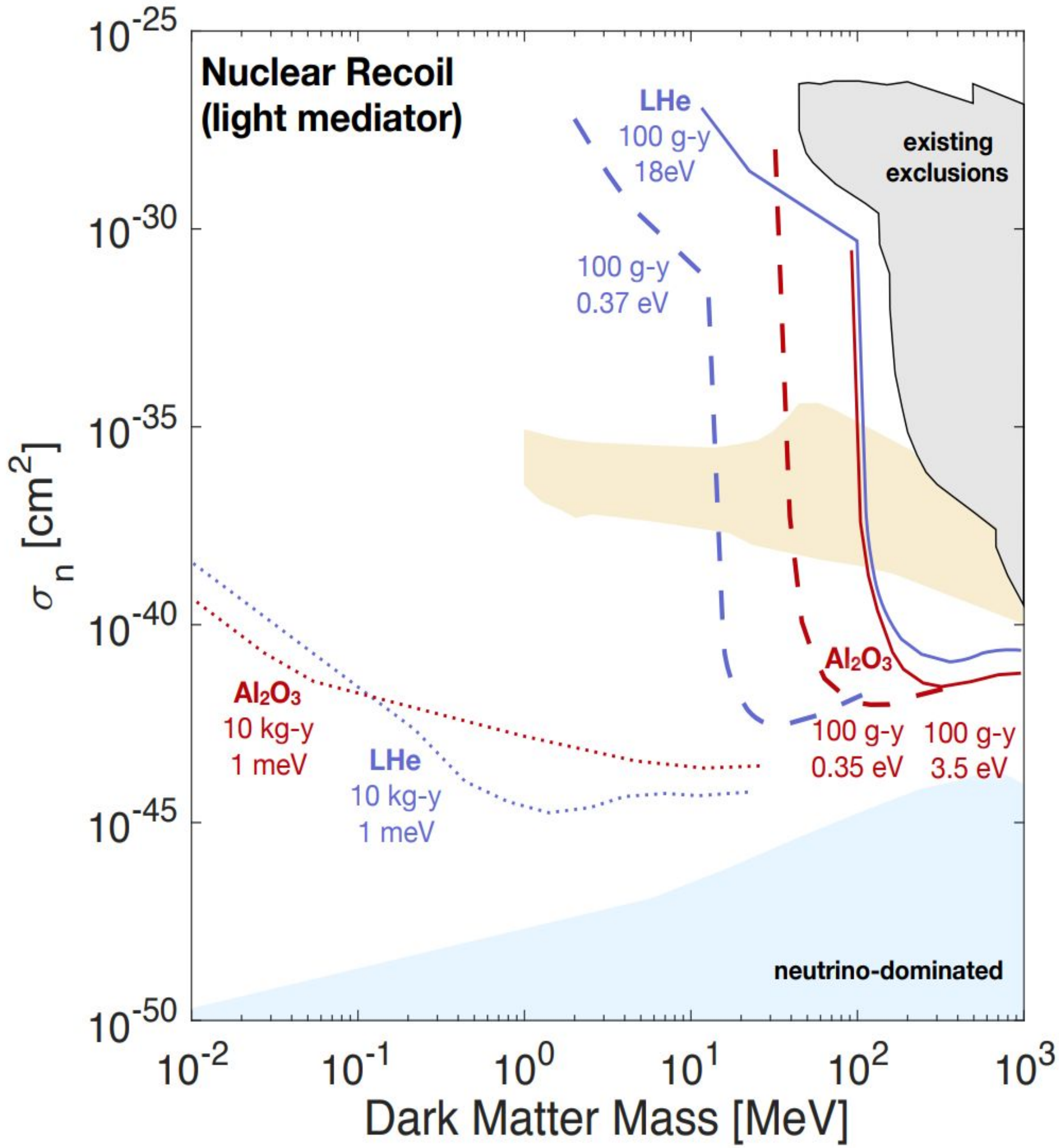
- Neutrioless $0\nu\beta\beta$ only allowed if Neutrino is its own anti-particle (Majorana)
- Nominal 1% energy resolution at ^{136}Xe $Q_{\beta\beta}$ value (2458 keV)
- $T_{1/2}$ (90% C.L.) > 1 x 10^{26} years in 1000 live days in 1 t fiducial volume

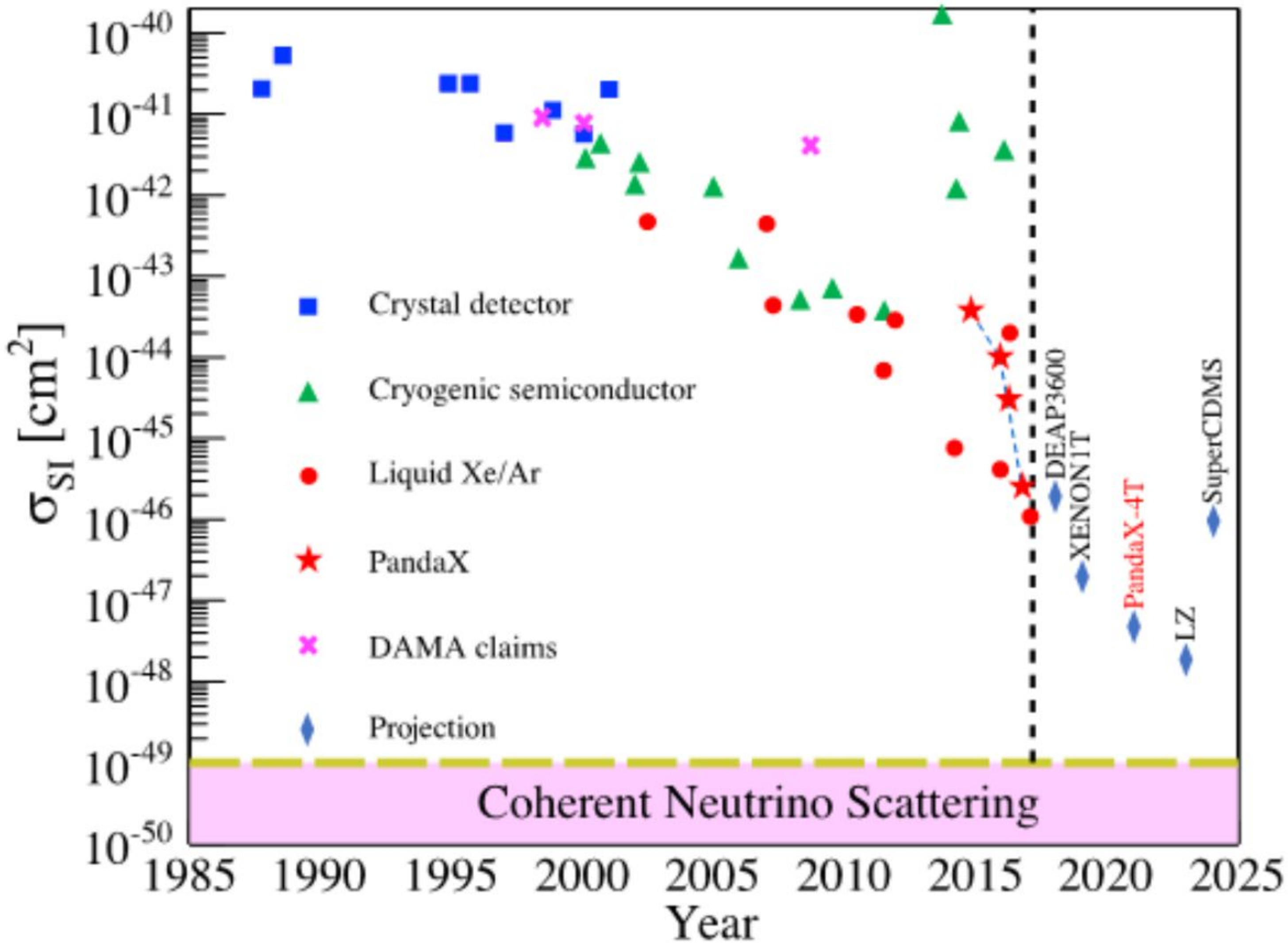


- 625 PMTs:
  - 253 x 3” top array
  - 241 x 3” bottom array
  - 93 x1” and 38 x2” skin



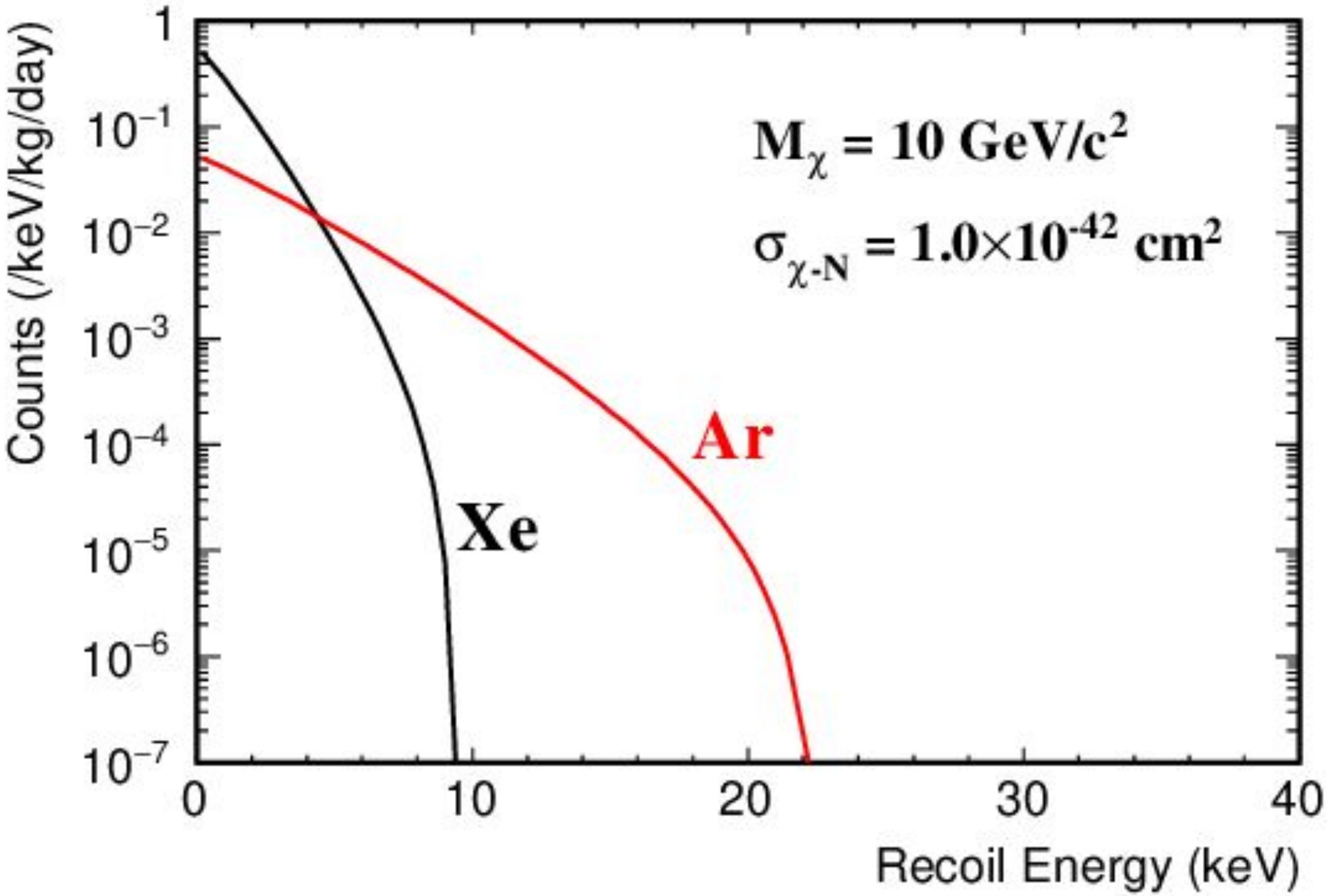
- Already producing **first papers**
- More projections [here]()
- Expecting new DM limits from demonstrator setups soon



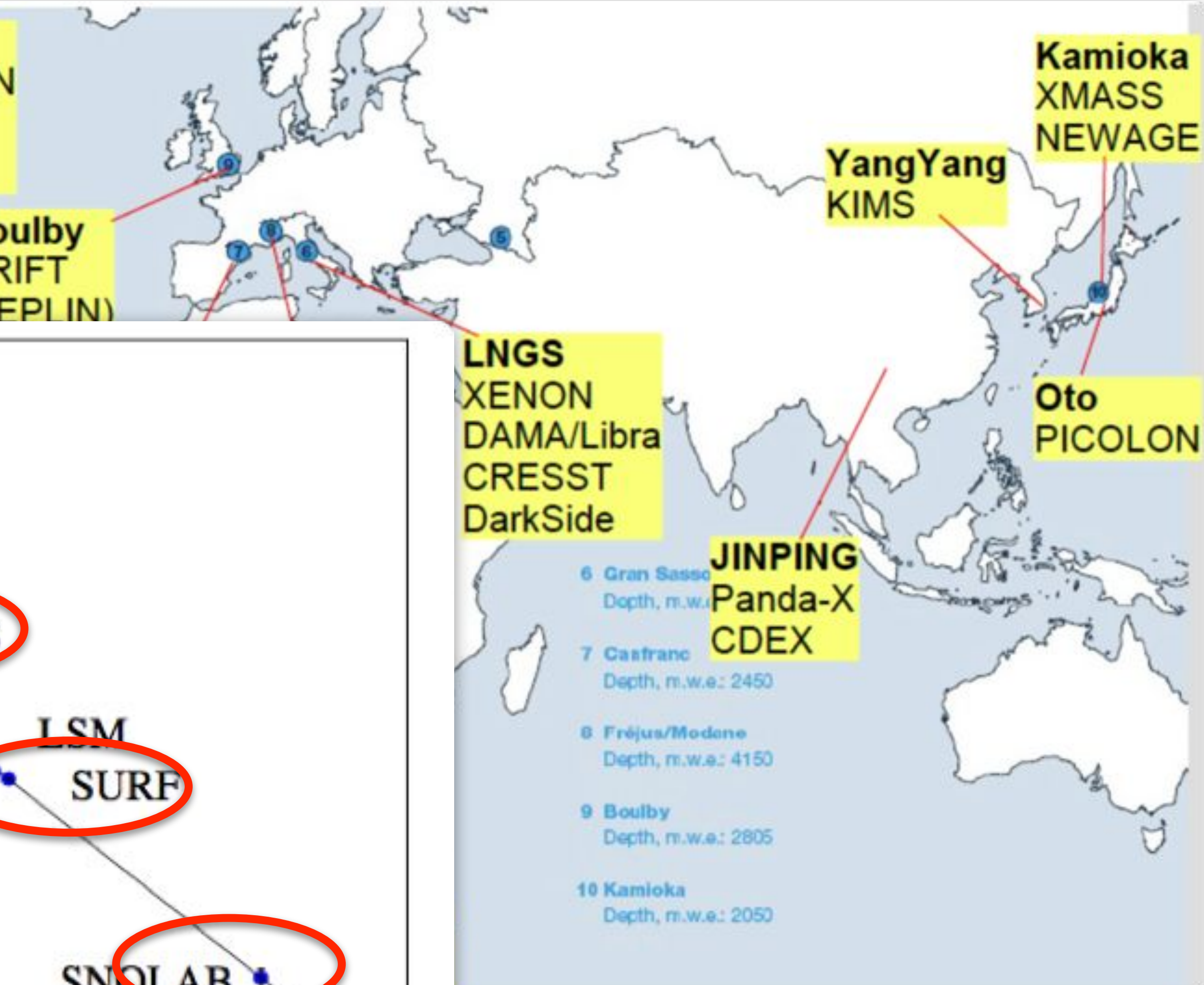


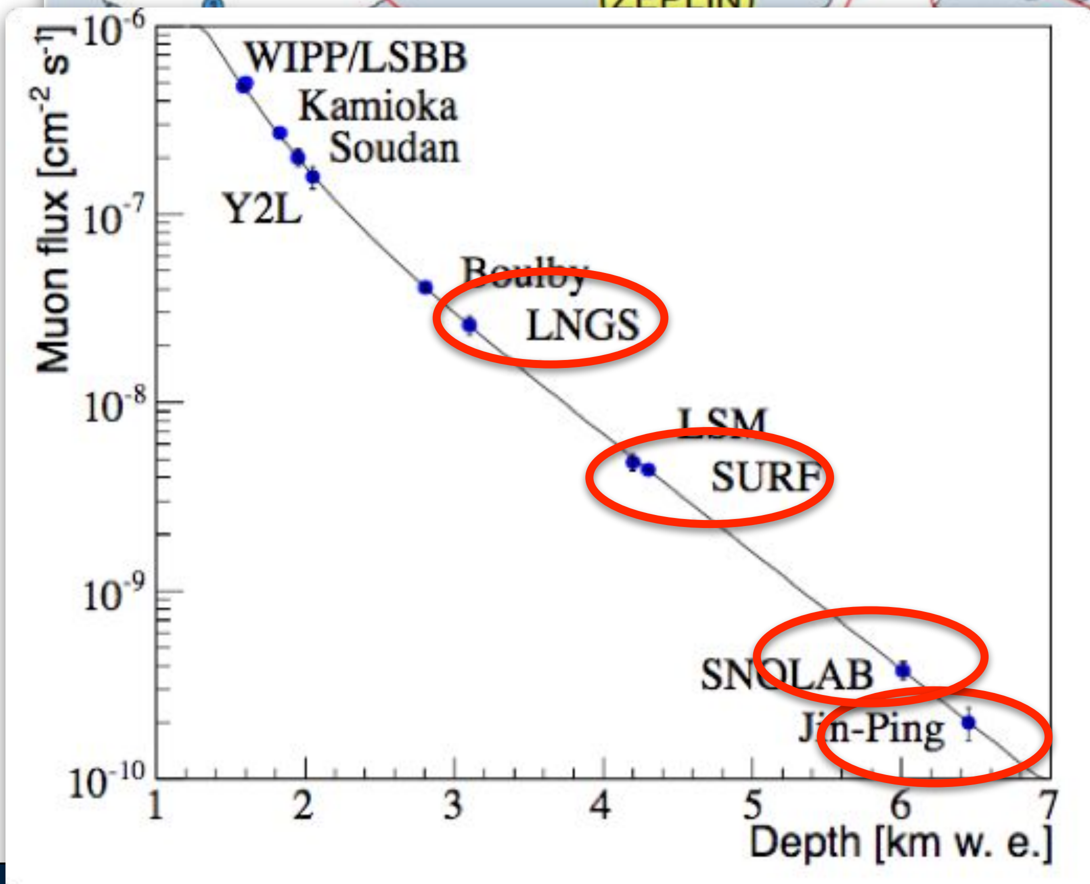
https://arxiv.org/abs/1806.02229

https://iopscience.iop.org/article/10.1088/1742-6596/1342/1/012069



- Recoil energy **spectrum and rates differ depending on DM mass** and **target mass**


Homestake/SURF
LUX
SNOLAB
DEAP/CLEAN
PICASSO
COUPP
Boulby
DRIFT
(ZEPLIN)
LNGS
XENON
DAMA/Libra
CRESST
DarkSide
YangYang
KIMS
Kamioka
XMASS
NEWAGE
Oto
PICOLON
JINPING
Panda-X
CDEX
6 Gran Sasso
7 Canfranc
Depth, m.w.e.: 2450
8 Fréjus/Modane
Depth, m.w.e.: 4150
9 Boulby
Depth, m.w.e.: 2805
10 Kamioka
Depth, m.w.e.: 2050


Muon flux [cm^{-2} s^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
WIPP/LSBB
Kamioka
Soudan
Y2L
Boulby
LNGS
LSM
SURF
SNOLAB
Jin-Ping
1
2
3
4
5
6
7
Depth [km w. e.]

- Spin-independent (SI) scattering, **scalar or vector** like particle, enhanced by A^2, like particle
  - Focus of this talk, favors **heavy targets,**

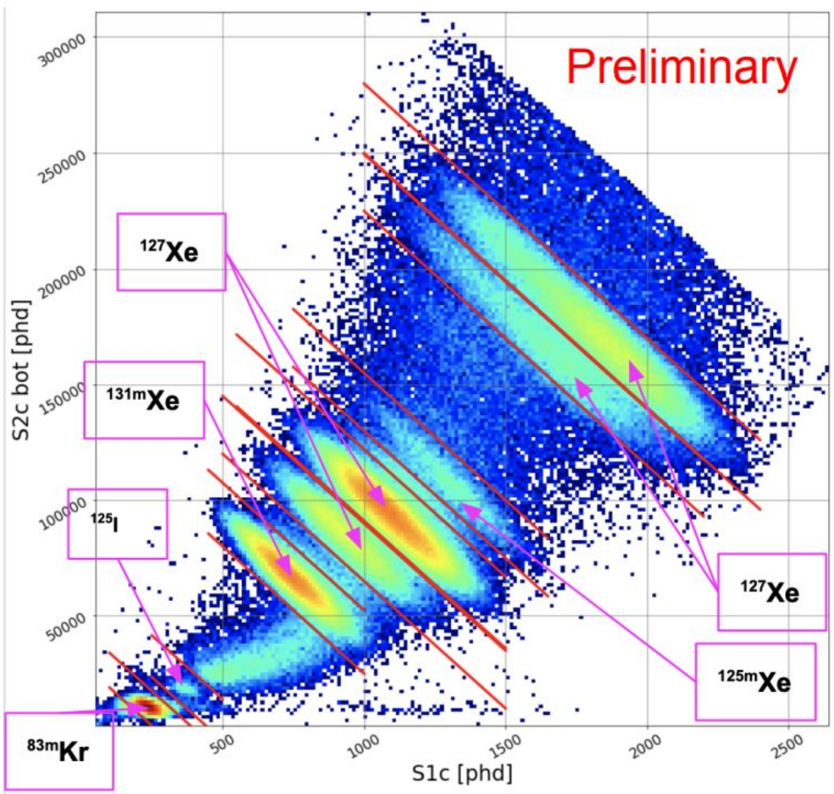
$$\sigma_{\mathrm{SI}} = \sigma_n \frac{\mu^2}{\mu_n^2} \frac{(f_p Z + f_n(A - Z))^2}{f_n^2} = \sigma_n \frac{\mu^2}{\mu_n^2} A^2$$

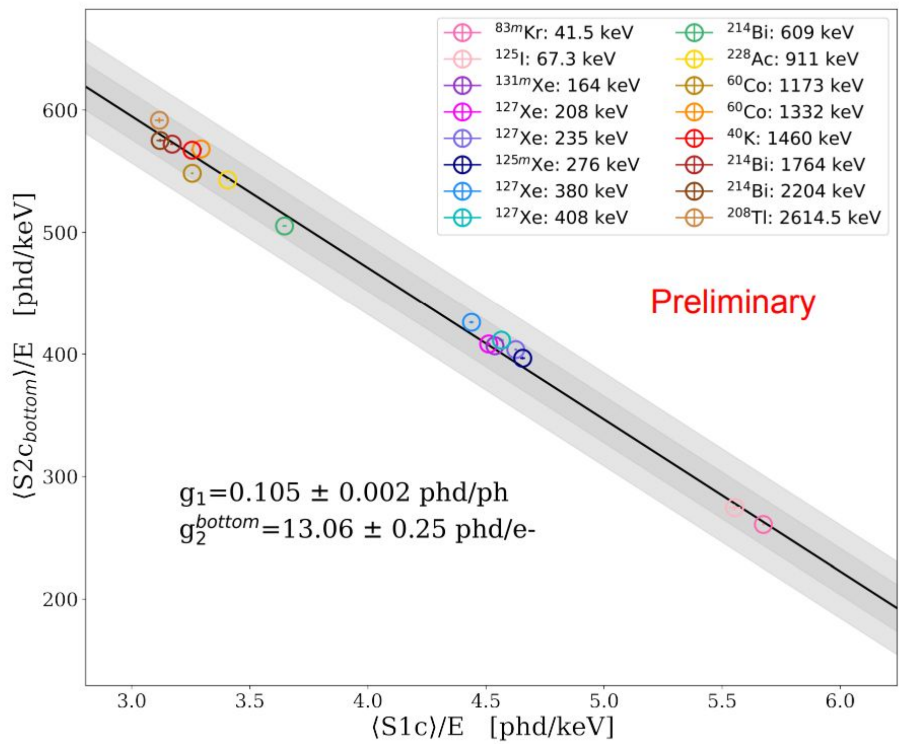
- Spin-dependent (SD), **axial-vector** particles
  - Favors targets with odd number of protons or neutrons (e.g. ^{7}Li, ^{131}Xe respectively)

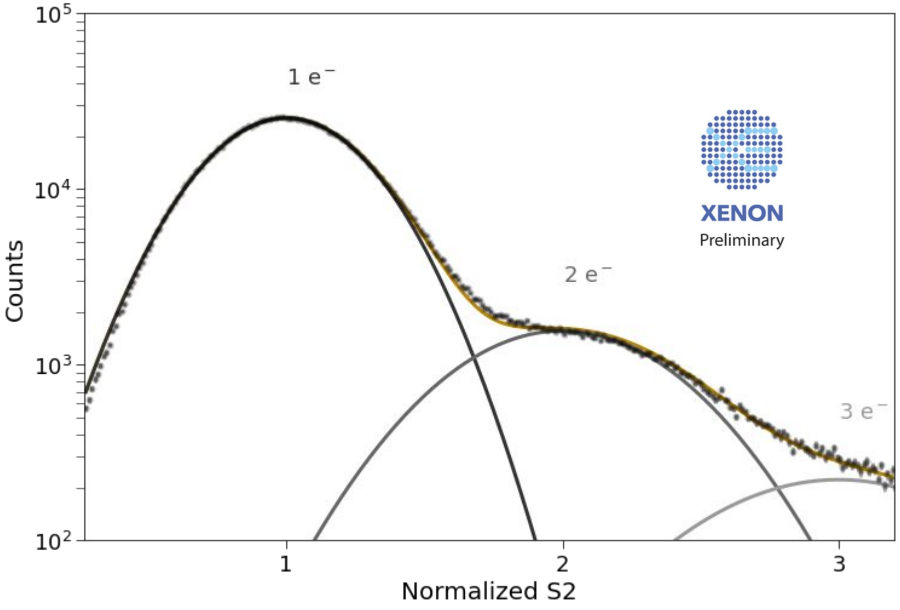
$$\frac{d\sigma_{\mathrm{SD}}}{d|\vec{q}|^2} = \frac{8G_F^2}{\pi v^2} \left[a_p \langle S_p \rangle + a_n \langle S_n \rangle\right]^2 \frac{J+1}{J} \frac{S(|\vec{q}|)}{S(0)}$$

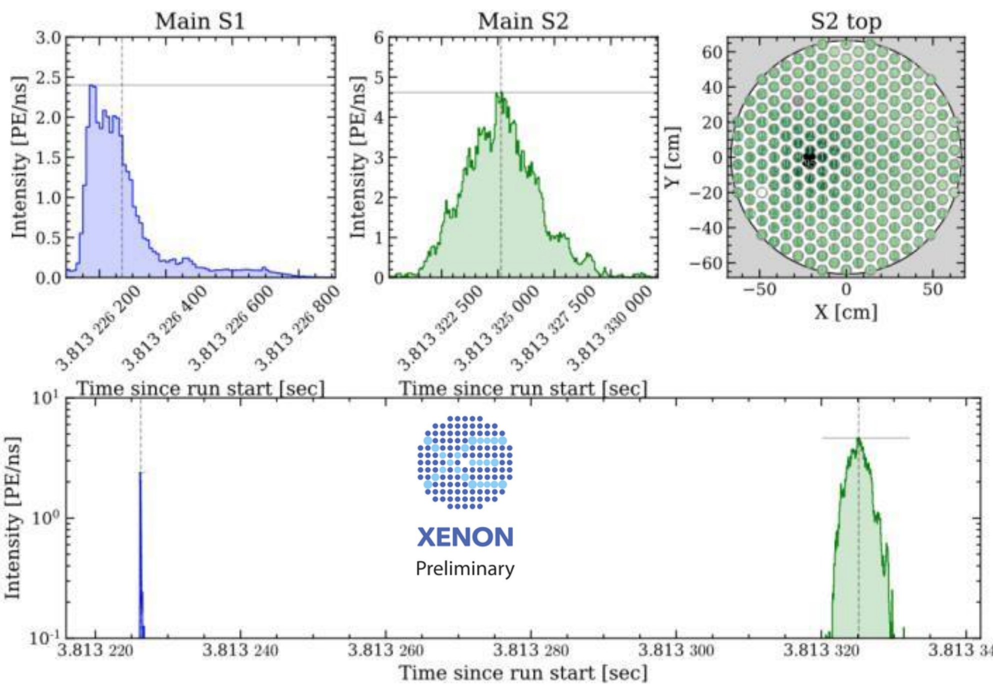
$$E = W\left(\frac{S1_c}{g_1} + \frac{S2_c}{g_2}\right)$$

- Mono-energetic ER peaks used to find:
  - g1, photons detected (phd) per prompt scintillation photon
  - g2, phd per ionisation electron









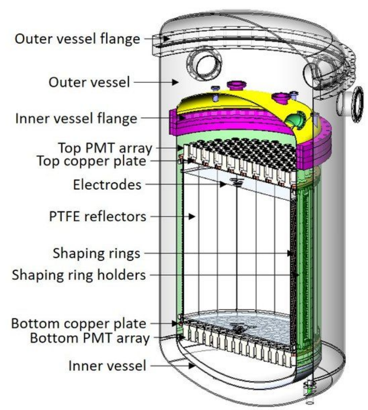
- XENONnT **taking data**
- PMTs have stable gains, average **QE is 34%**
- Good **single-electron** resolution

PandaX = Particle and Astrophysical Xenon Experiments

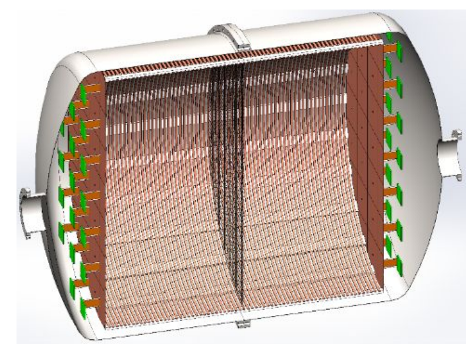
PANDA X

Phase I:
120 kg DM
2009-2014

Phase II:
500 kg DM
2014-2017



PandaX-4T:
multi-ton DM
2020-



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