

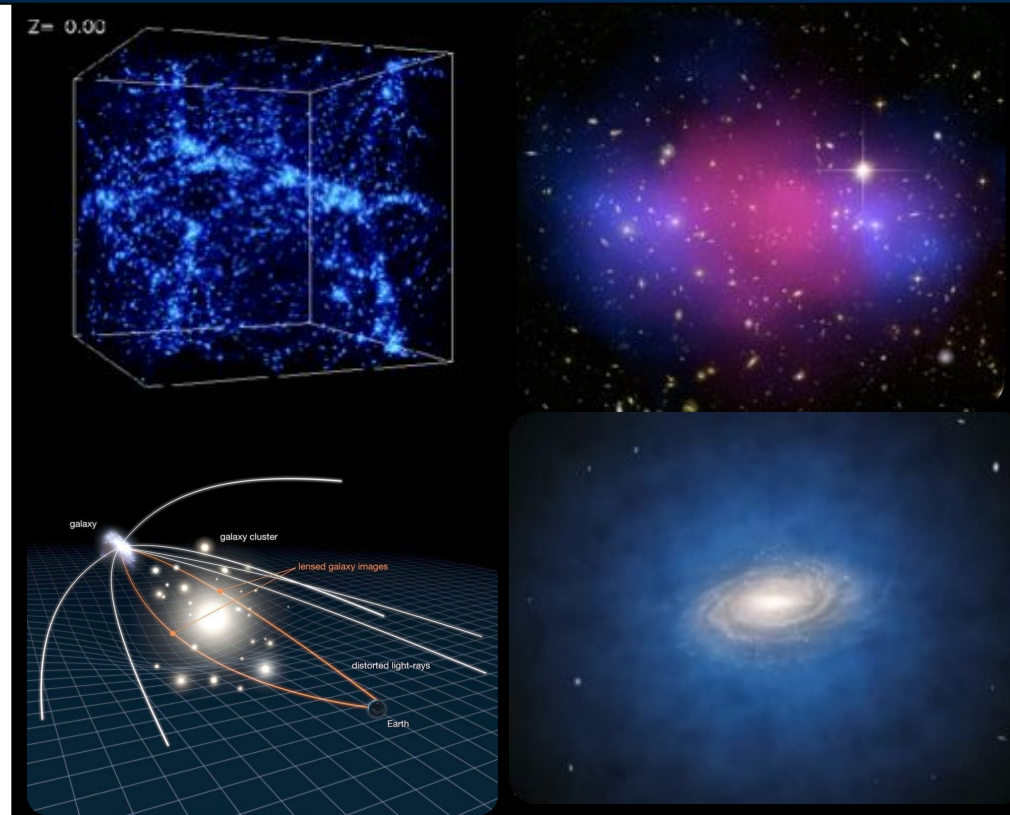
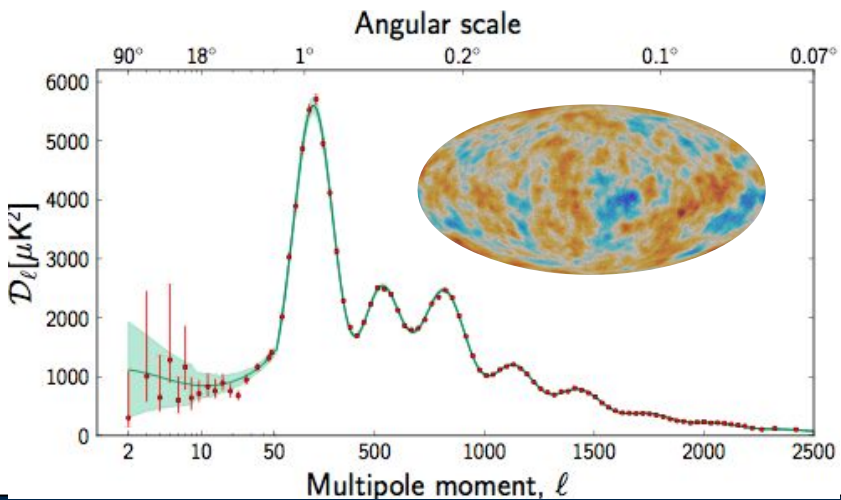
Status of Noble Liquid DM Searches



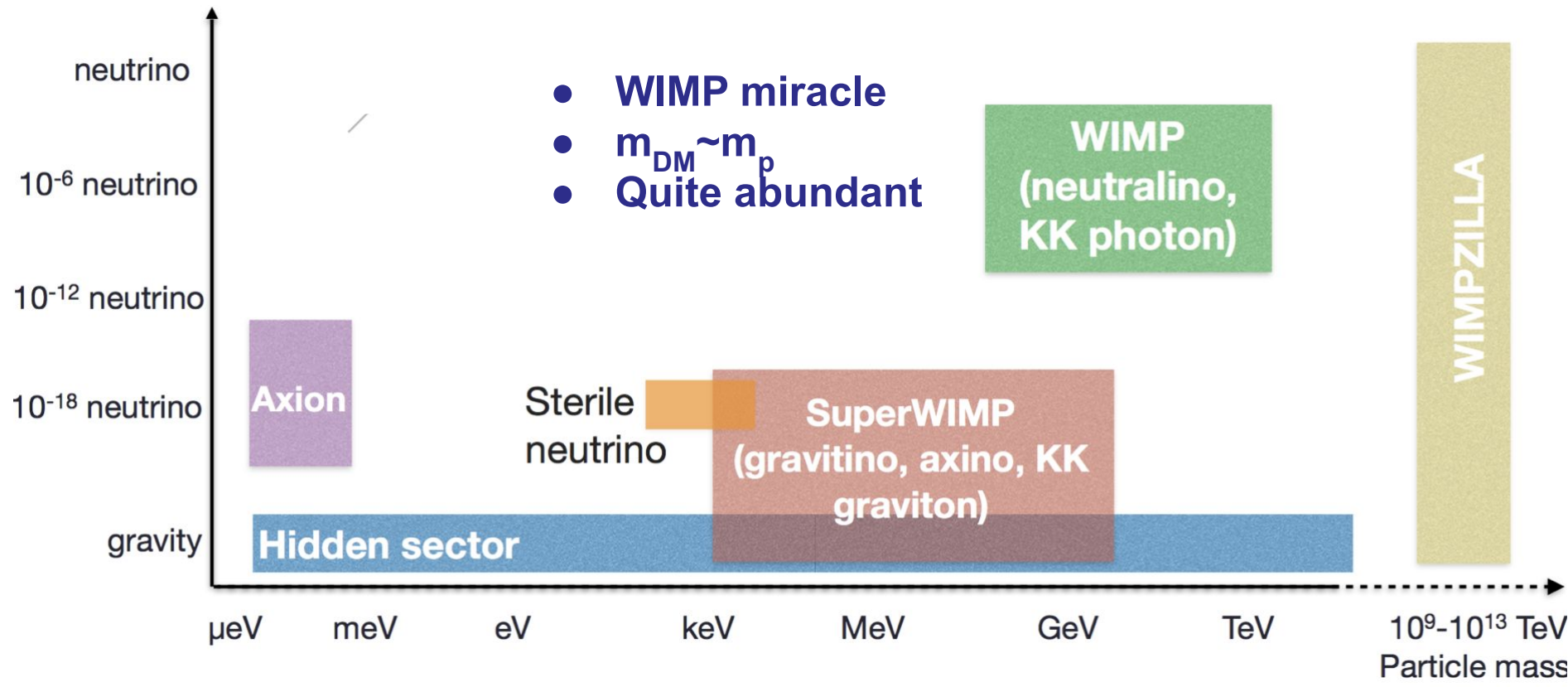
B. Penning

• 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

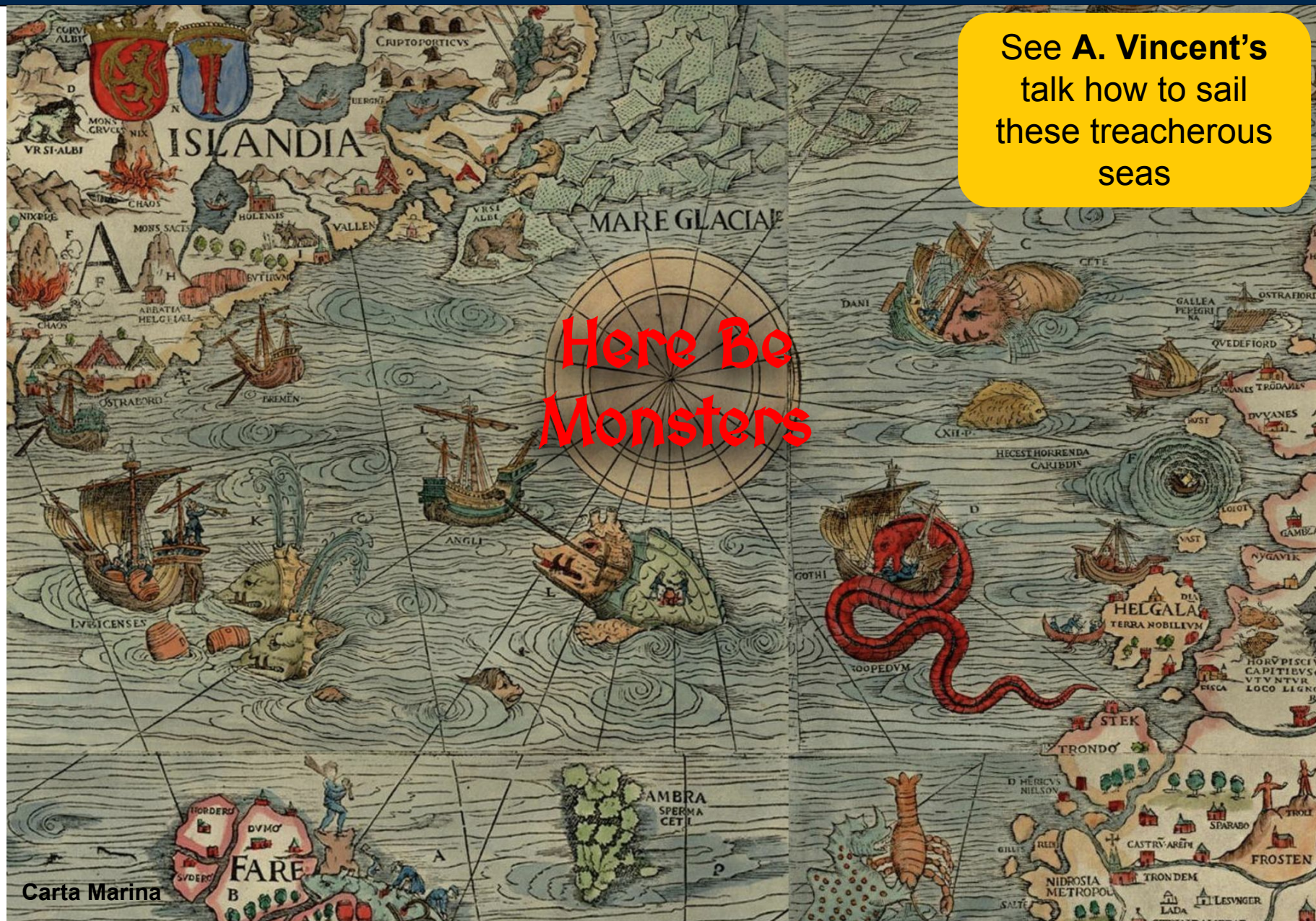


- **DM is already discovered**, just not yet identified
- Standard Model of Cosmology, Λ CDM:
 $\Omega_\Lambda \approx 0.68$, $\Omega_{\text{DM}} \approx 0.27$, $\Omega_b \approx 0.05$



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





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

- Detection means interaction

Diagram illustrating the differential rate equation for WIMP detection:

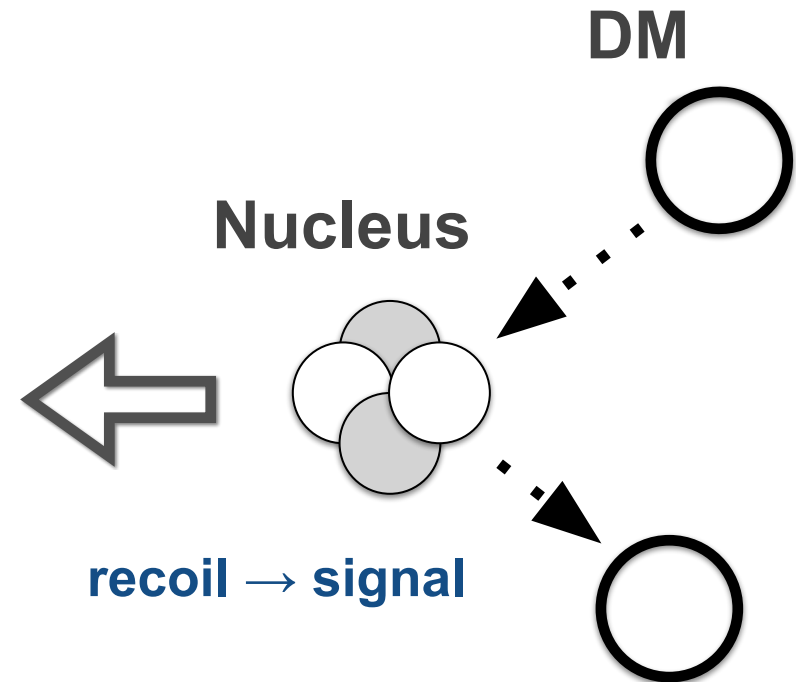
$$\frac{dR}{dE_{nr}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma}{dE_{nr}} dv \propto \exp\left(-\frac{E_{nr}}{E_0} \frac{4m_\chi m_N}{(m_\chi + m_N)^2}\right) F^2(E_{nr})$$

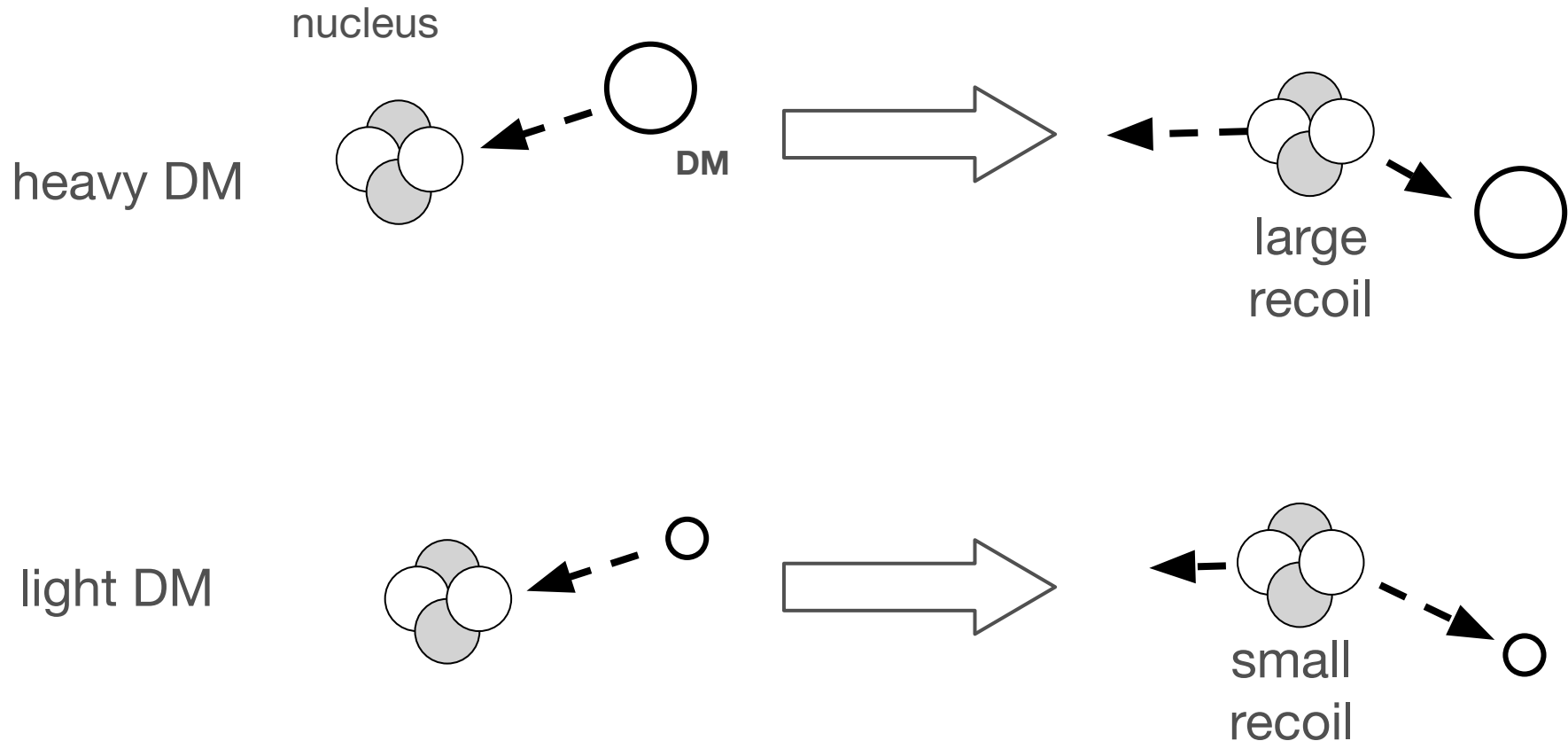
Callouts and their corresponding terms in the equation:

- local DM density $\sim 0.3 \text{ GeV/cm}^3$** : ρ_0
- detector mass**: M
- target nucleus & DM mass**: $m_N m_\chi$
- WIMP velocity**: v
- cross section**: $\frac{d\sigma}{dE_{nr}}$
- recoil energy**: E_{nr}
- WIMP energy**: E_0
- Nuclear Form Factor**: $F^2(E_{nr})$

- **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: $v \sim 10^{-3} c$
→ Kinetic energy $O(100 \text{ keV})$
- Very rare interactions $O(1/\text{yr}/\text{kg})$
- This means for our detector:
 - Very **stringent cleanliness** and **background rejection** requirements
 - **Ultra sensitive**
- Noble liquid detectors demonstrated to have best sensitivity

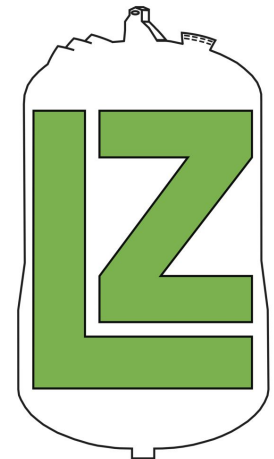




- Purely kinematic process, momentum transfer crucial
- Low mass difficult

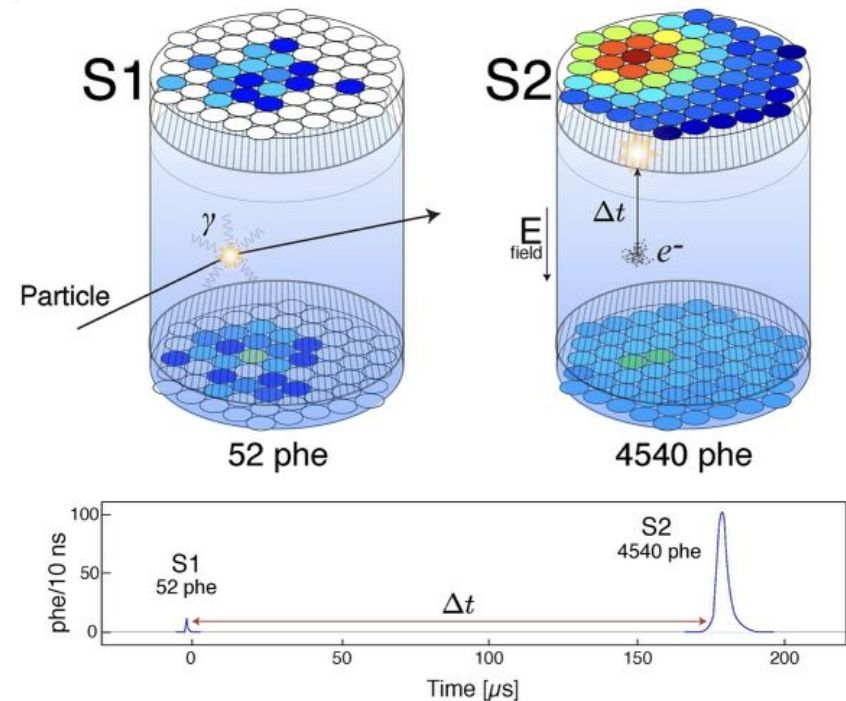
Xenon Detectors

1 H Hydrogen																	2 He Helium																												
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon																												
11 Na Sodium	12 Mg Magnesi...											13 Al Aluminium	14 Si Silicon	15 P Phosph...	16 S Sulfur	17 Cl Chlorine	18 Ar Argon																												
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Mangan...	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germani...	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton																												
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybde...	43 Tc Techneti...	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon																												
55 Cs Caesium	56 Ba Barium	57 La Lanthan...	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon																												
87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfo...	105 Db Dubnium	106 Sg Seaborg...	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitneri...	110 Ds Darmsta...	111 Rg Roentge...	112 Cn Coperni...	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovi...	116 Lv Livermor...	117 Ts Tenness...	118 Og Oganes...																												
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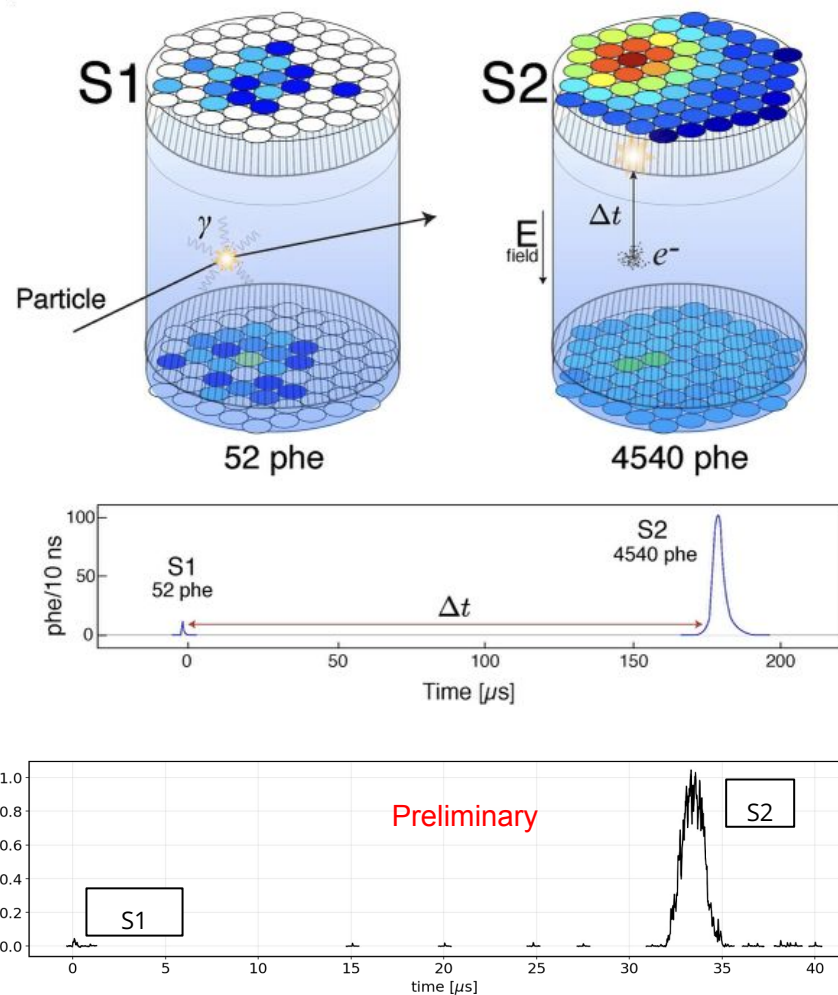


I will explain common techniques of **LXe detectors** based on LZ

- 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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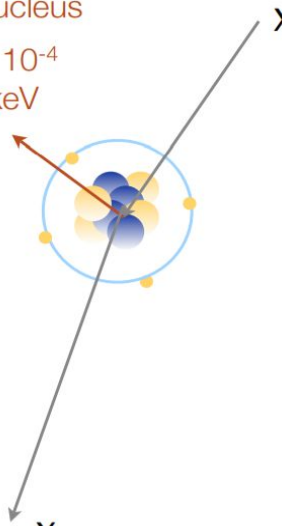


Signal (WIMPs)

recoiling nucleus

$$v/c \approx 7 \times 10^{-4}$$

$$E_R \approx 10 \text{ keV}$$

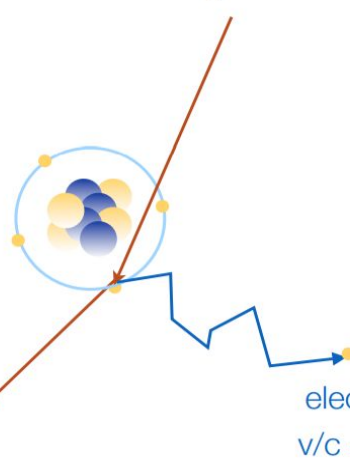


Background (γ, β)

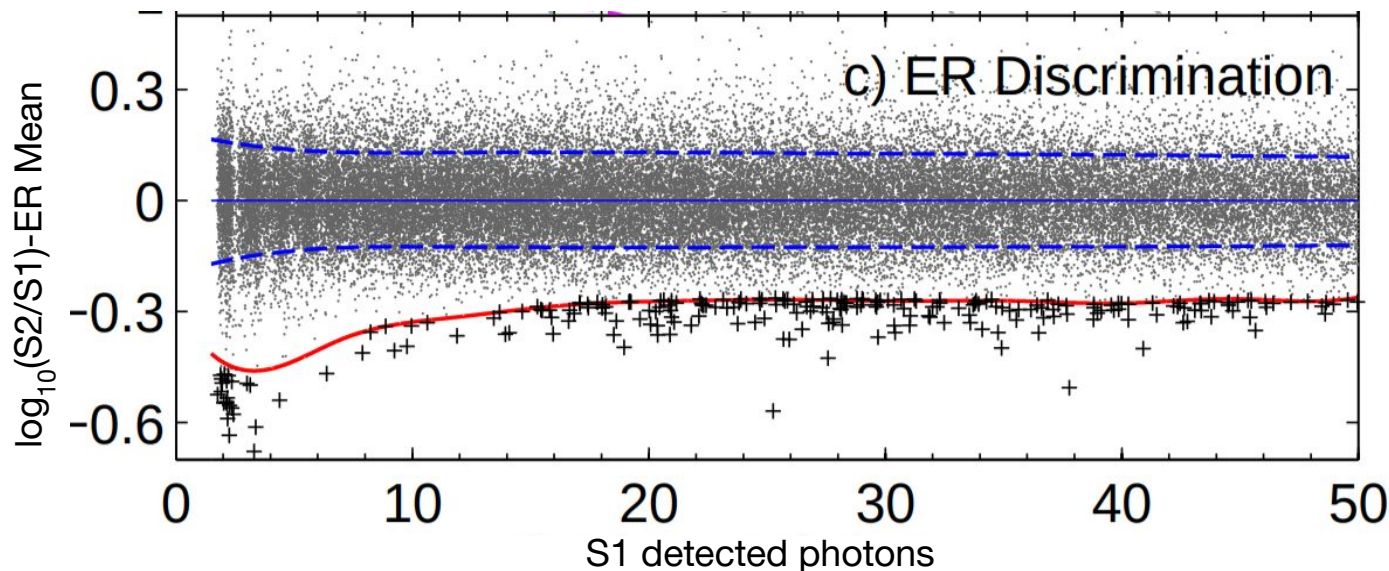
gamma

gamma

electron
 $v/c \approx 0.3$



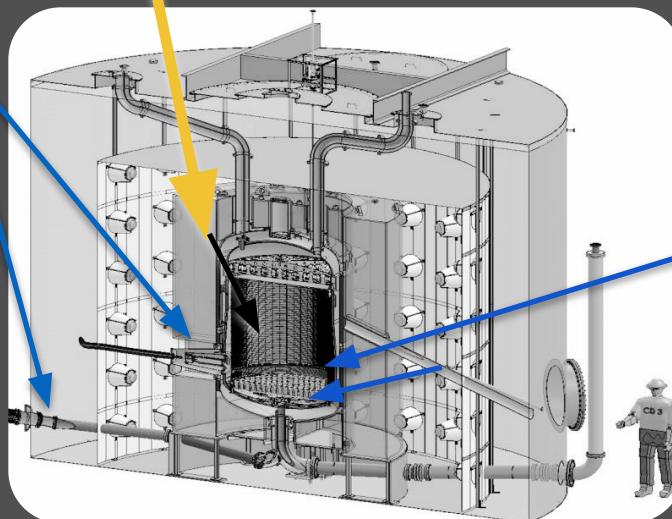
- Ionization/excitation (charge/light) depends on dE/dx
- **Excellent discrimination** of signal (WIMPS \rightarrow NR) and most backgrounds ($\gamma \rightarrow$ ER)
- **99.5% separation** before statistical methods





Cosmic Rays

1 mi deep

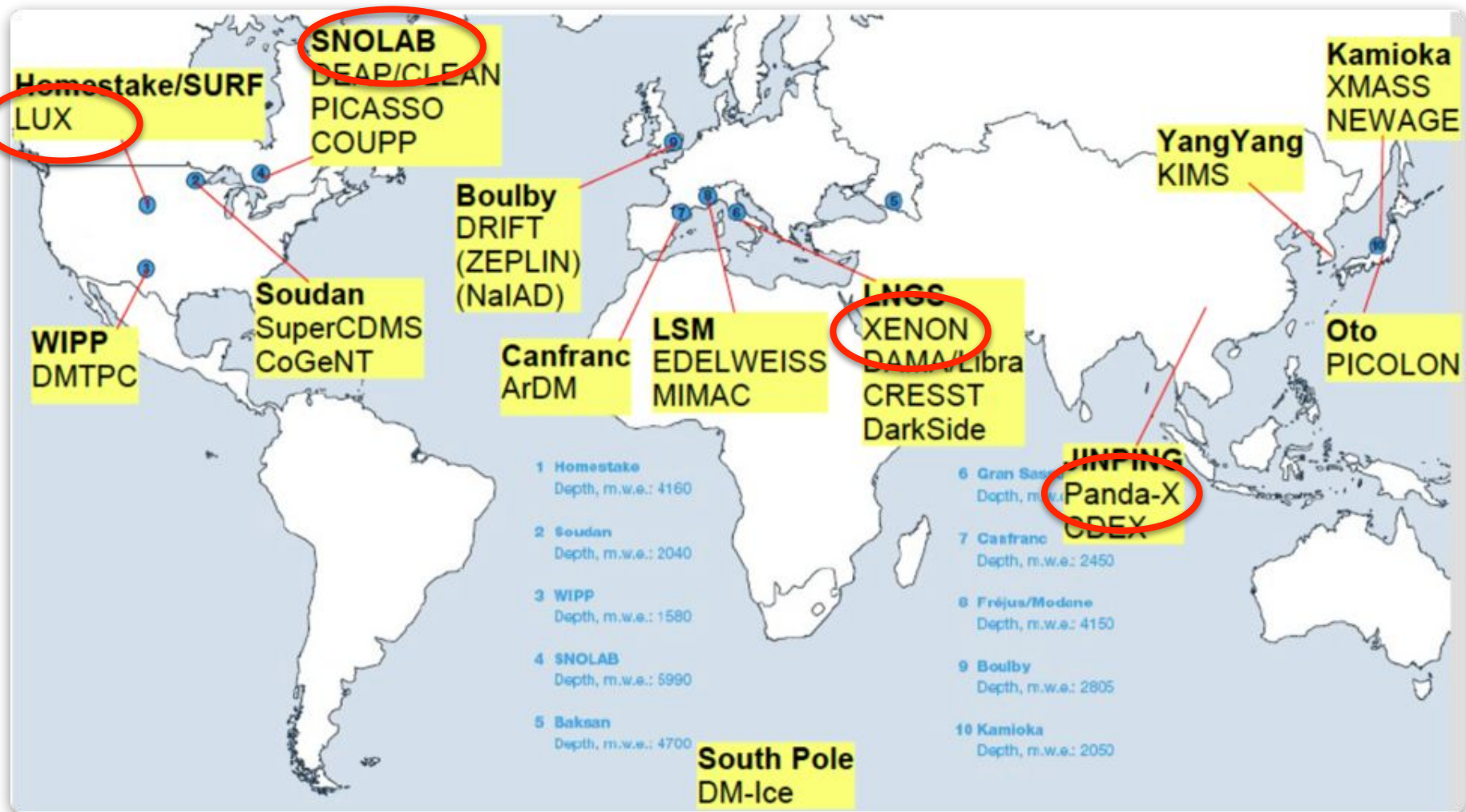


Radioactive backgrounds



- 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,





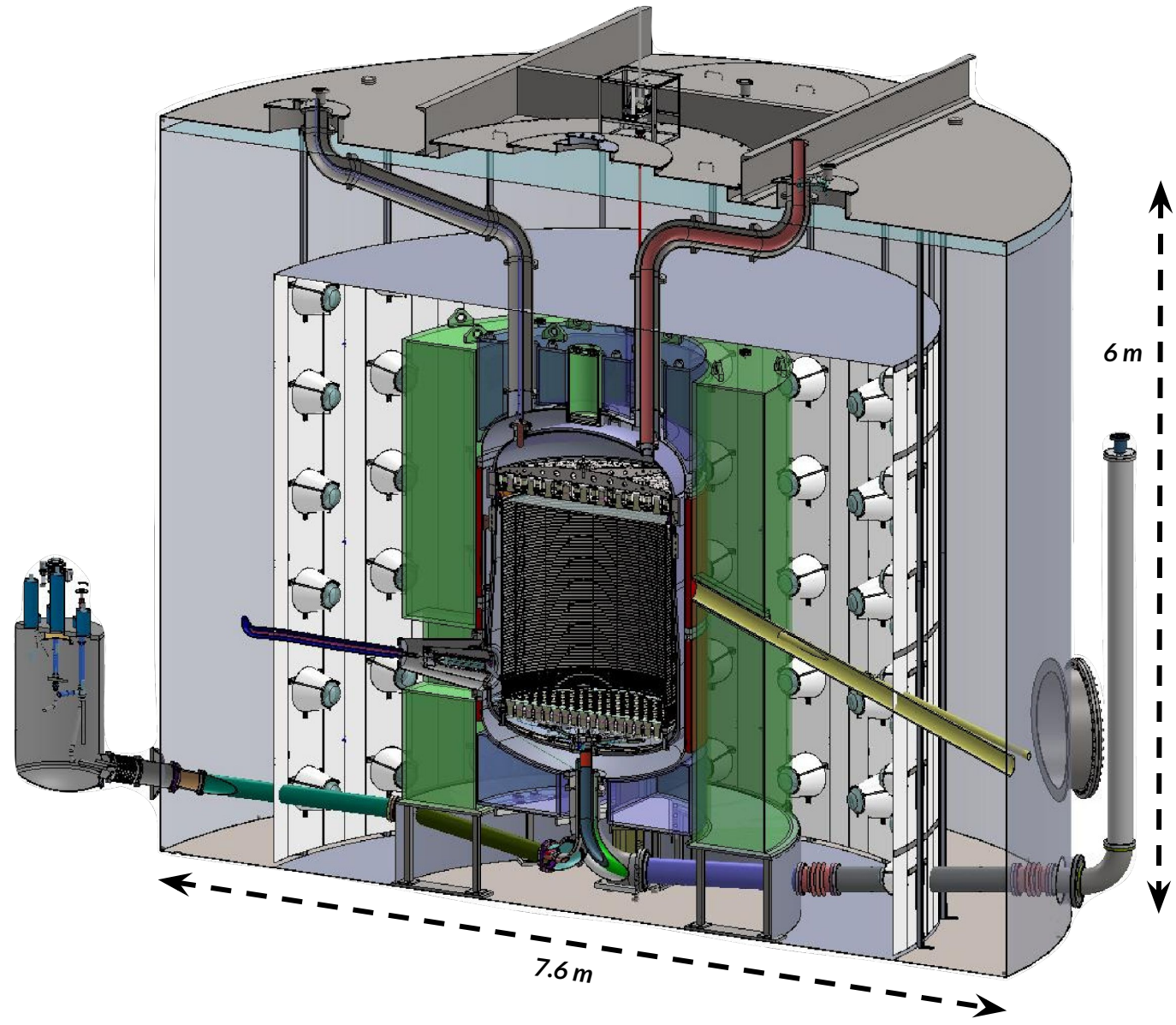


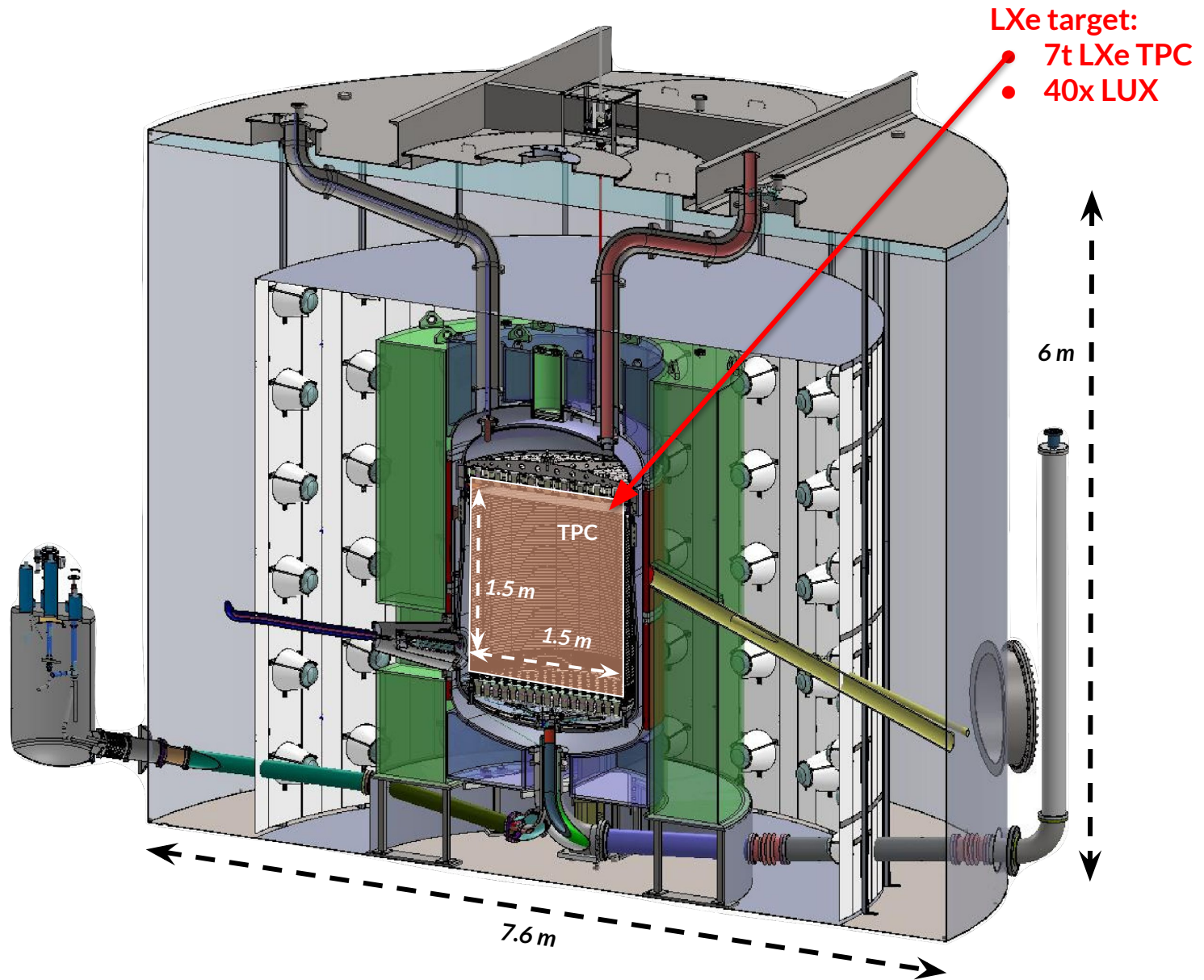
1 Banana = 15 Bq

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

- **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 $O(\text{ng}/\text{cm}^2)$
 - Keep circulating and purifying target material: aim Xenon contaminants to **$O(0.015 \text{ ppt})$**





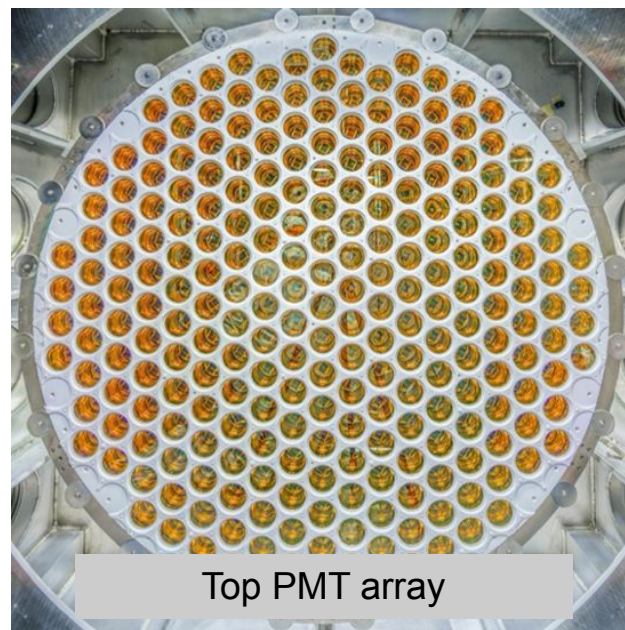




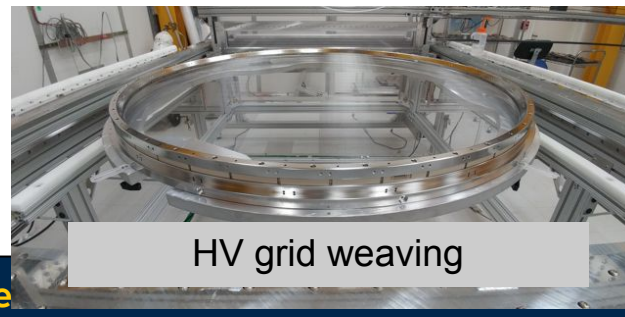
Assembled TPC (July 2019)



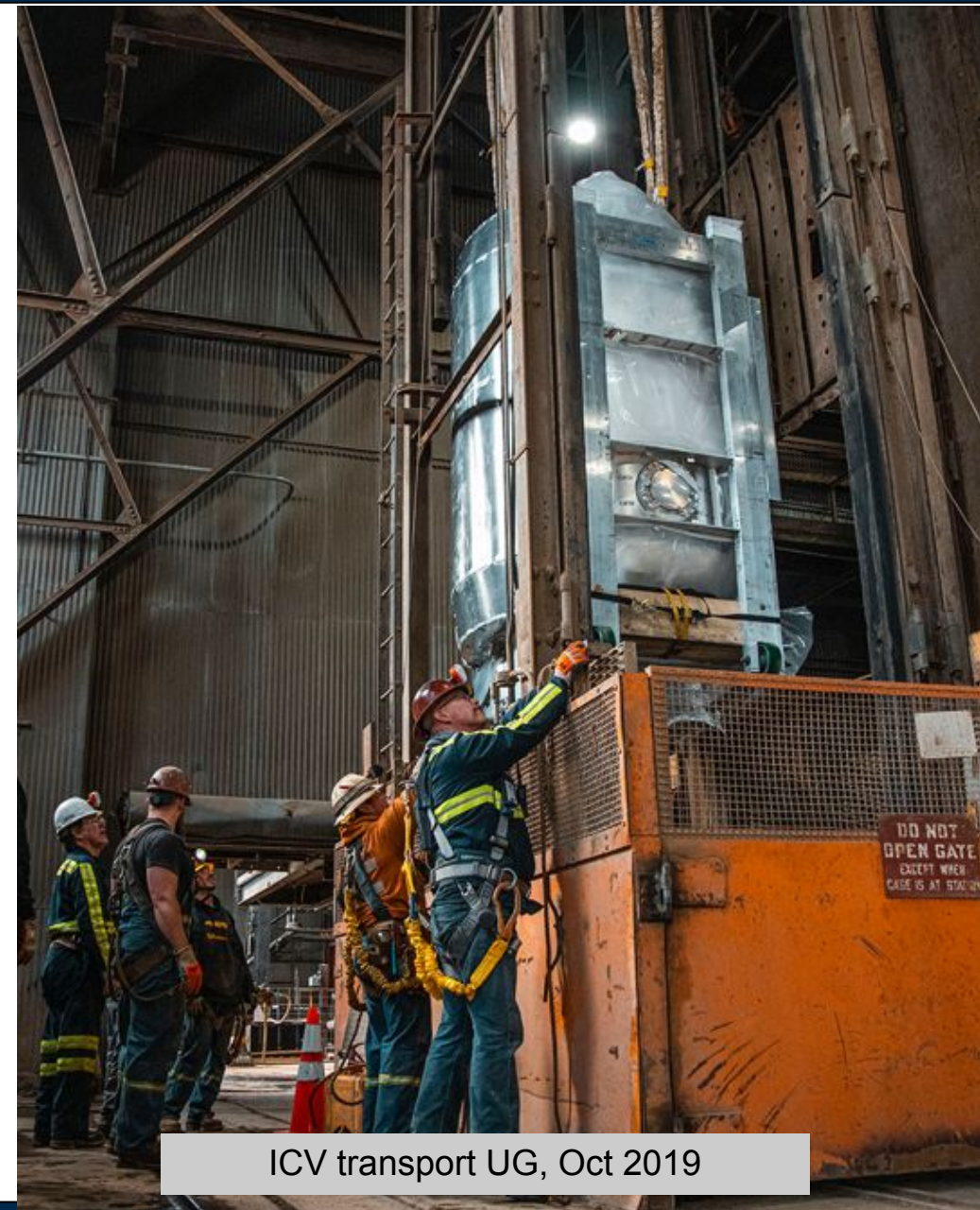
Bottom PMT array
with field cage



Top PMT array



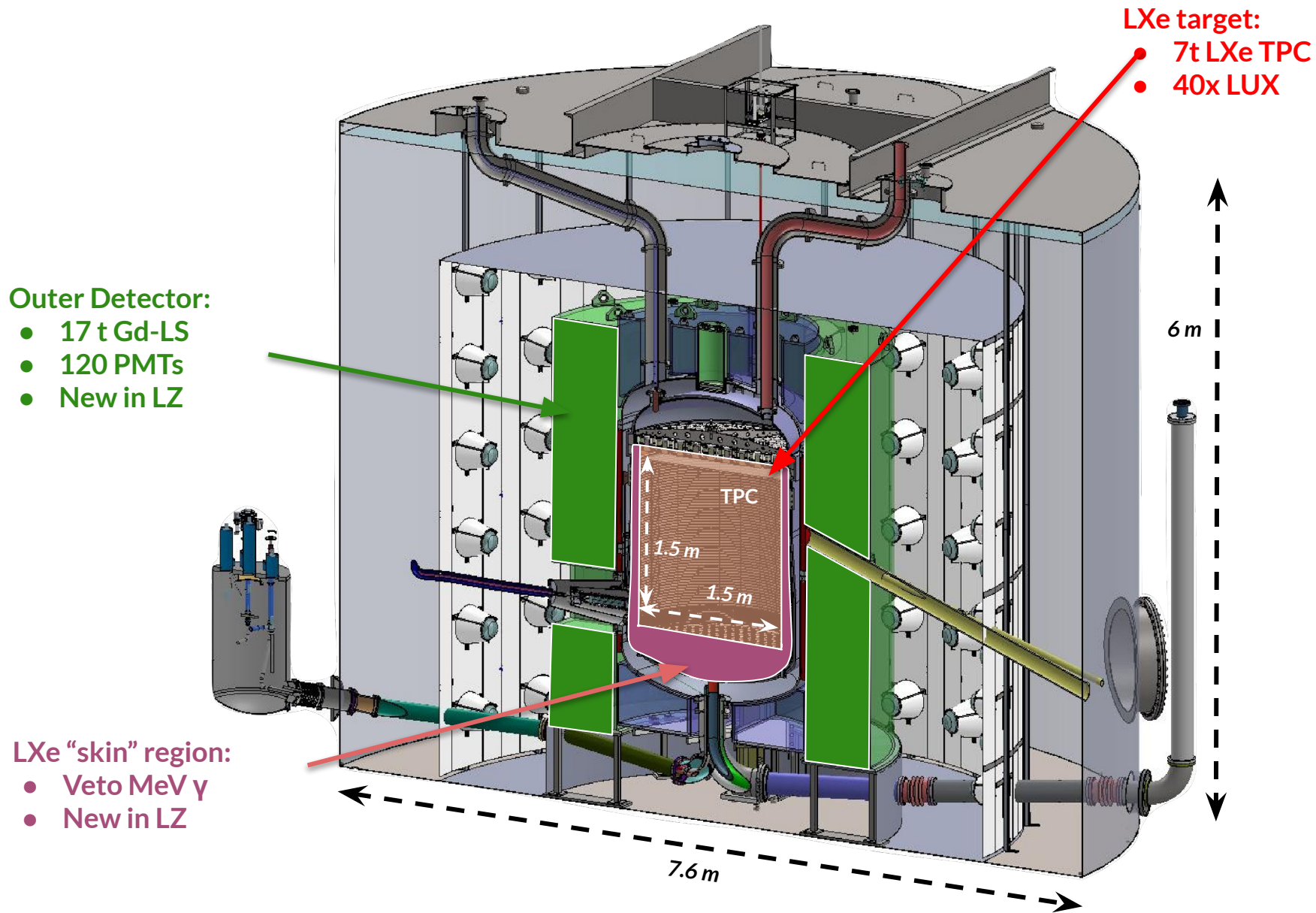
HV grid weaving



ICV transport UG, Oct 2019





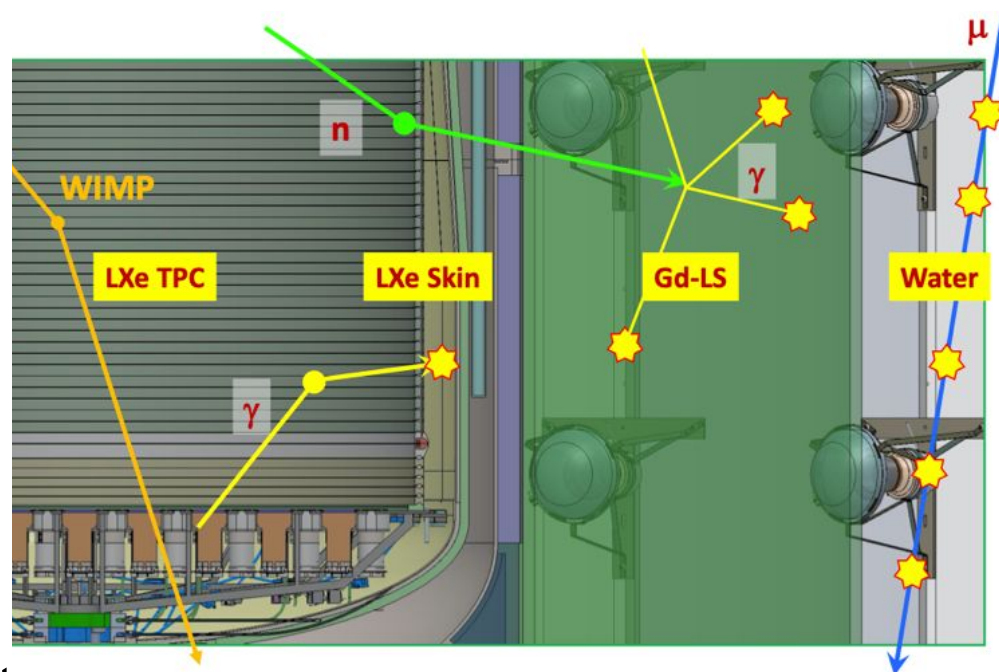


Outer Detector:

- **17 tonnes Gd-loaded liquid scintillator** in acrylic vessels viewed by 120 8" PMTs
- Anti-coincidence detector for γ -rays and neutrons
- Observe **~ 8 MeV γ -rays** 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:

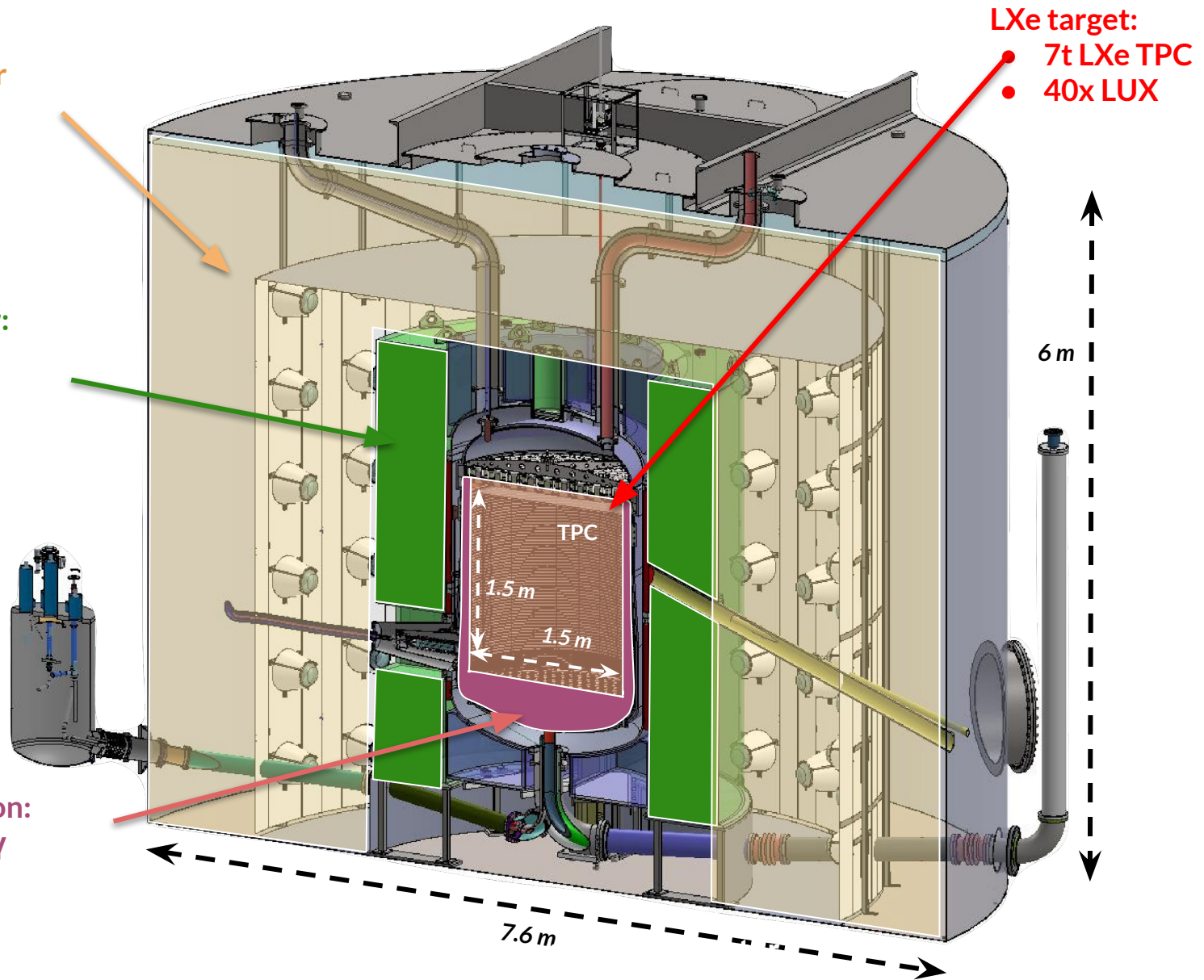
- 230 t DI water
- Instrumented

Outer Detector:

- 17 t Gd-LS
- 120 PMTs
- New in LZ

LXe "skin" region:

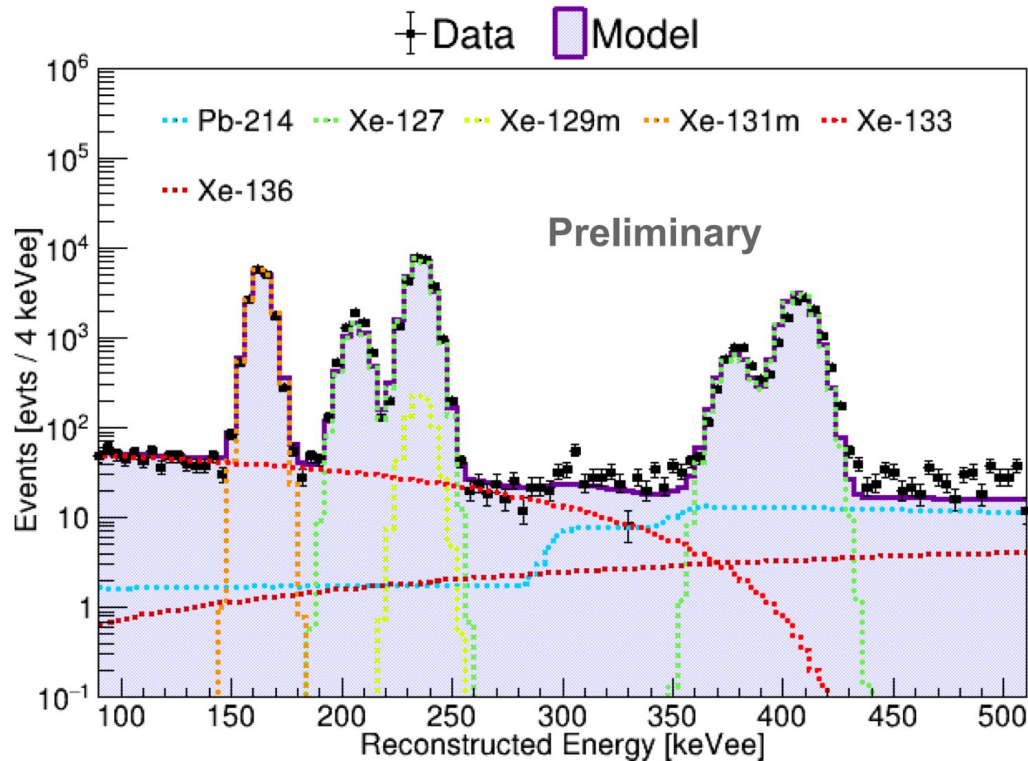
- Veto MeV γ
- New in LZ



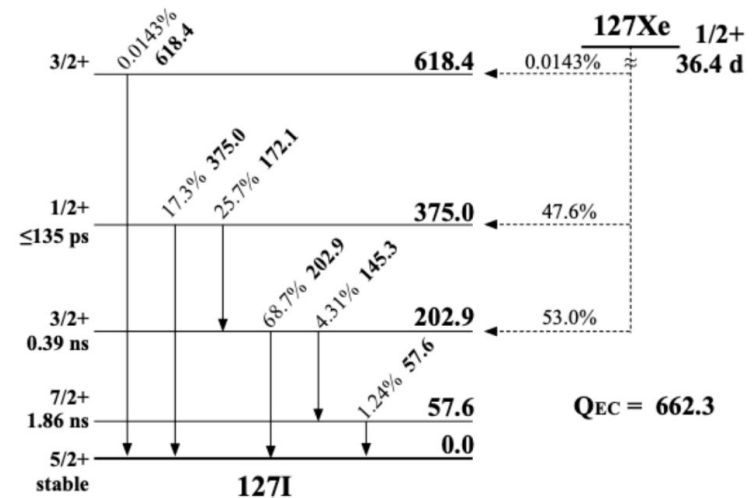


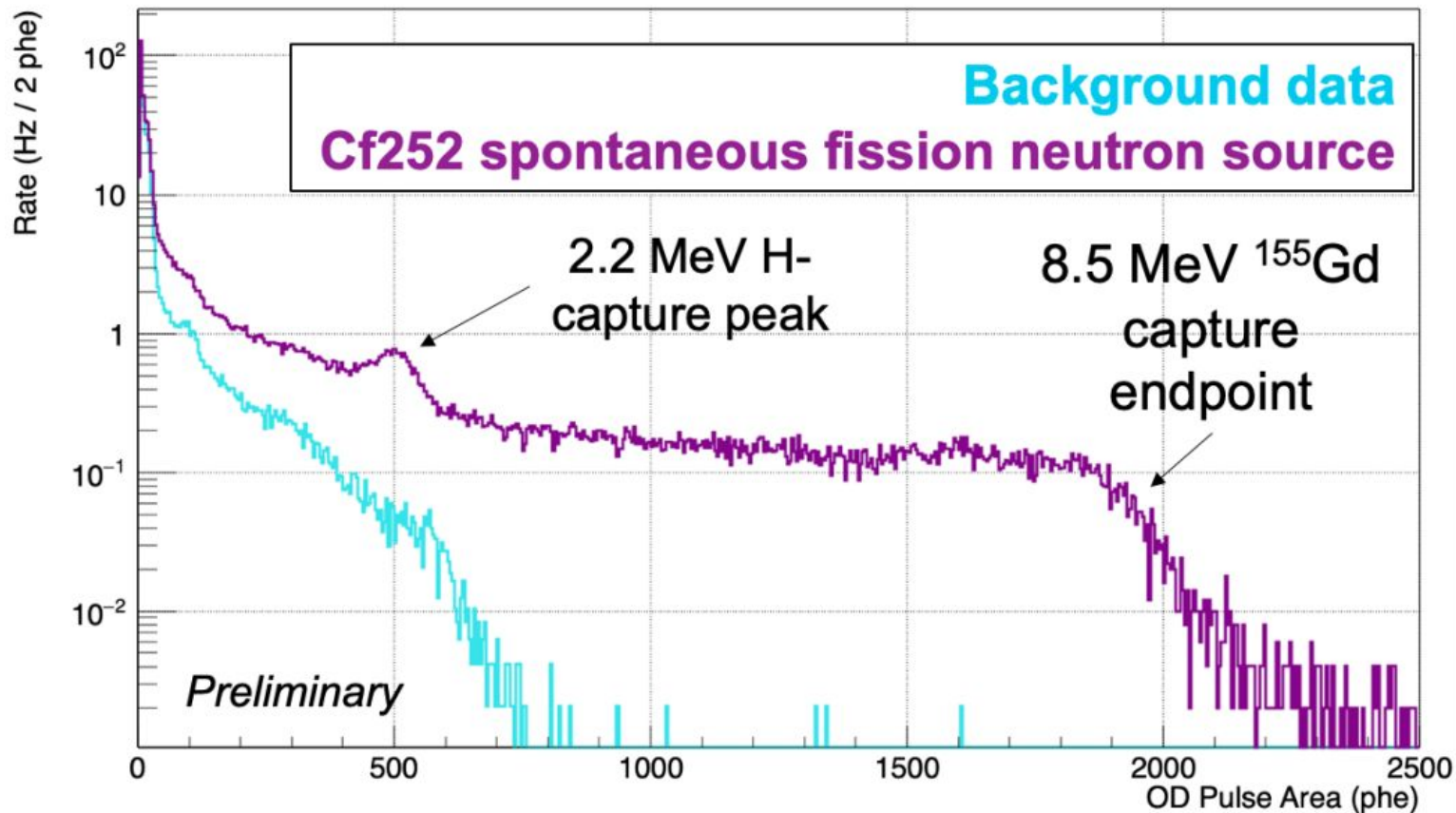
- We have data!
- All hands on deck!

- 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)

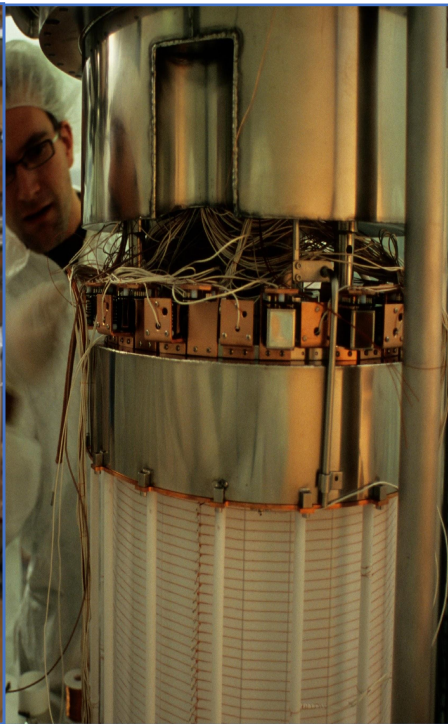


Xe-127 decays by electron capture





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



Xenon10

14 kg Xe
2005-2007

Xenon100

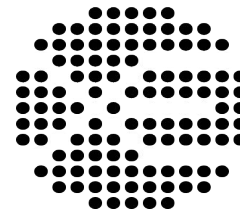
62 kg Xe
2008-2016

XENON1T

2 T Xe
2012-2018

XENONnT

5.9 T Xe
2019-2020

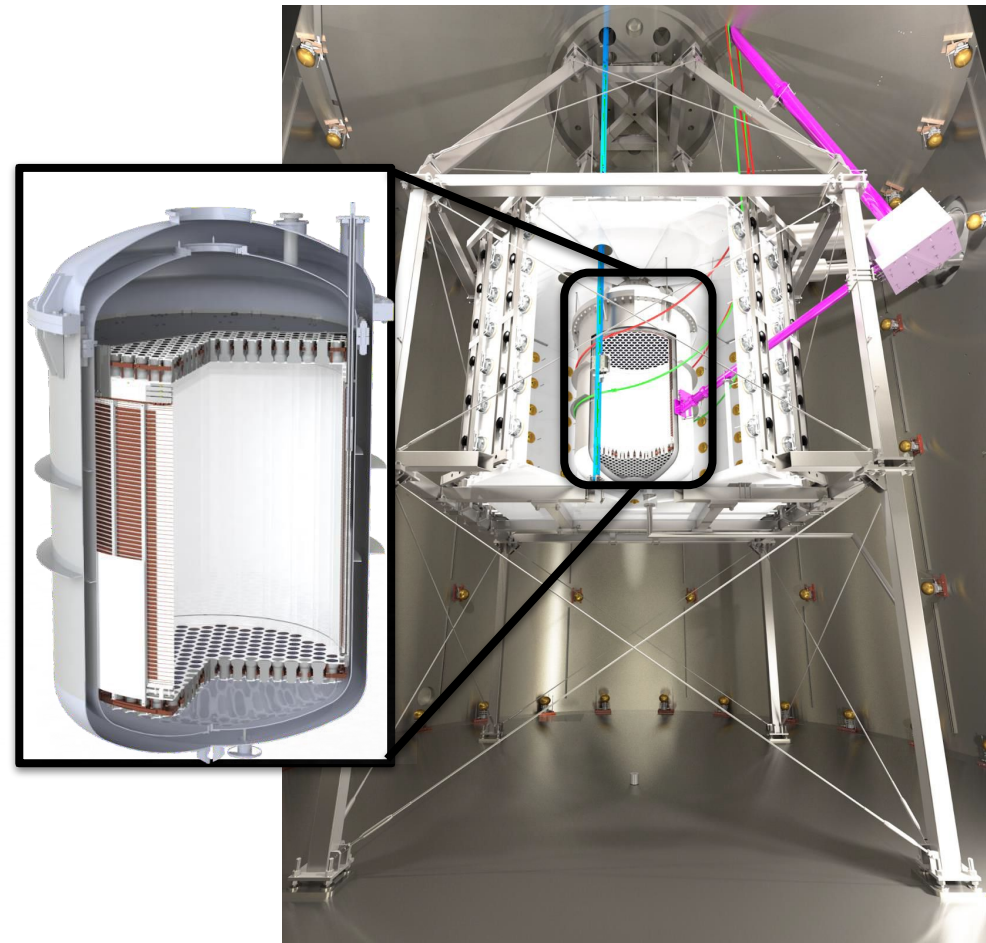


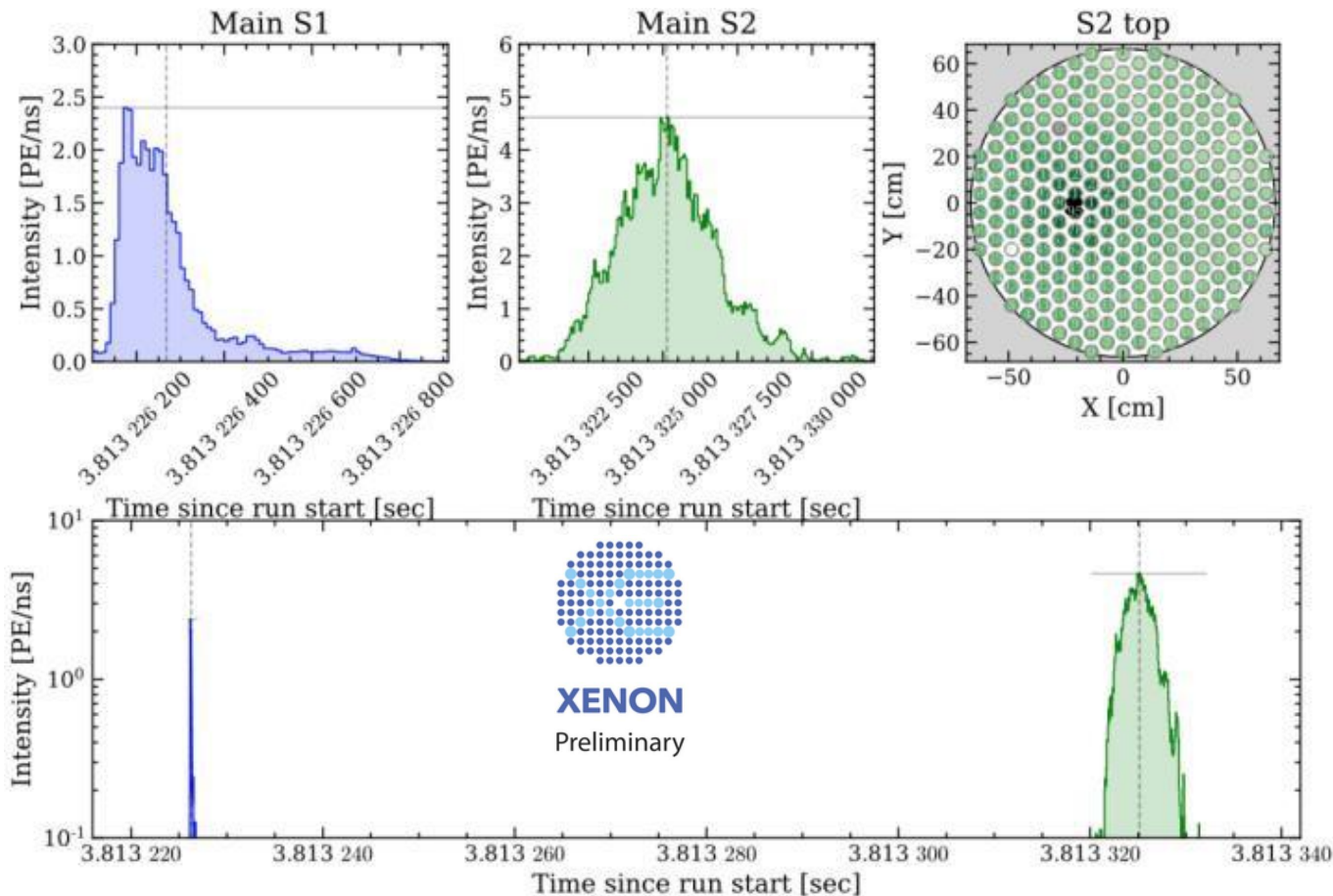
XENON

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

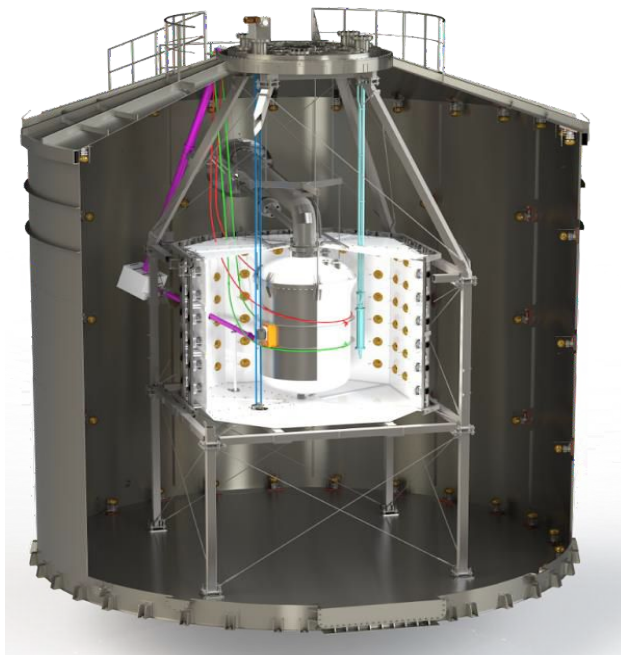
- Larger TPC than XENON1T
 - Active Xe mass **2t** → **5.9t** (3x)
 - Drift length **1m** → **1.5m** (1.5x)
 - PMTs **248** → **494** (2x)
- The larger a detector the higher the purity needs to be
 - Strict radioassay program
 - Rn emanation rate: $4.2 \mu\text{Bq/kg}$ (simulated, **1/3 of XENON1T**)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

<https://arxiv.org/abs/2112.05629>

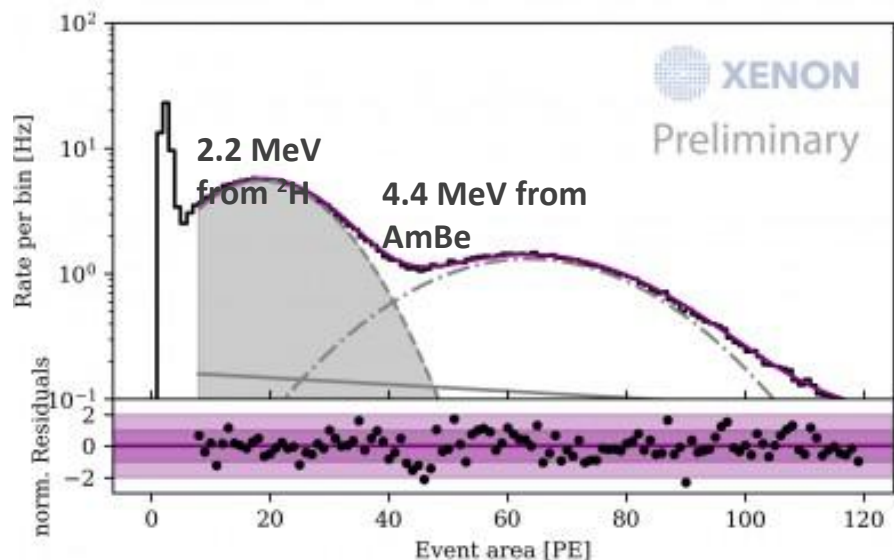


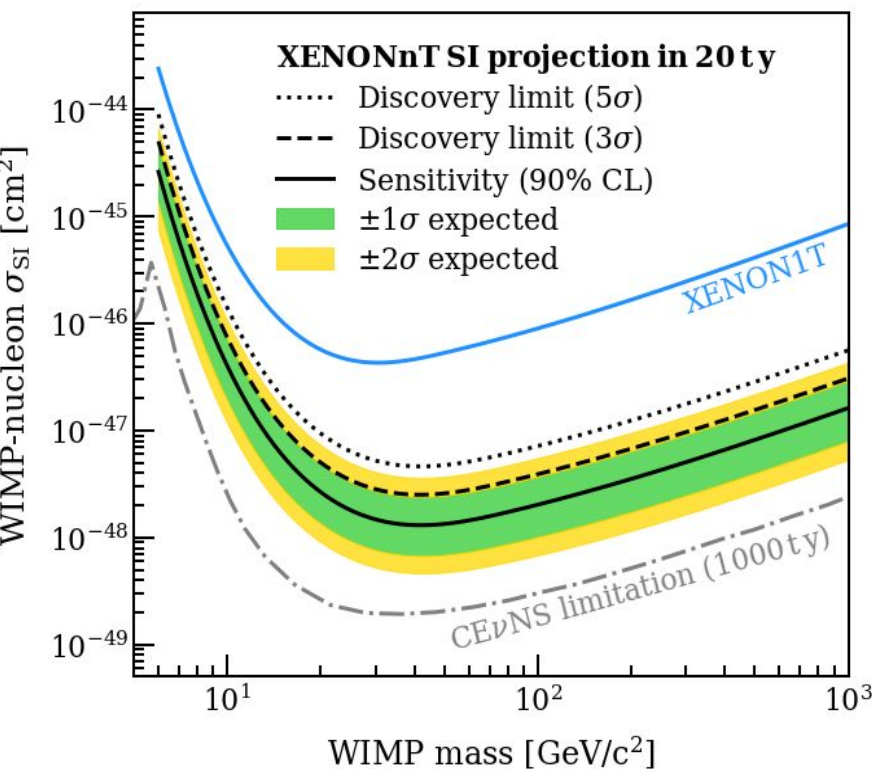


- XENONnT taking data
- PMTs have stable gains, average **QE is 34%**
- Good **single-electron** resolution

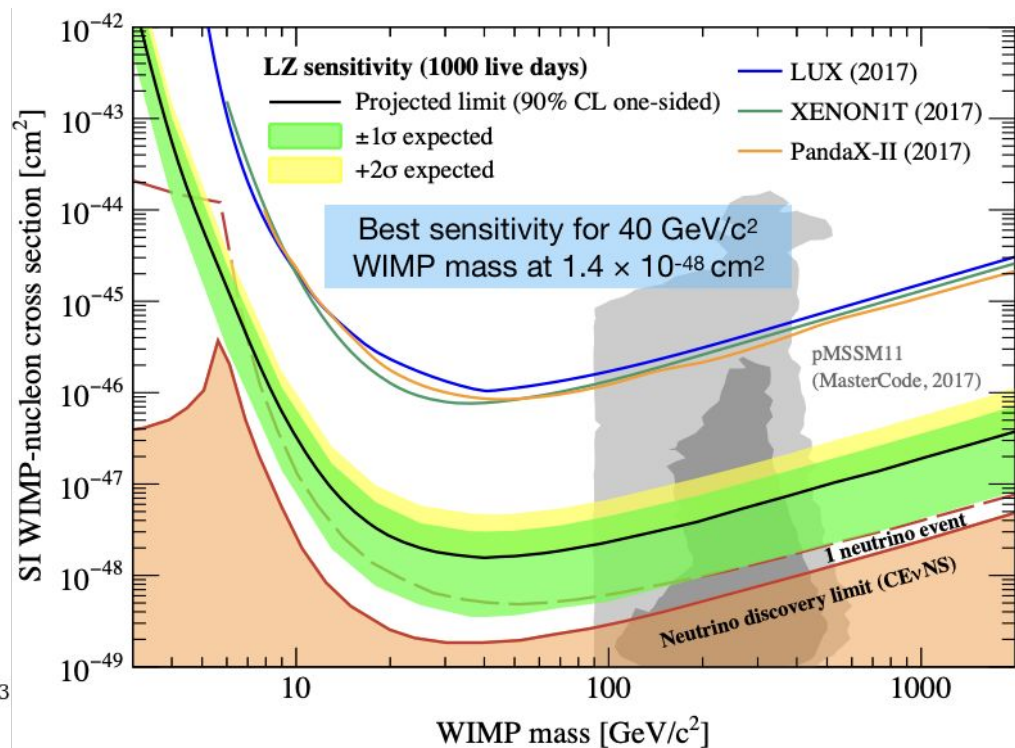


- Gd-Water Cherenkov detector
 - 33m³, with 120 PMTs inside ePTFE panels
 - **87% expected neutron tagging efficiency with Gd-doped water**
 - Trigger on 4.4 MeV AmBe, 90% efficiency in detecting neutron capture with demi-water
- Translate to **65% tagging efficiency with water** (match with sim)
- Goal: <1 evt / (20 t × yr)



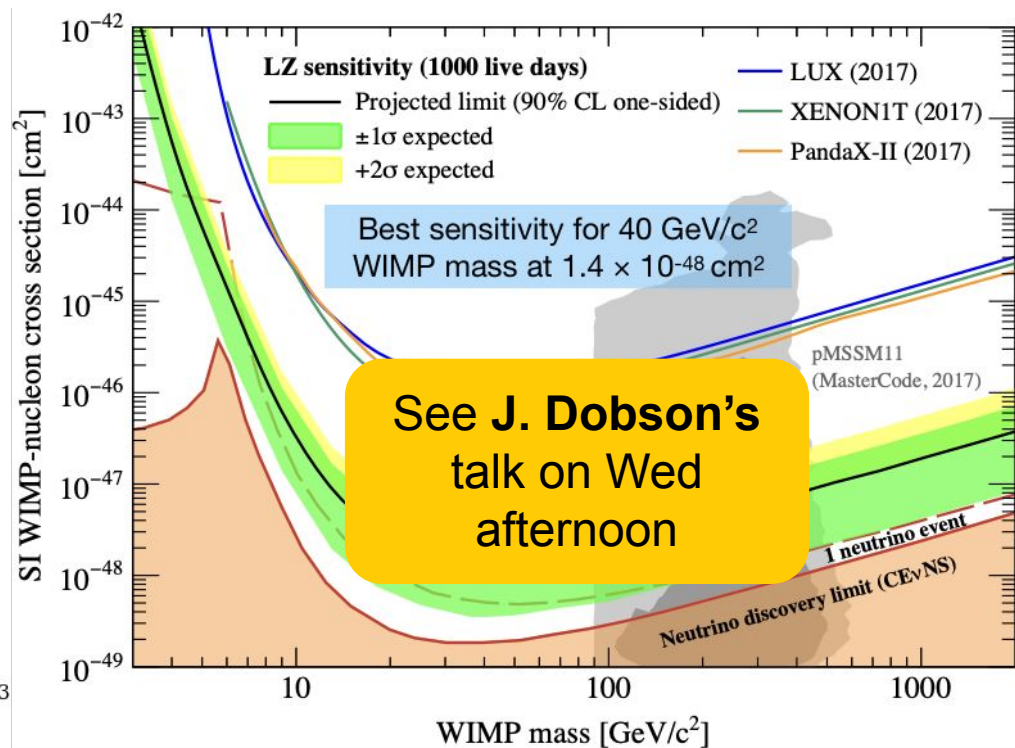
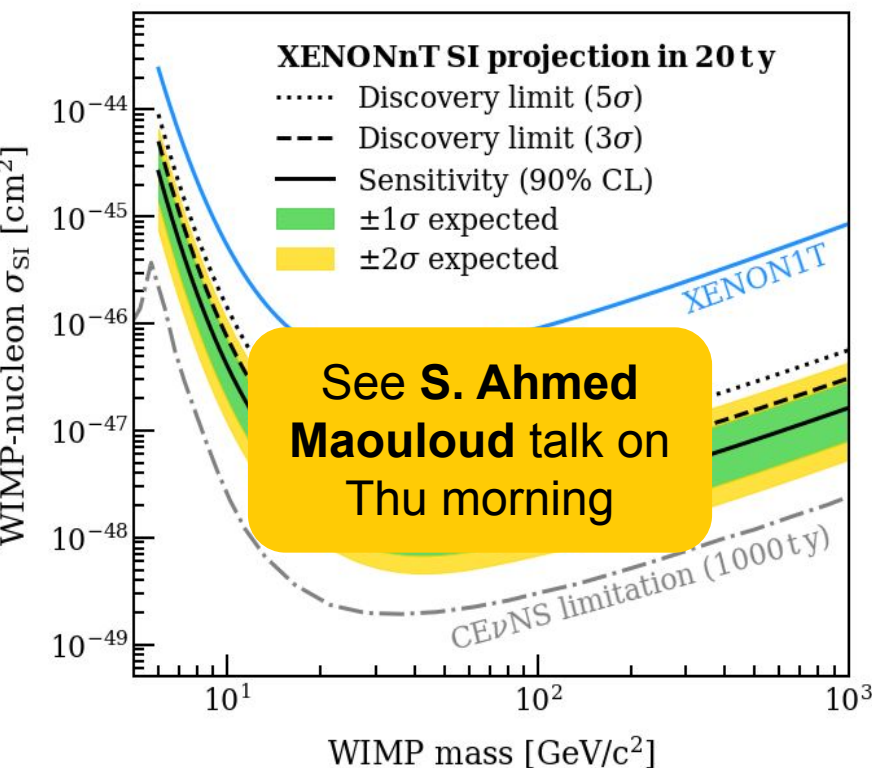


$1.4 \times 10^{-48} \text{ cm}^2 @ 50 \text{ GeV}/c^2$



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

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



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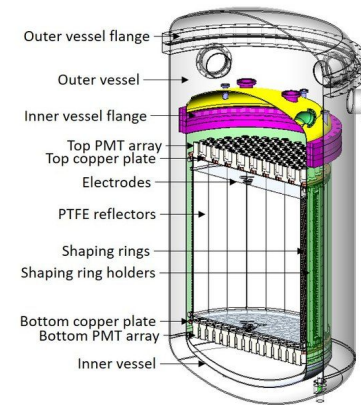
PandaX = Particle and Astrophysical Xenon Experiments



Phase I:
120 kg DM
2009-2014



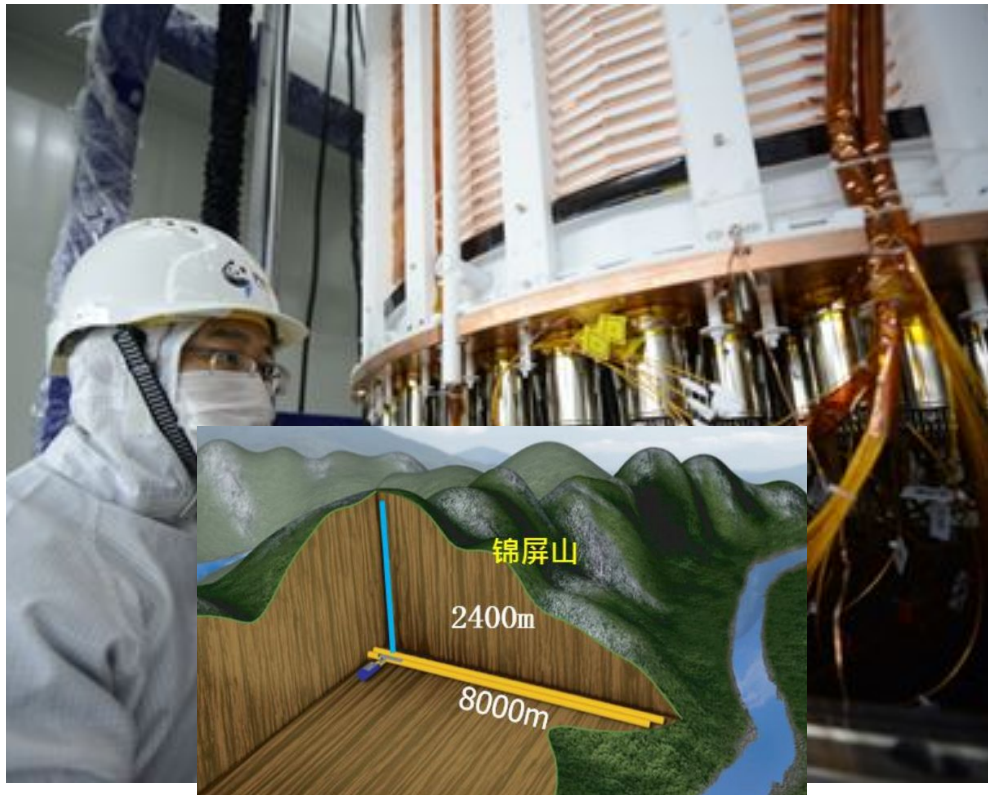
Phase II:
500 kg DM
2014-2017



PandaX-4T:
multi-ton DM
2020-

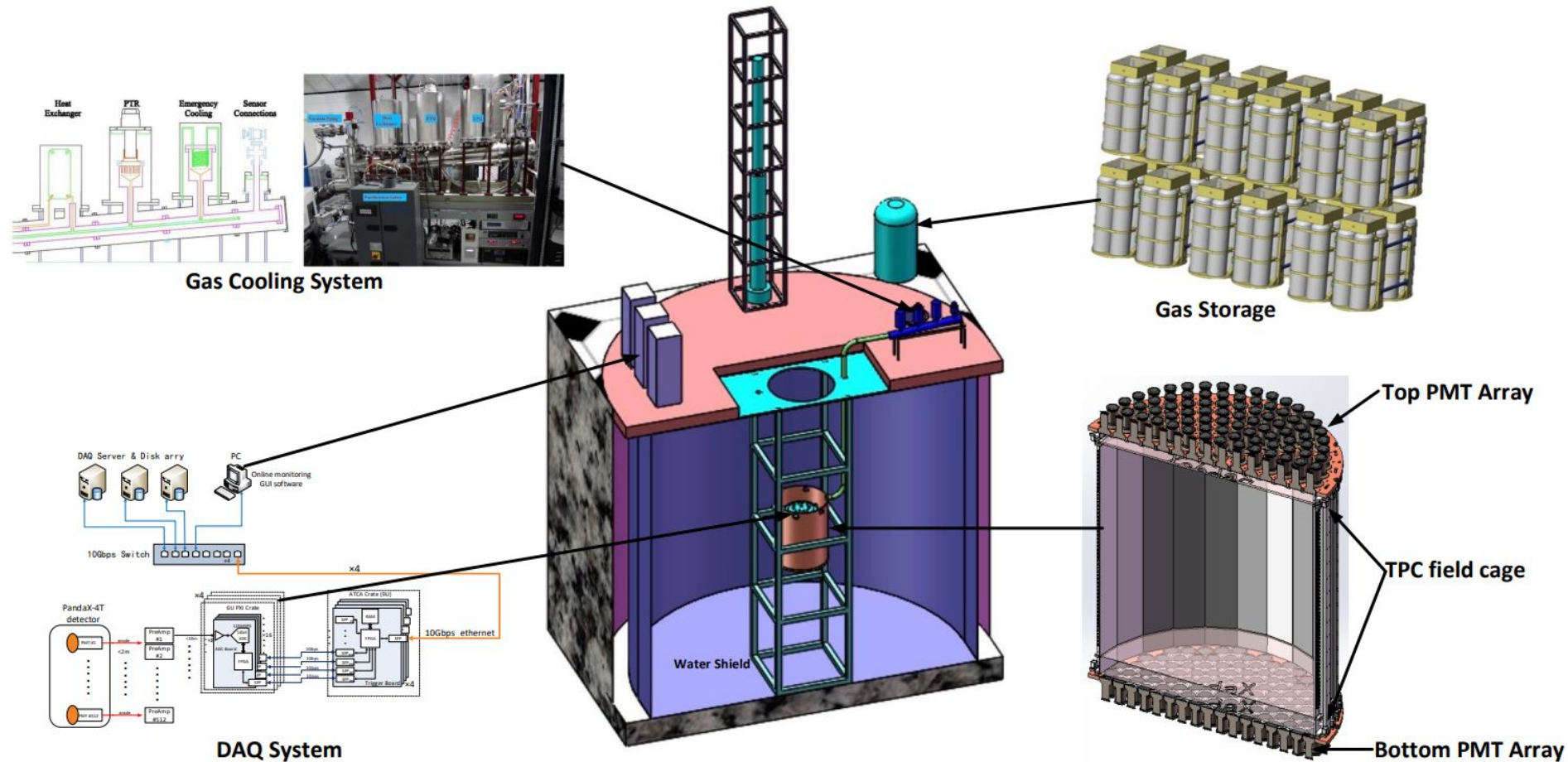


PANDA X

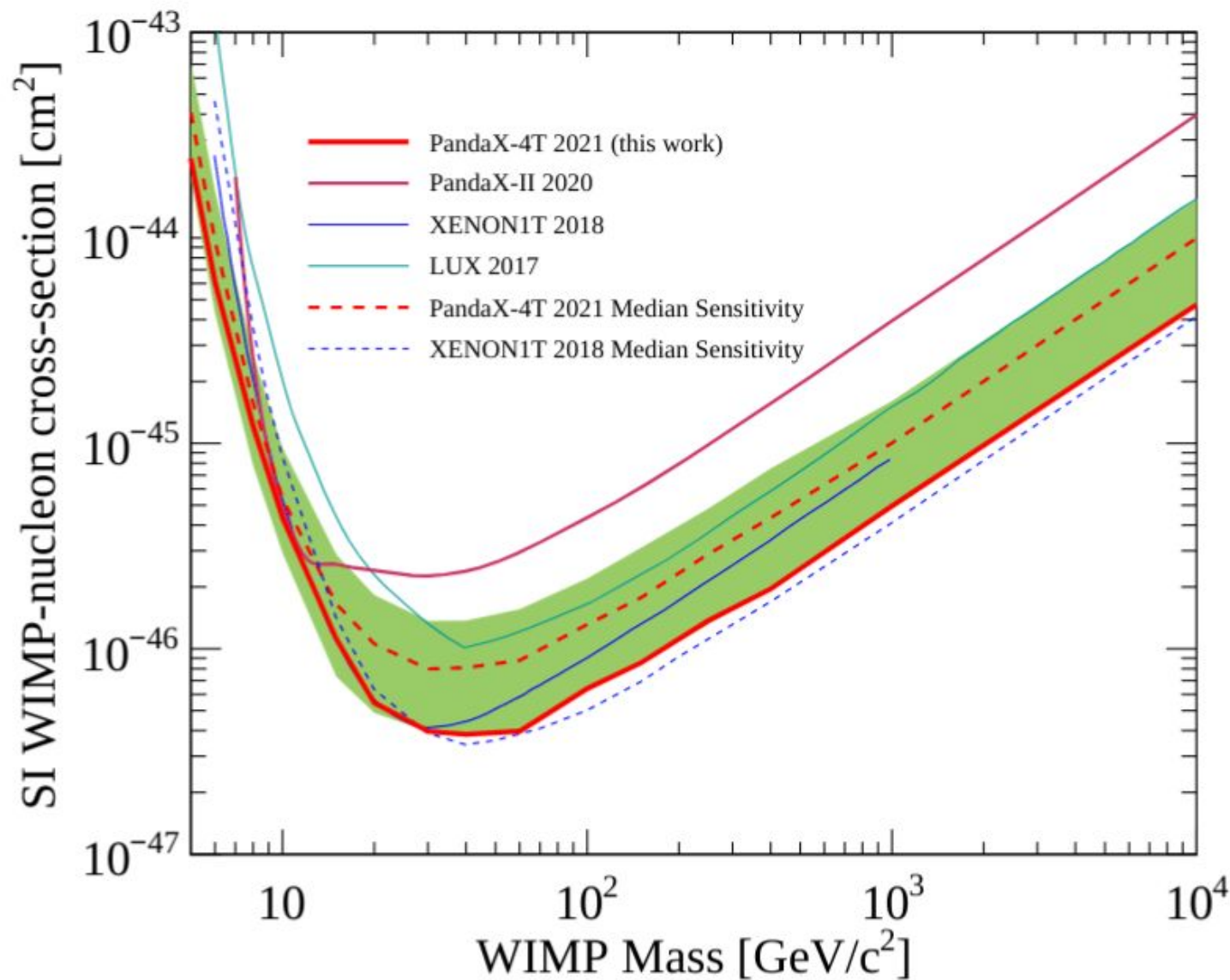


<https://arxiv.org/abs/2107.13438>

- 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



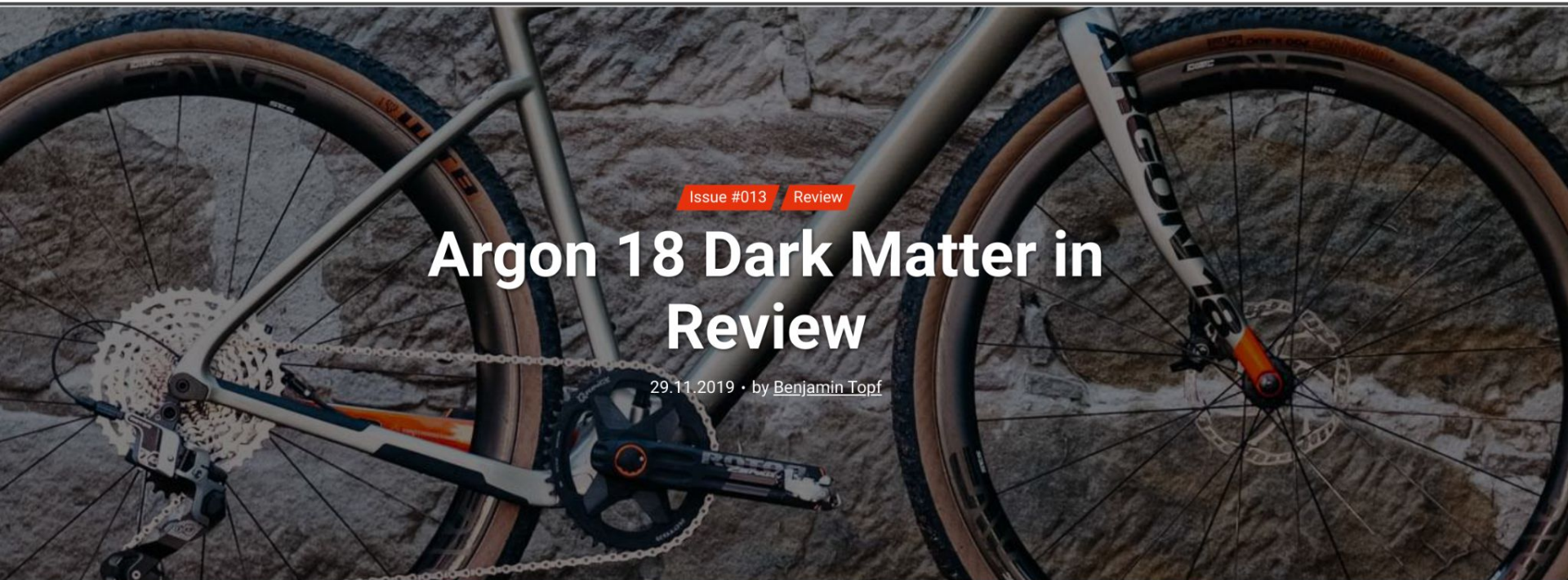
- PandaX-4T impressive performance
- Fast construction/operations with a relatively small team



Argon Detectors

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87 Fr Francium	88 Ra Radium	89 Ac Actinium	104 Rf Rutherfo...	105 Db Dubnium	106 Sg Seaborg...	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitneri...	110 Ds Darmsta...	111 Rg Roentge...	112 Cn Coperni...	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovi...	116 Lv Livermor...	117 Ts Tenness...	118 Og Oganes...																												
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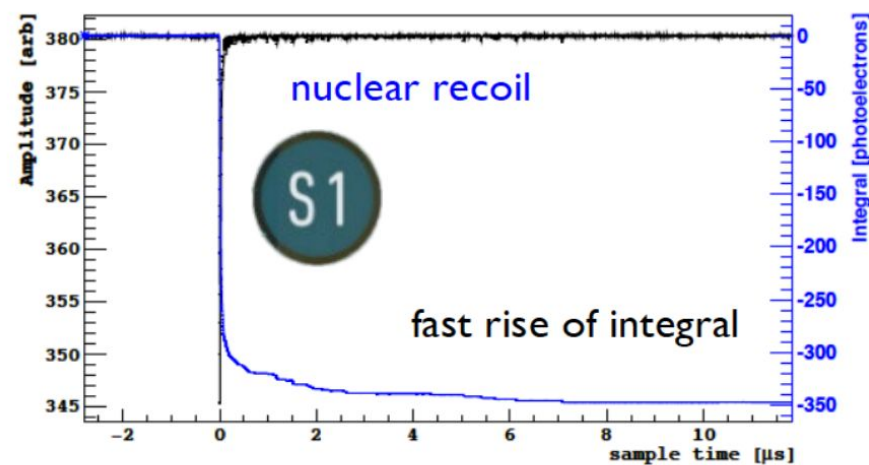
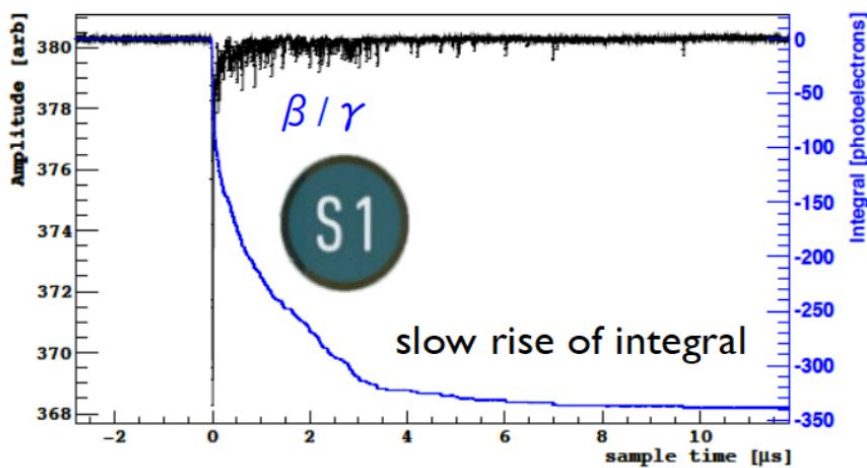
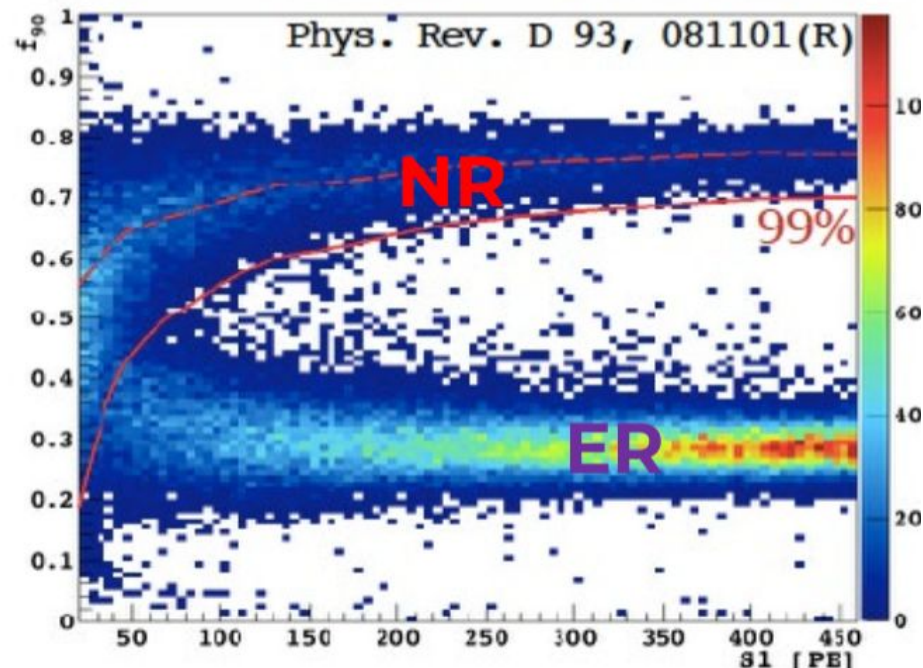
Issue #013 Review

Argon 18 Dark Matter in Review

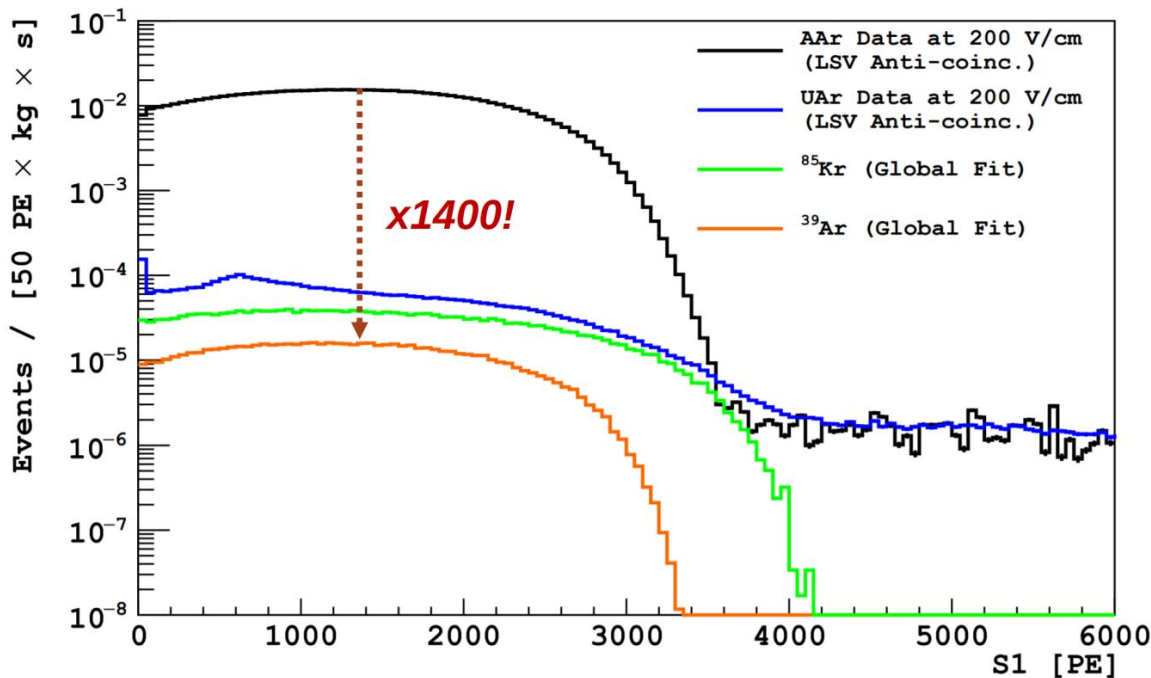
29.11.2019 · by [Benjamin Topf](#)

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.

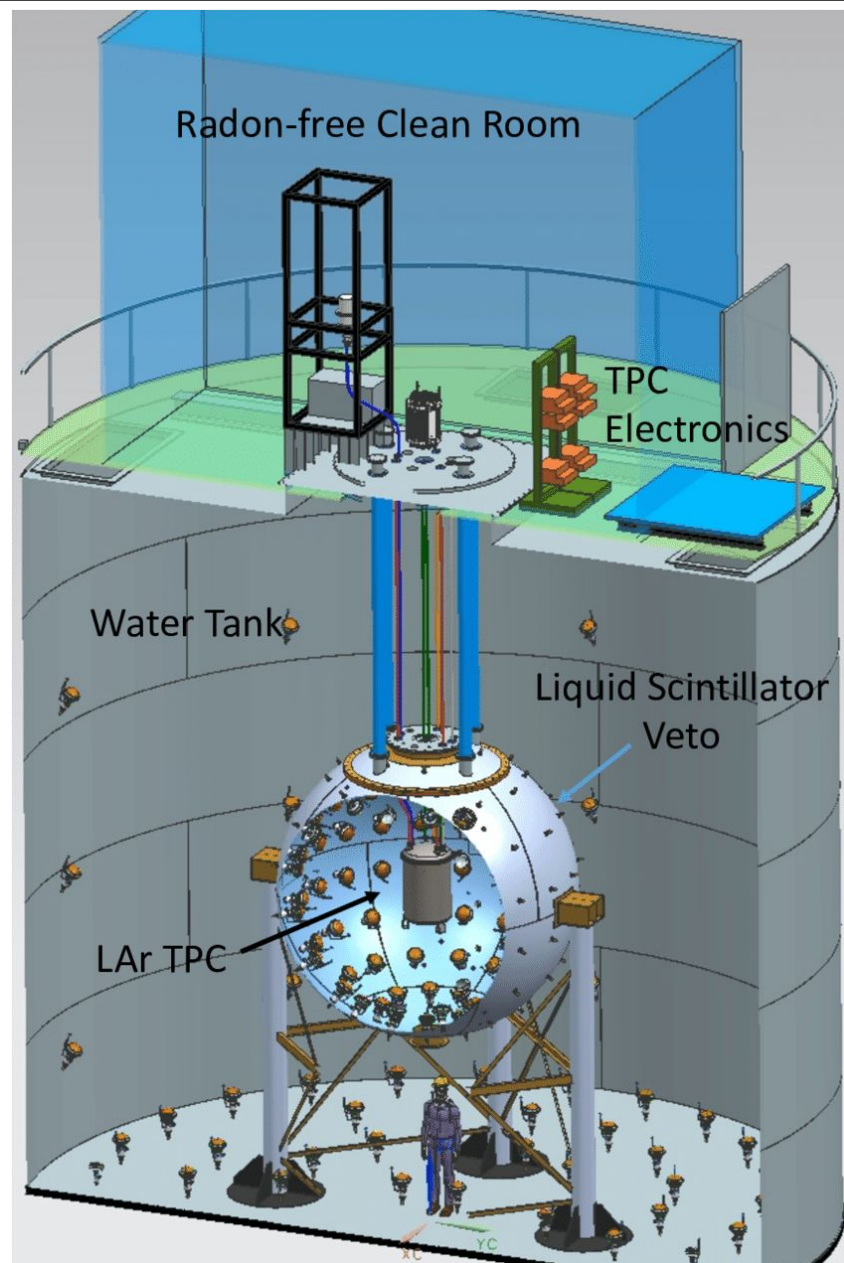
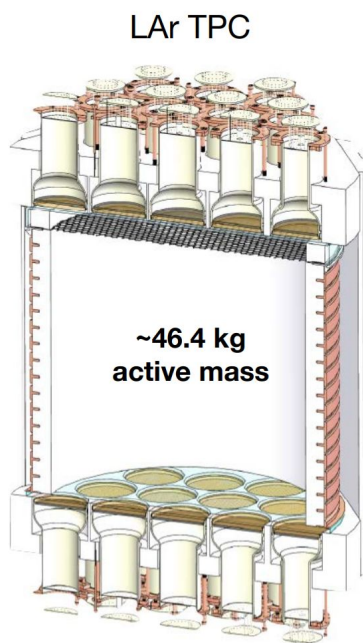
- At has different decay times: singlet ($\sim 7\text{ns}$) vs. triplet ($\sim 1.6\mu\text{s}$) state.
 - ER cause relatively more triplet
 - NR cause relatively more singlets
- Use pulse shape discrimination



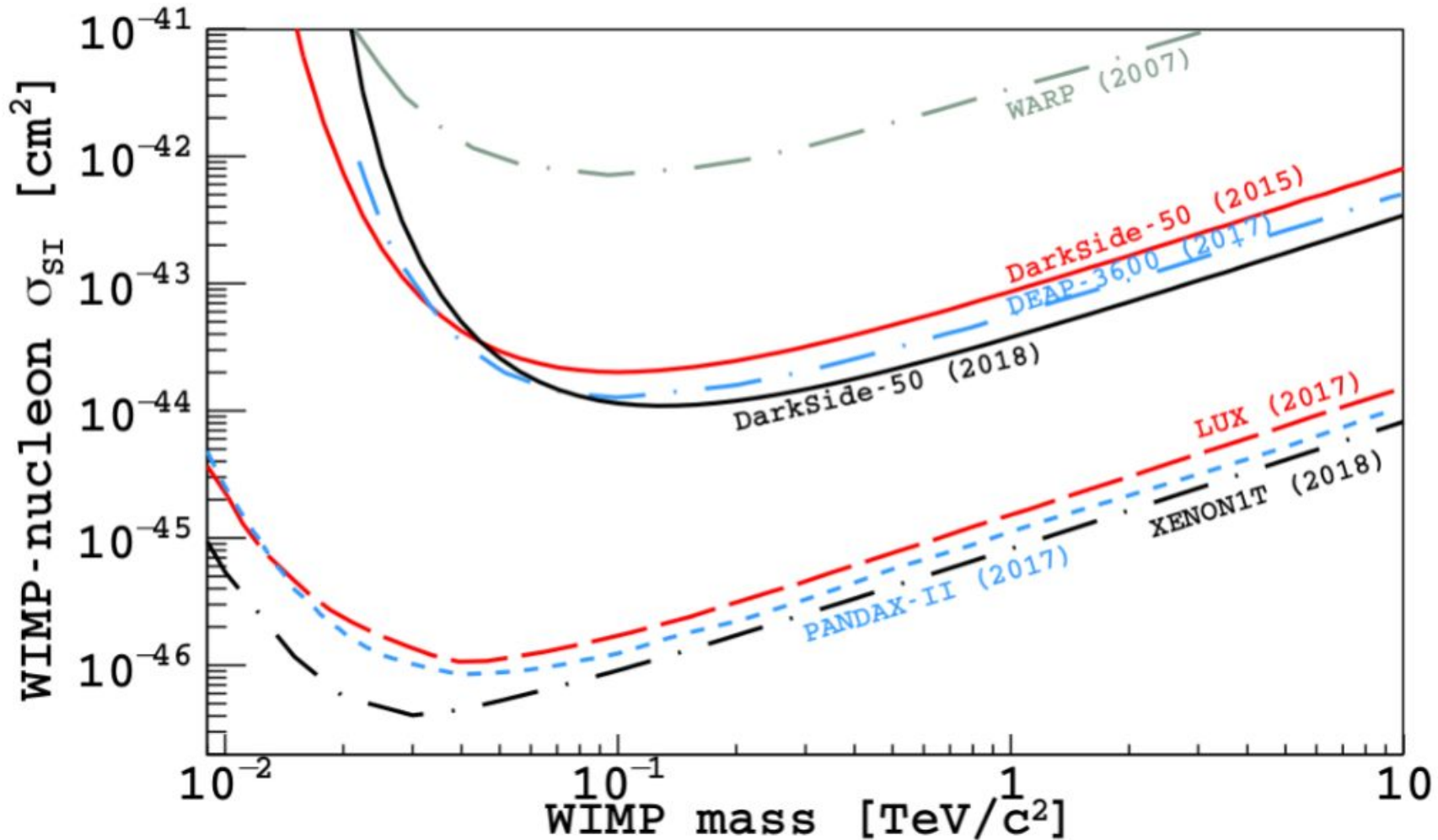
- **Ar** is the **most abundant noble gas** in the atmosphere,
- Much less expensive than Xe plus PSD
 - However, **cosmogenic ^{39}Ar production** limits the size of detectors due to pile-up
 - $10^{-15}\text{g/g} \rightarrow \text{natAr} \sim 1\text{Bq/kg}$, 269 yr half-life
- **Solution:** Source 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**

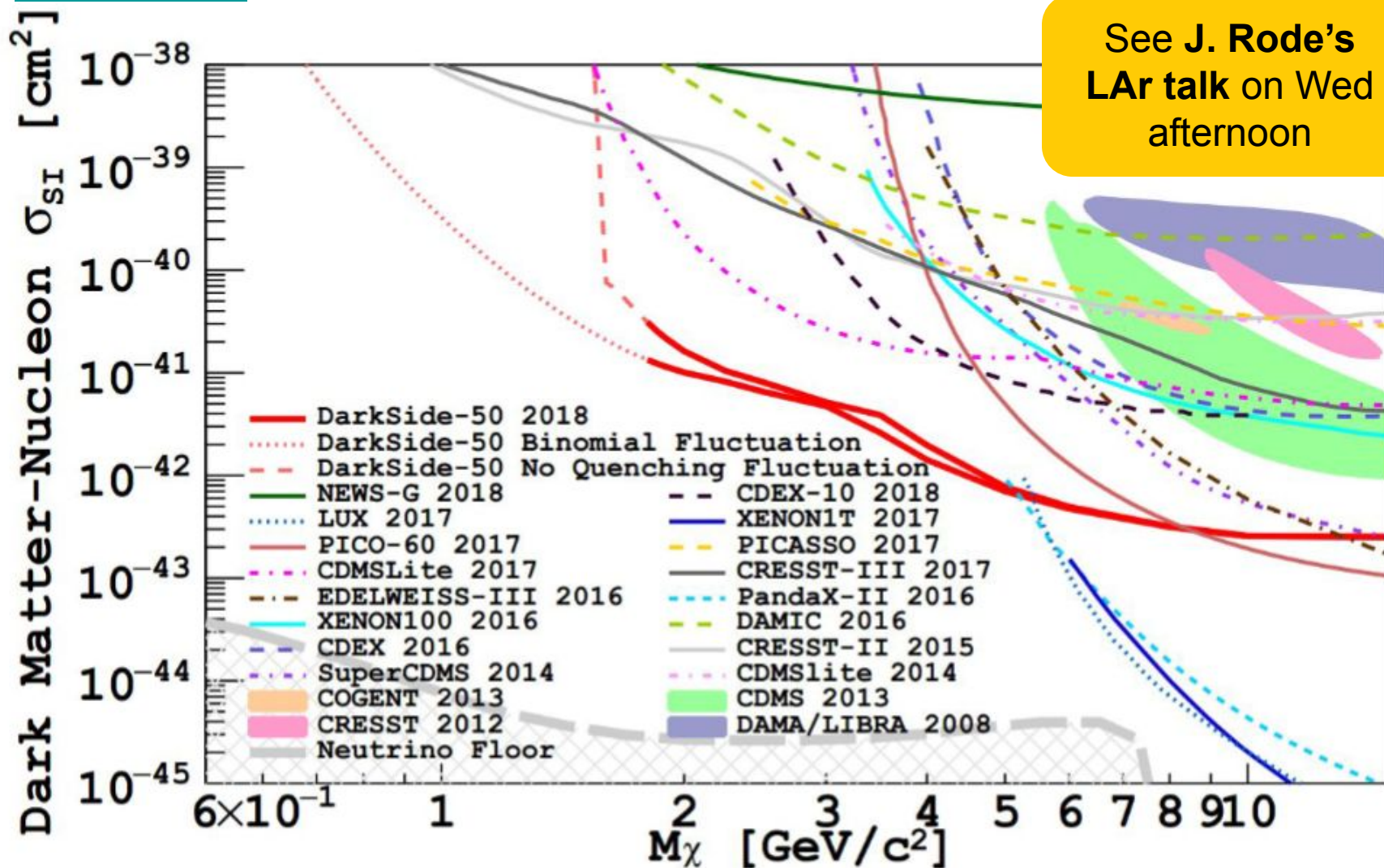


[arxiv:1802.07198](https://arxiv.org/abs/1802.07198)



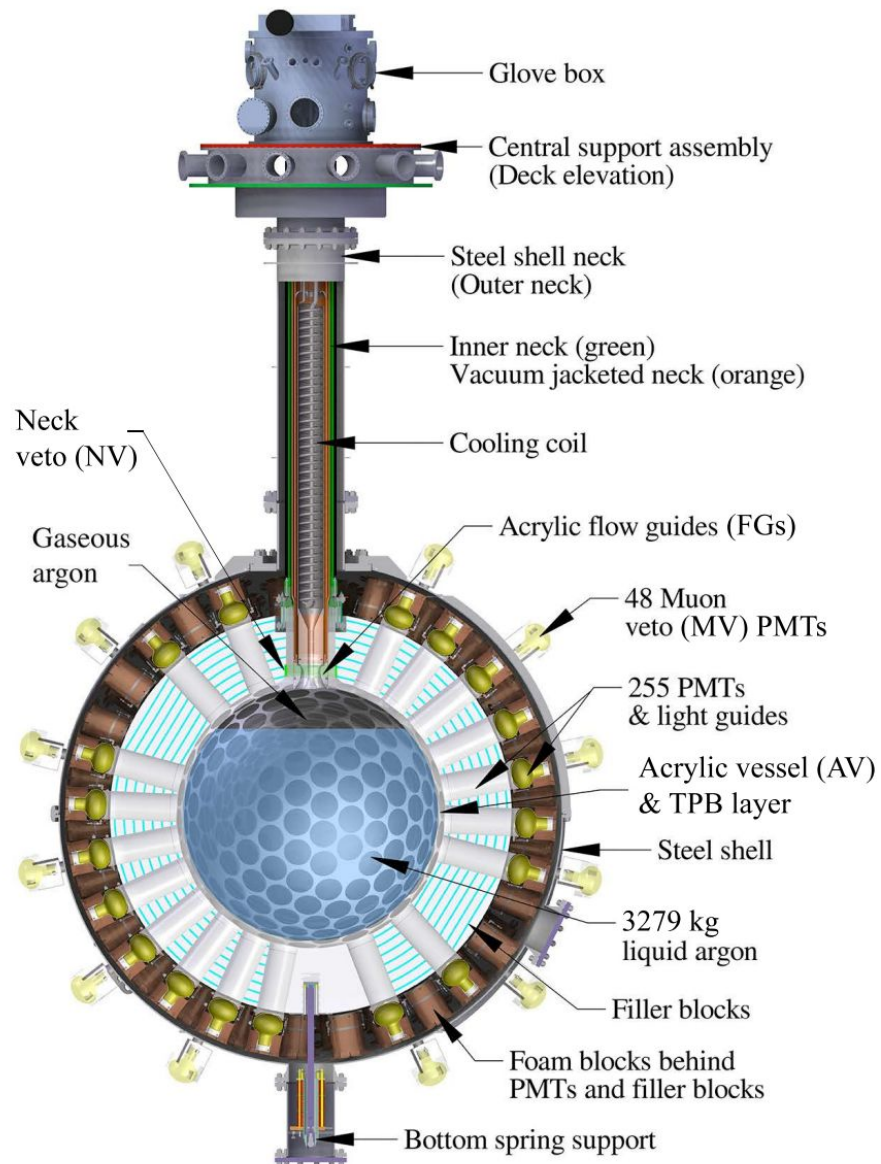
- High Mass DM exclusion $\sigma_{\text{xN}} > 1.1 \times 10^{-44} \text{ cm}^2 @ 100 \text{ GeV}/c^2$

[arxiv:1802.06994](https://arxiv.org/abs/1802.06994)

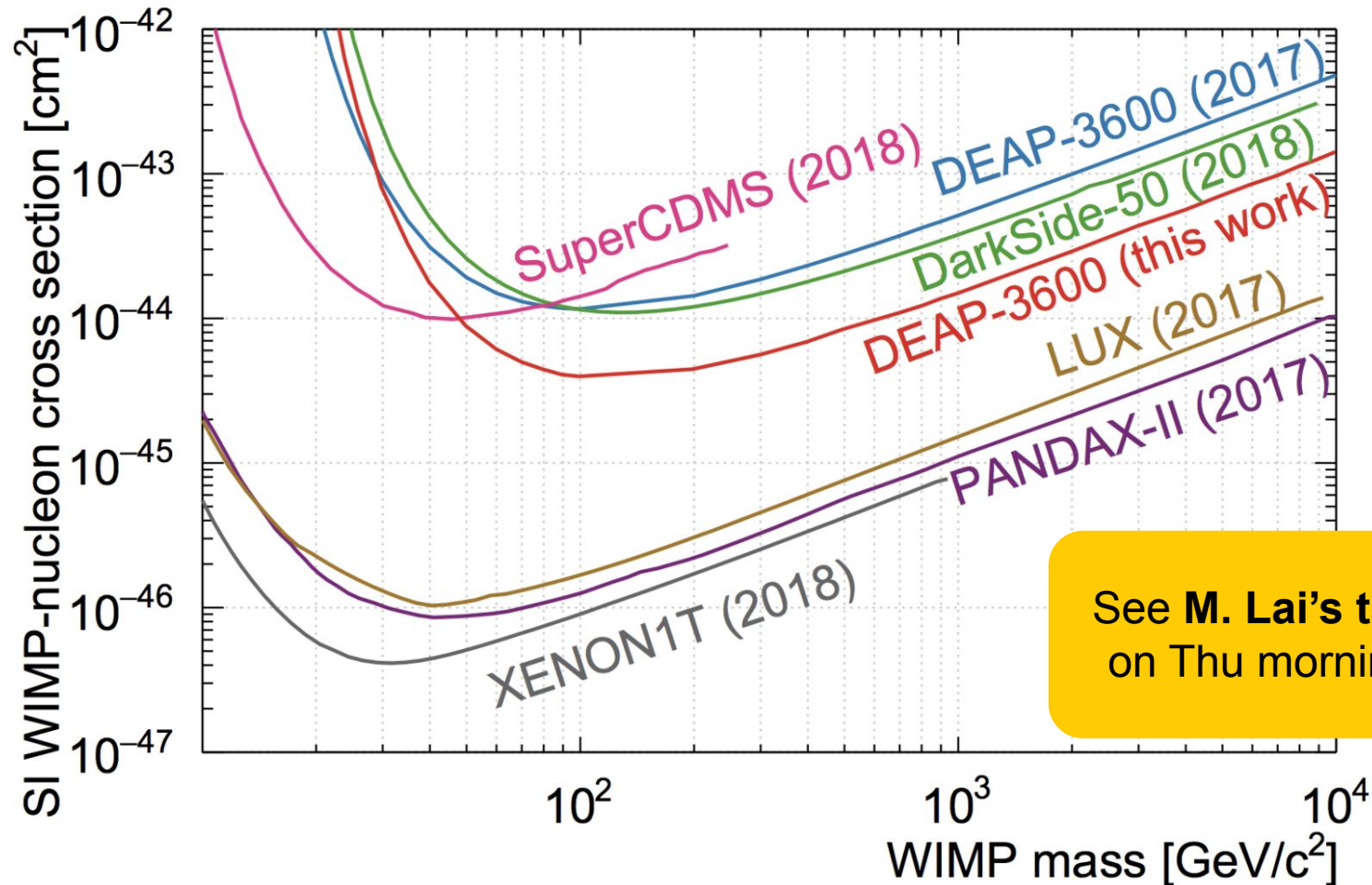


- DarkSide-20k performed leading **low mass analysis (S2 only)**

- **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>

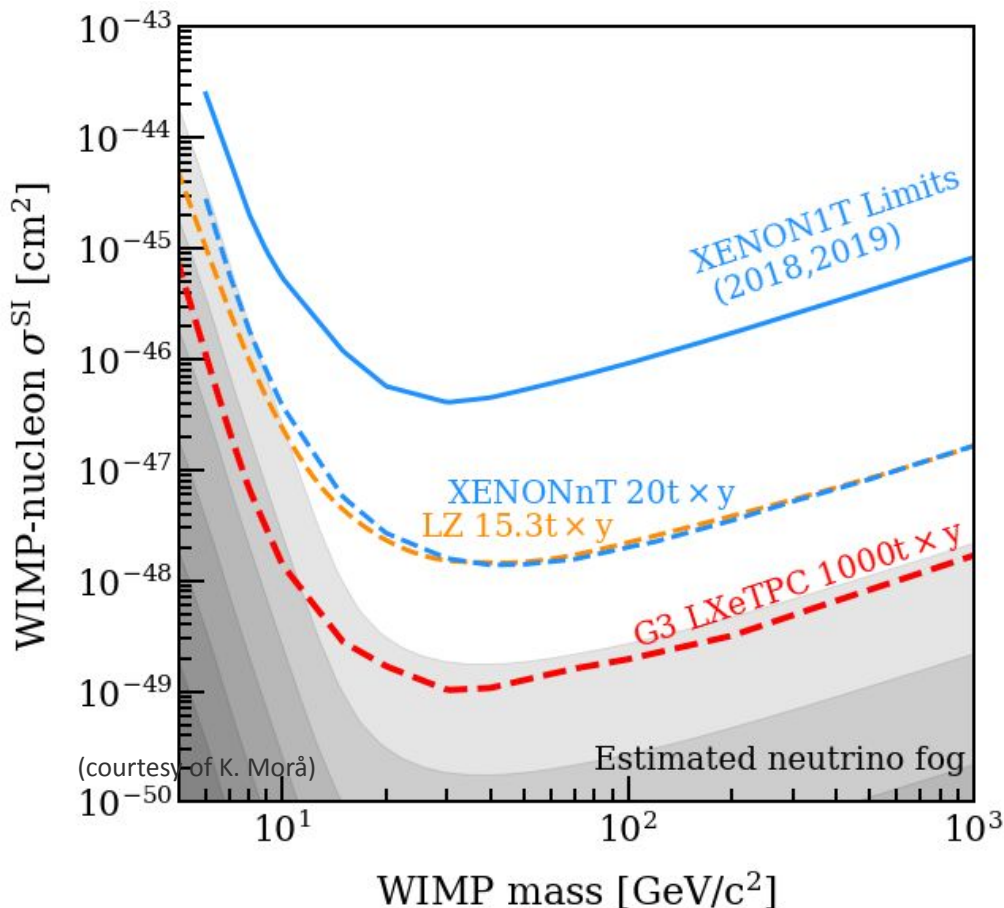


See M. Lai's talk
on Thu morning

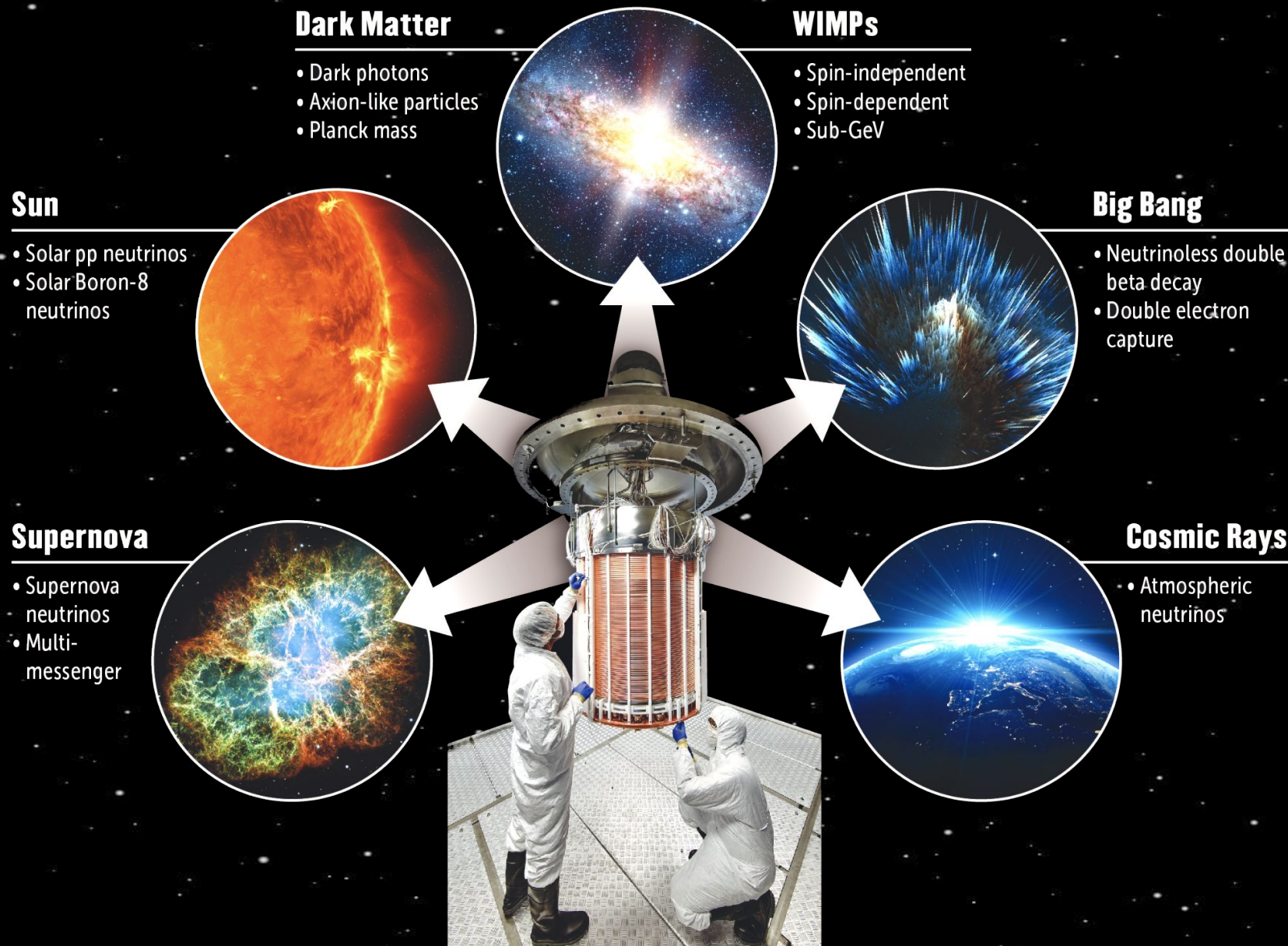
- Limit off $\sigma_{xN} = 3.9 \times 10^{-45} \text{ cm}^2$ for a 100 GeV WIMP at 90% C.L.,
- Leading **exclusion curve for argon detector.**

The Future

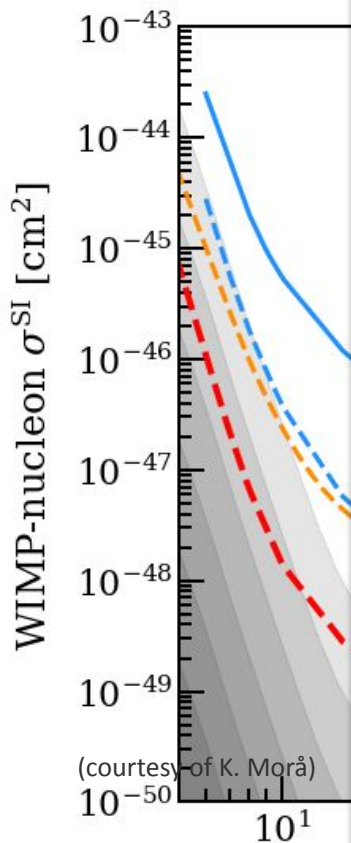
[2203.02309](#)



- WIMPs remain the most compelling DM models
 - The “neutrino fog” is still far away
- Lots of other interesting physics other than simply DM ($0\nu\beta\beta$, 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



2203.02309



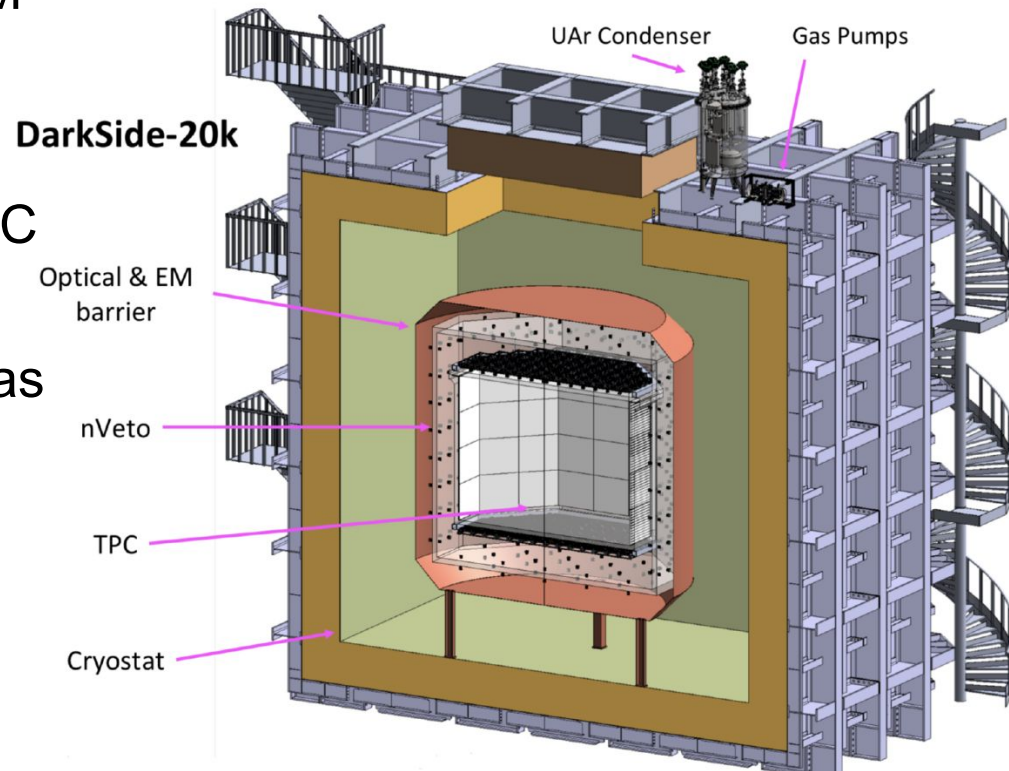
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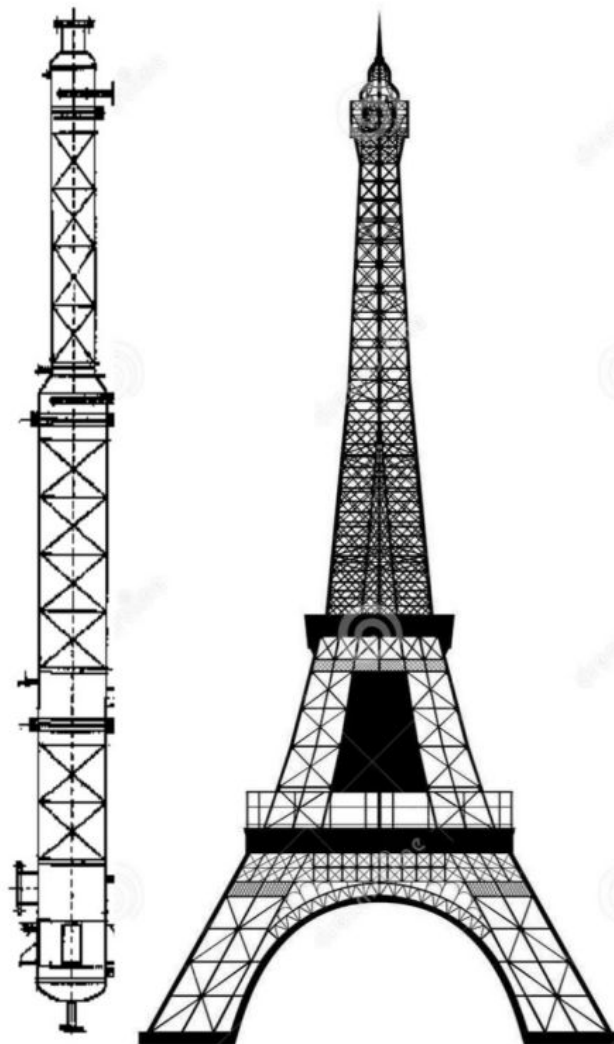
G3 whitepaper
 arXiv: [2203.02309](https://arxiv.org/abs/2203.02309)
 500+ authors

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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;

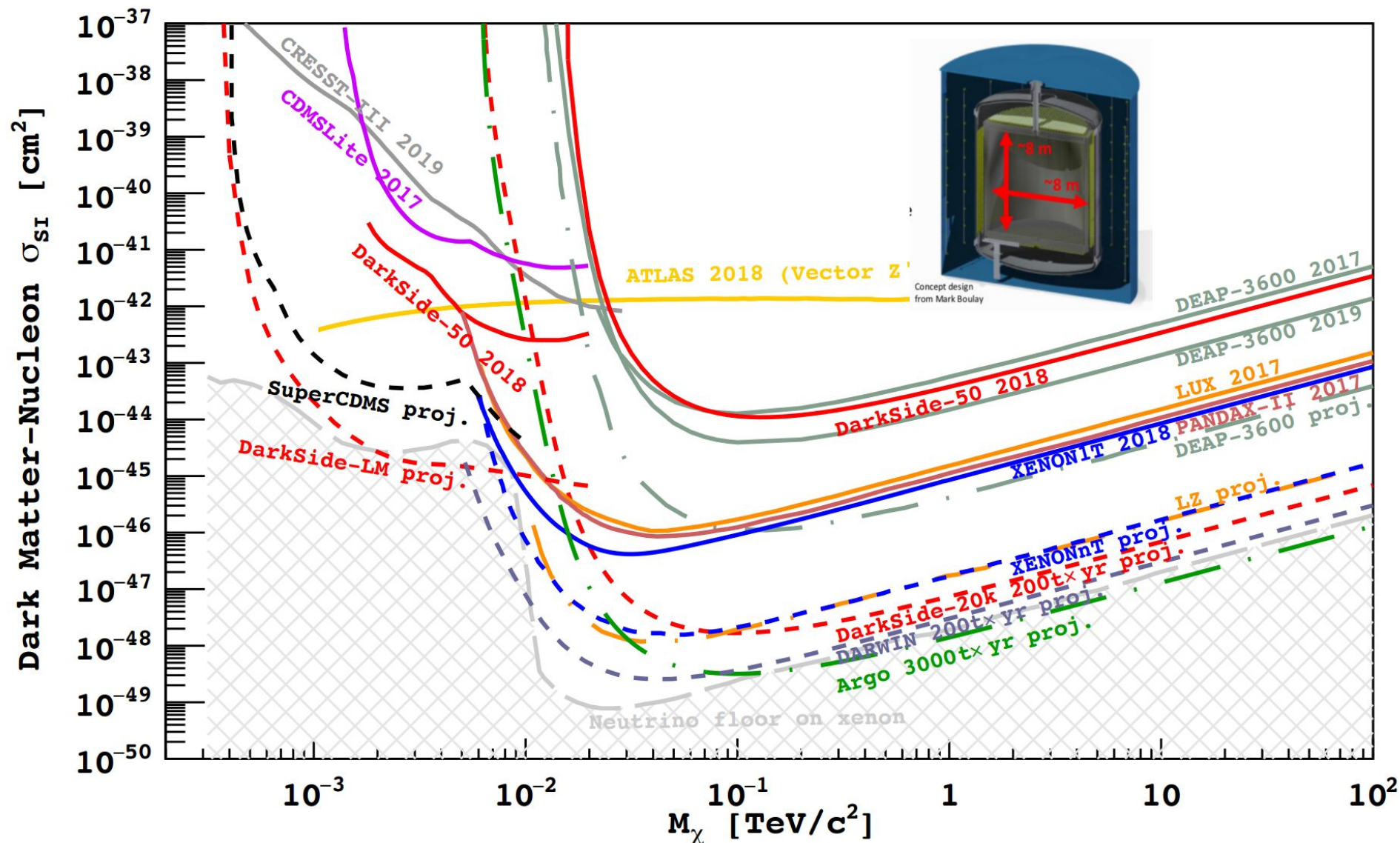


DarkSide-20k
50 T LAr



- **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>

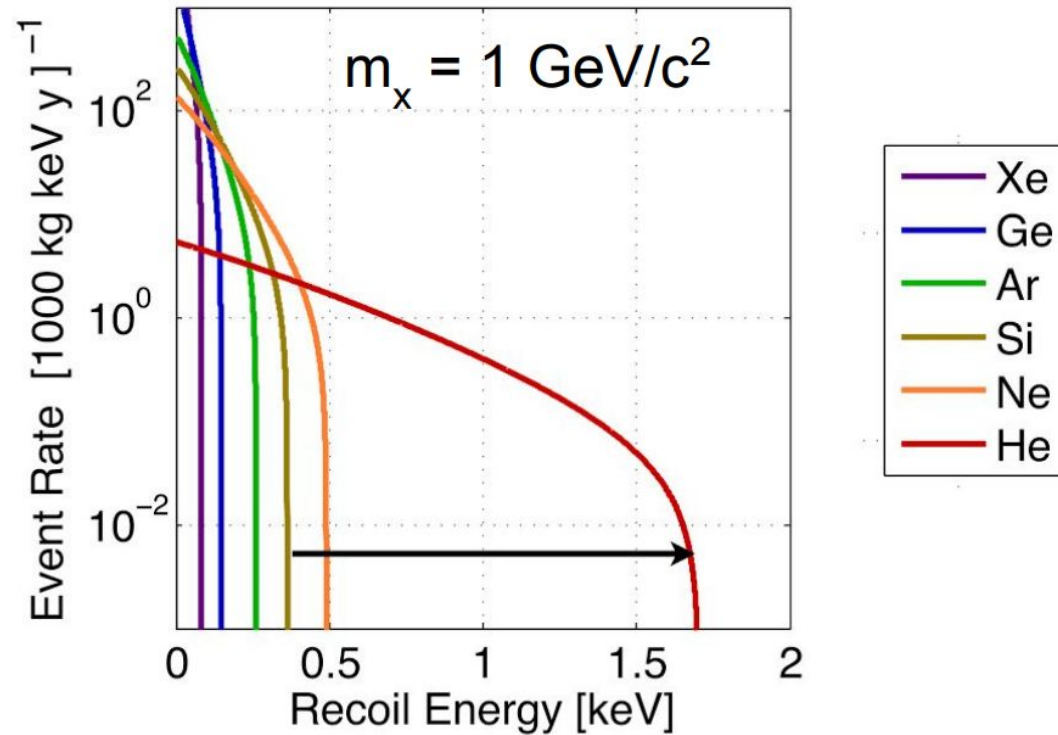


- Long term goal for 300T (!) detector: **ARGO**

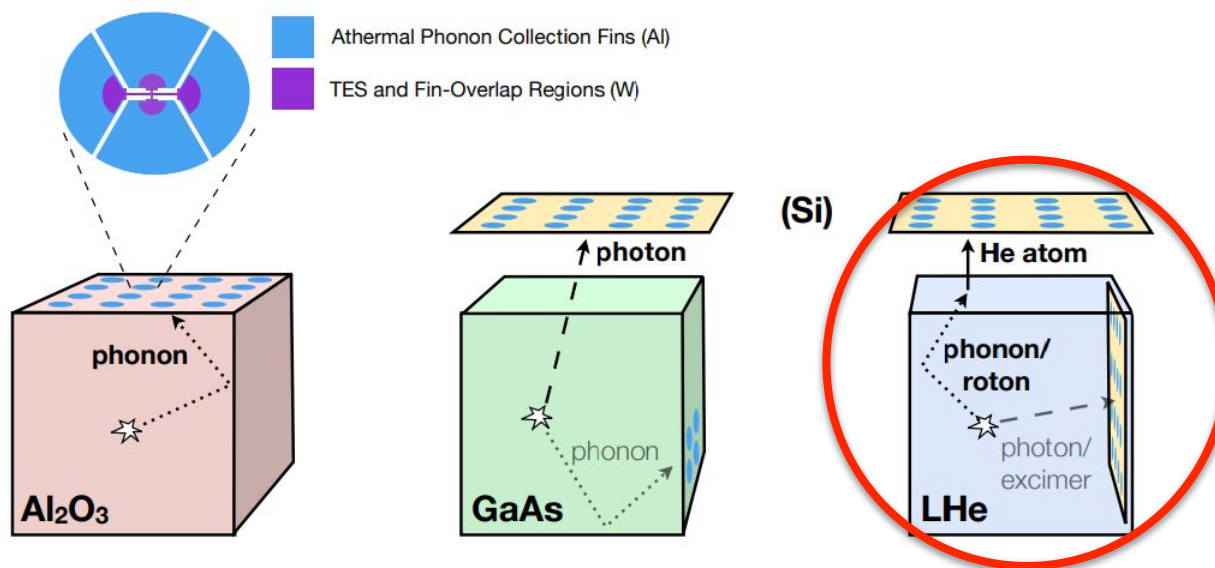
LHe Detectors

1 H Hydrogen																	2 He Helium																												
3 Li Lithium	4 Be Beryllium																	5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon																						
11 Na Sodium	12 Mg Magnesi...																	13 Al Aluminium	14 Si Silicon	15 P Phosph...	16 S Sulfur	17 Cl Chlorine	18 Ar Argon																						
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Mangan...	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germani...	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton																												
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybde...	43 Tc Techneti...	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon																												
55 Cs Caesium	56 Ba Barium	57 La Lanthan...	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon																												
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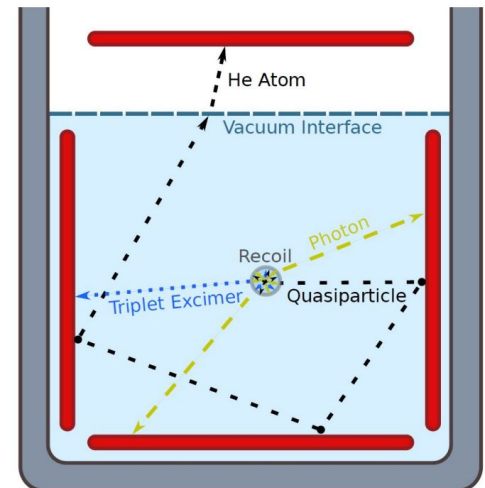
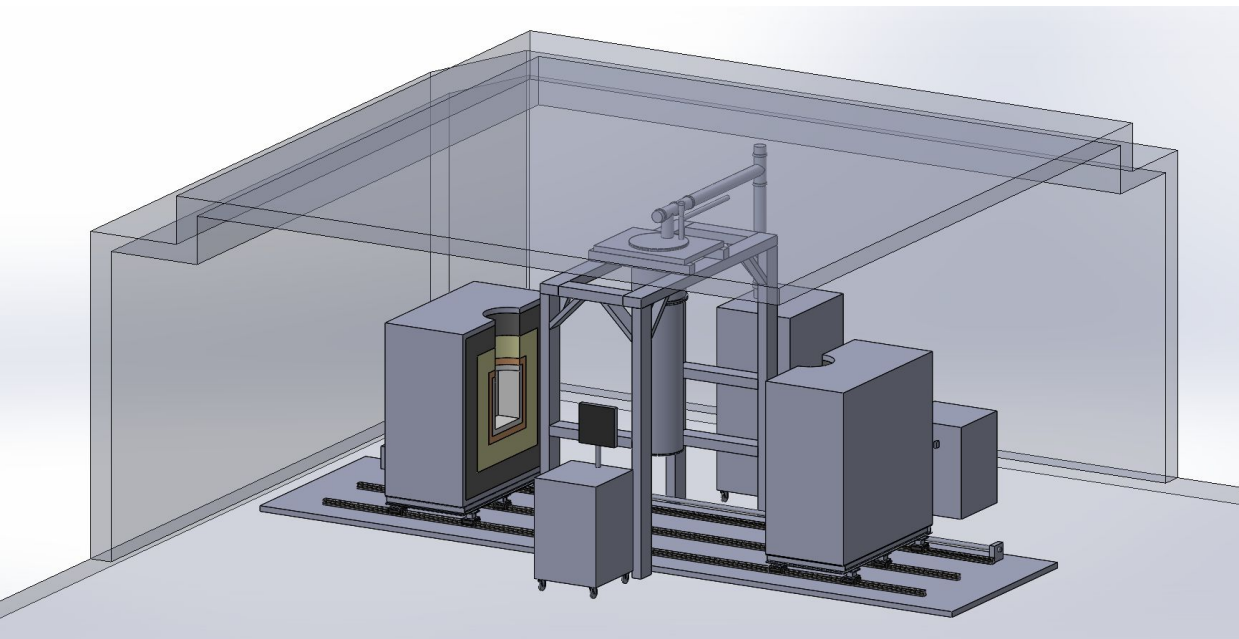
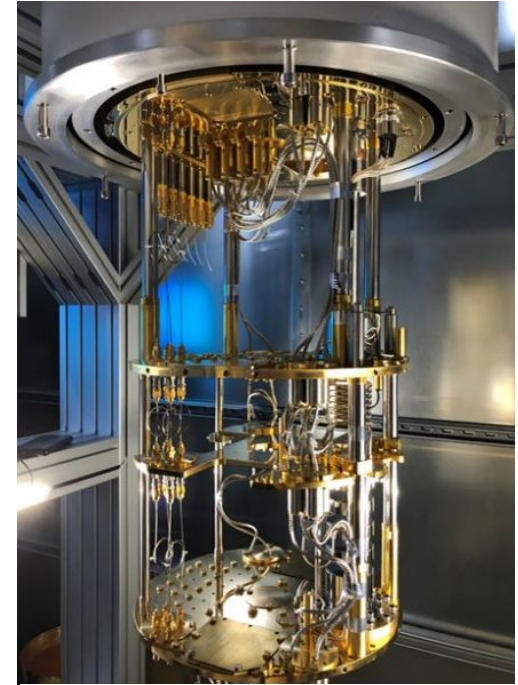
- With sufficiently low threshold and/or a light target, lower dark matter masses may be probed
- He^4 is fairly **cheap**, **radiopure**, **scalable**
- **Novel signal channels** reach sensitivities that can not be realized using only ionization or scintillation signals (**rotons, phonons, scintillation, triplet excimers**)



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

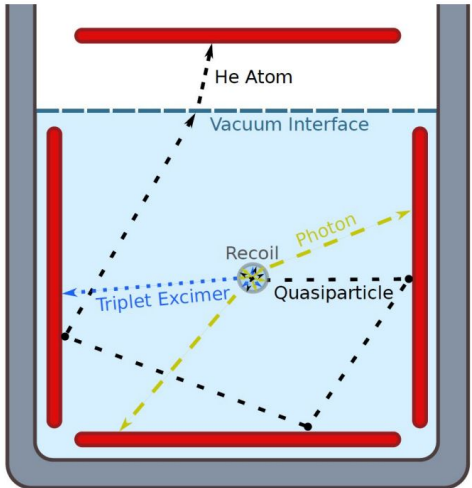
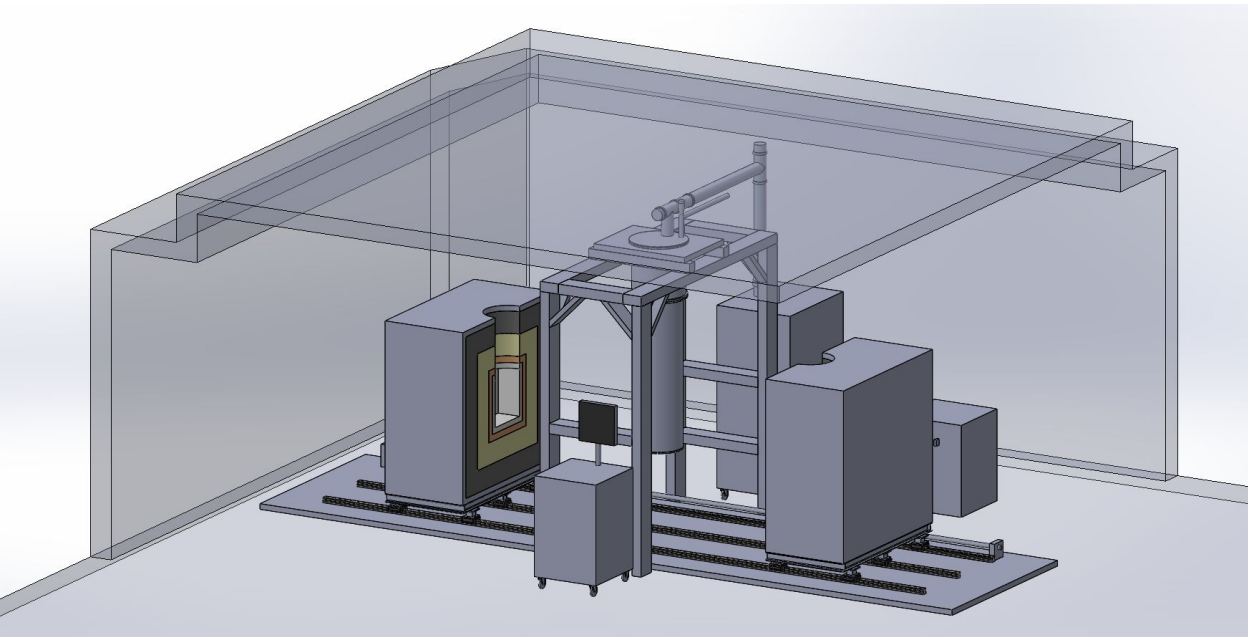


- Heart of the experiment is a **dilution fridge (DR) in a multilayer shielding**
 - Swappable payload
 - SPICE (polar crystals) & HeRALD (superfluid helium)
- Shielding design has converged on a **compact lead/polyethylene approach with TI cryostat**

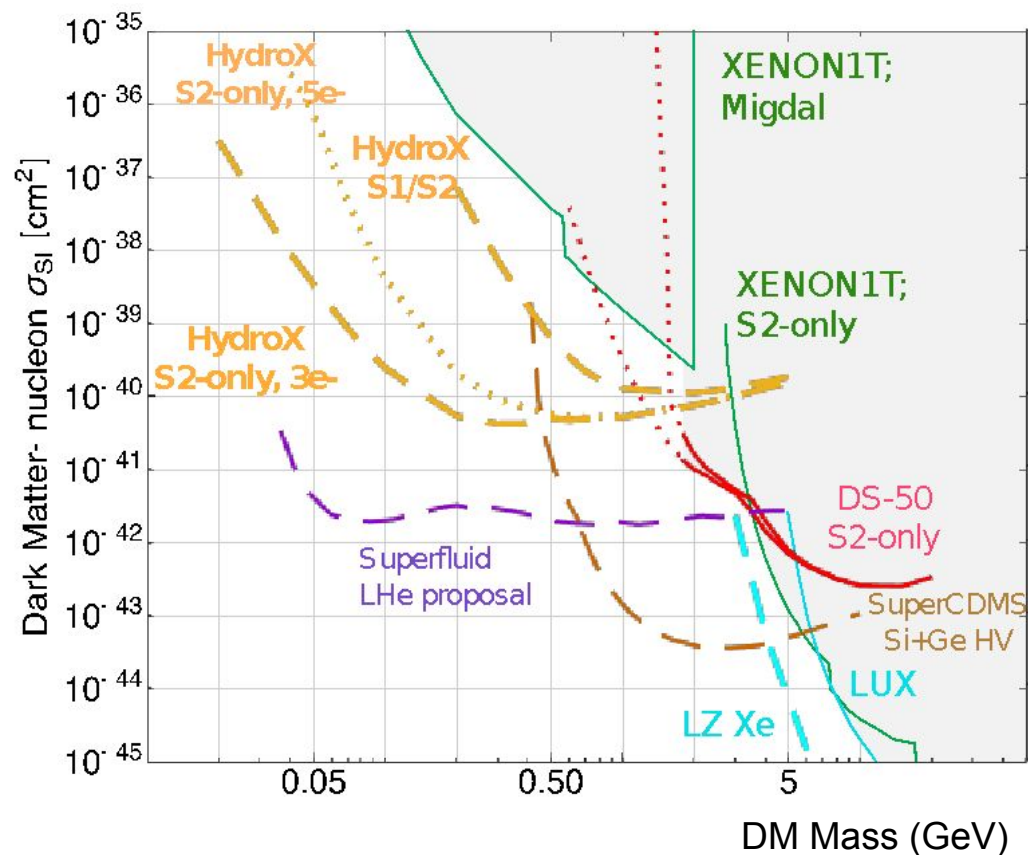
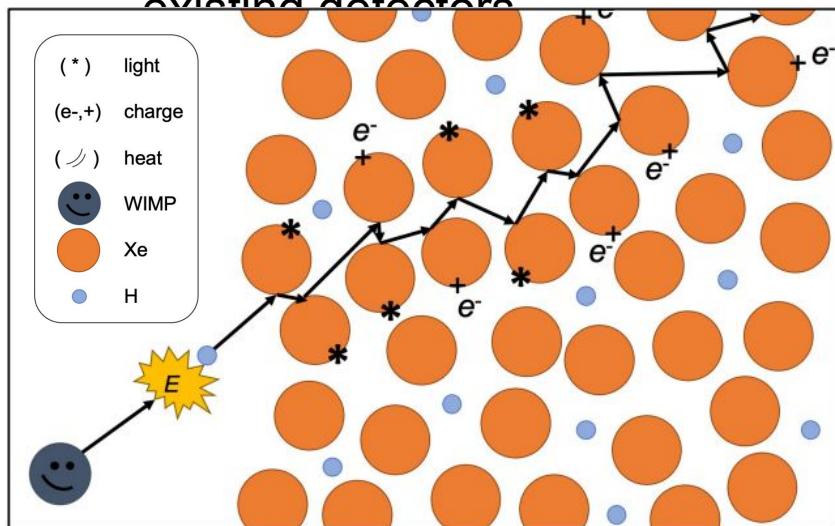


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 - Swappable payload
 - SPICE (polar crystals) & HeRALD (superfluid **helium**)
- Shielding design has converged on a **compact lead/polyethylene approach with TI cryostat**

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**



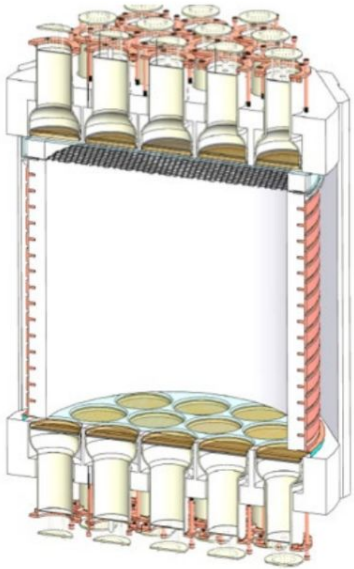
Credit: A. Monte, H. Lippincott

- **DM is out there** and will transform our understanding of the Universe
- WIMP's remain 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

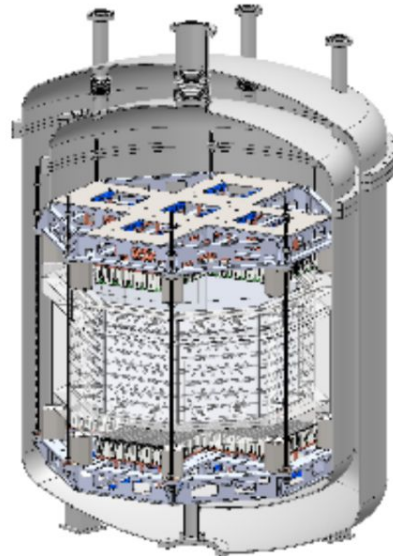


Backup

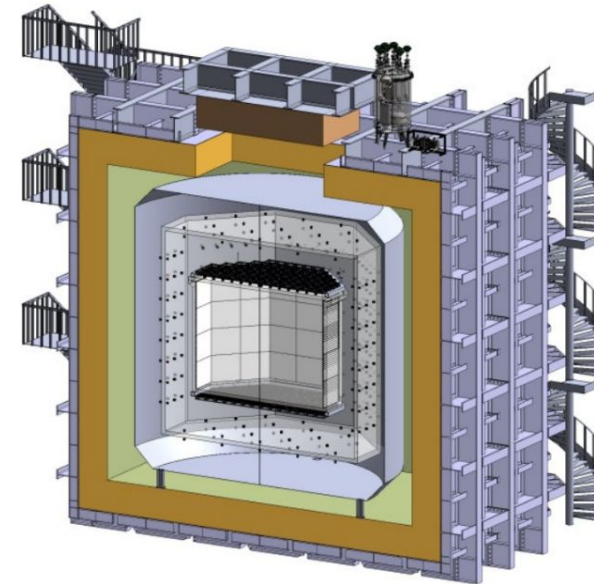
- DarkSide: Multi-stage DM program searching using LAr TPCs at Gran Sasso



DS-50
50Kg LAr

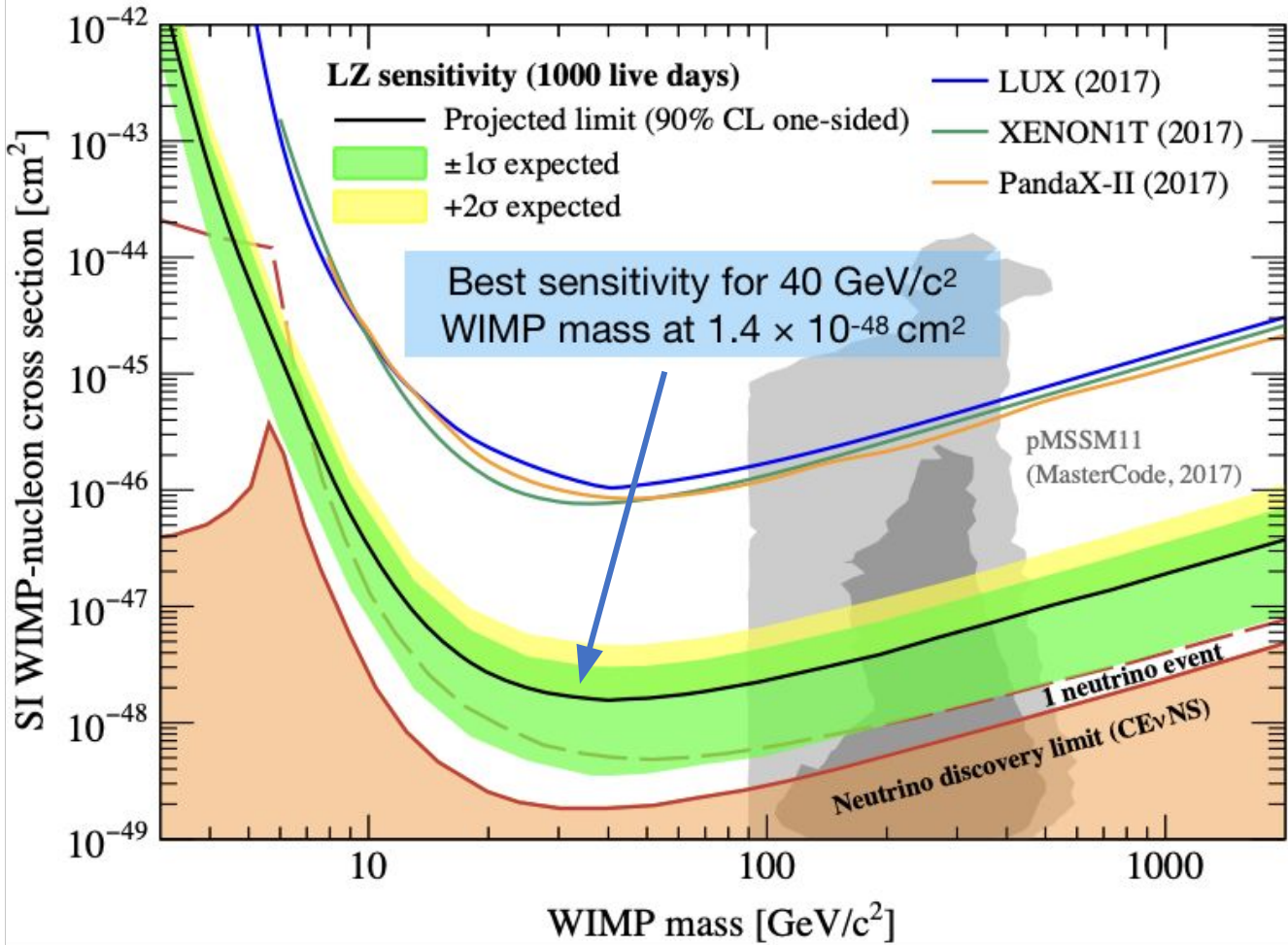


DS-Proto-1t
175Kg LAr



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)



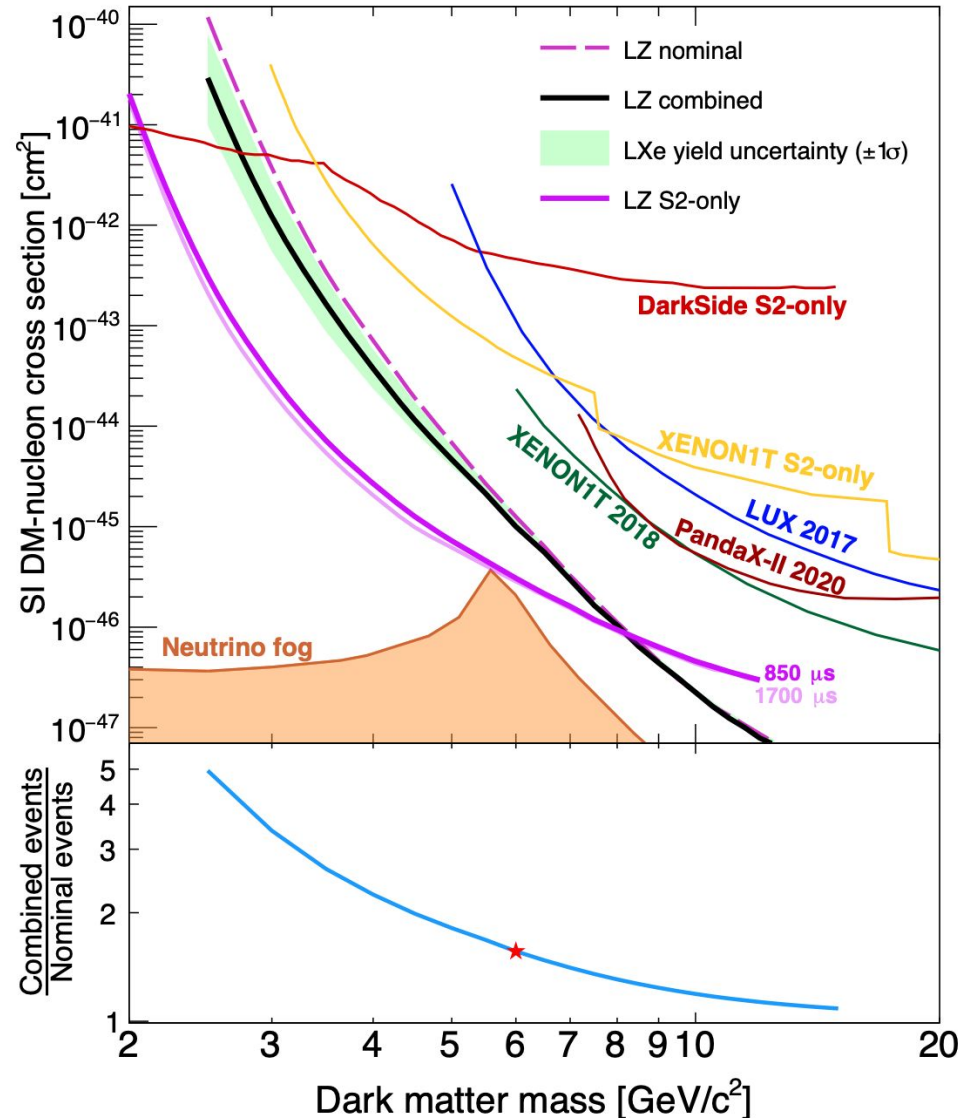
Source	ER [cts]	NR [cts]
Total	1131	1.03
99.5% ER discr., 50% NR eff.	5.66	0.52

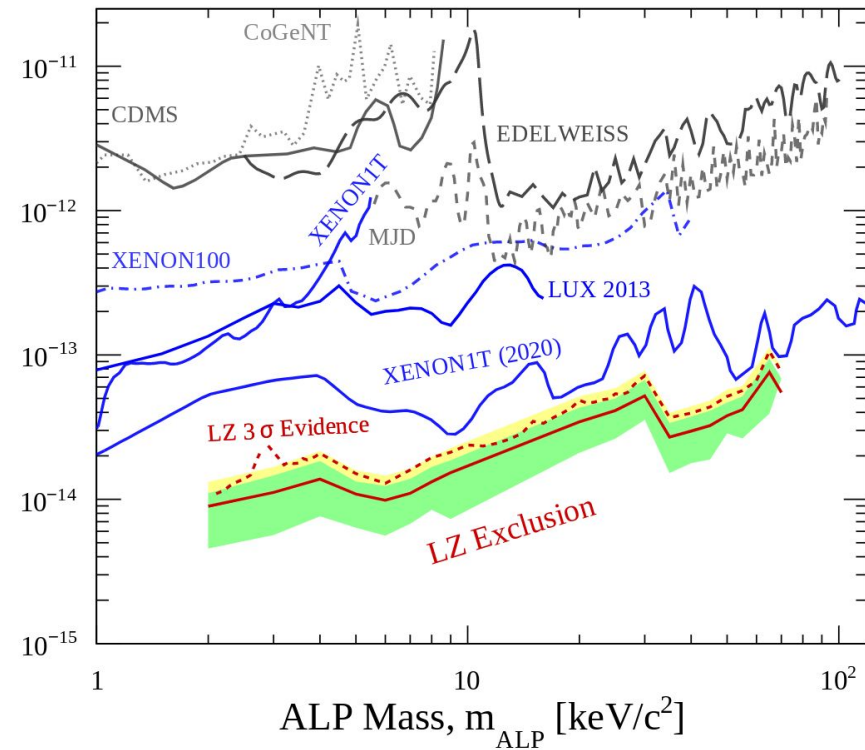
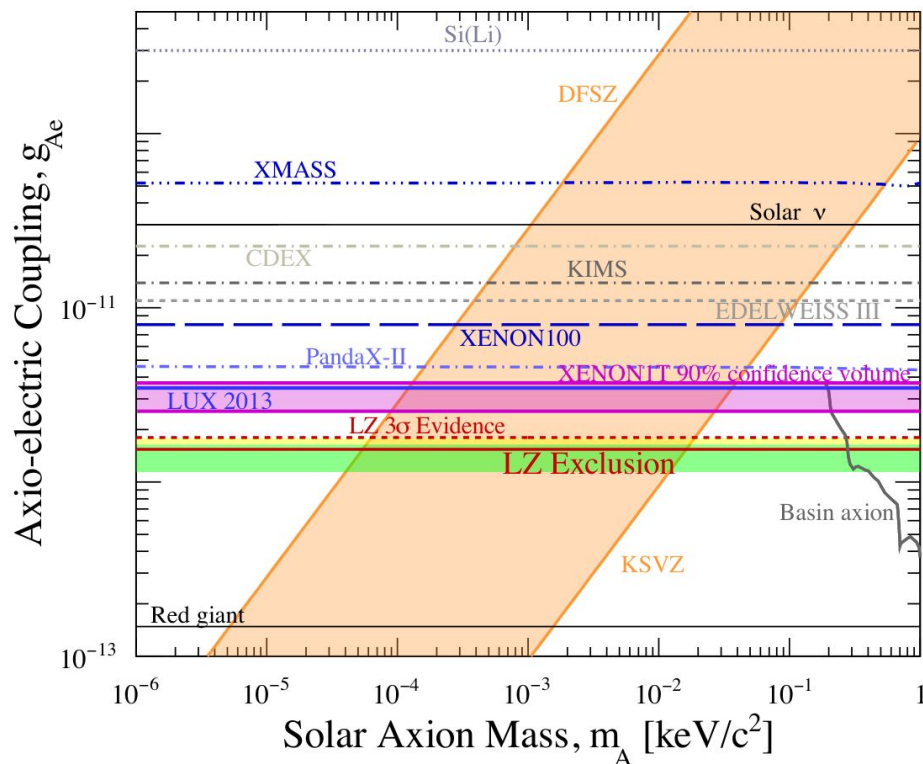
Radon comprises almost half our expected backgrounds

- Non-vetoed single scatters of $1.5-6.5 \text{ keV}_{ee}$ ($6-30 \text{ keV}_{nr}$) in 5.6 t fiducial volume: 6.18 background counts after 1000 live days



- Lower the energy threshold
 - Reduce S1 coincidence requirement from 3 to 2 (exploiting PMT double photoelectric effect)
 - About 4 x improvement at $2.5 \text{ GeV}/c^2$
 - 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

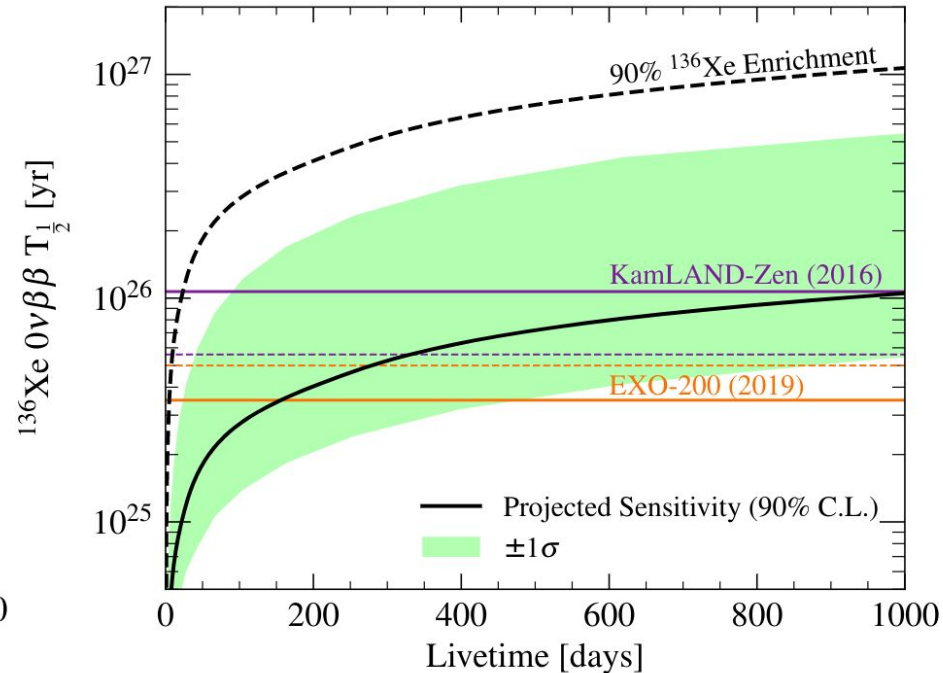
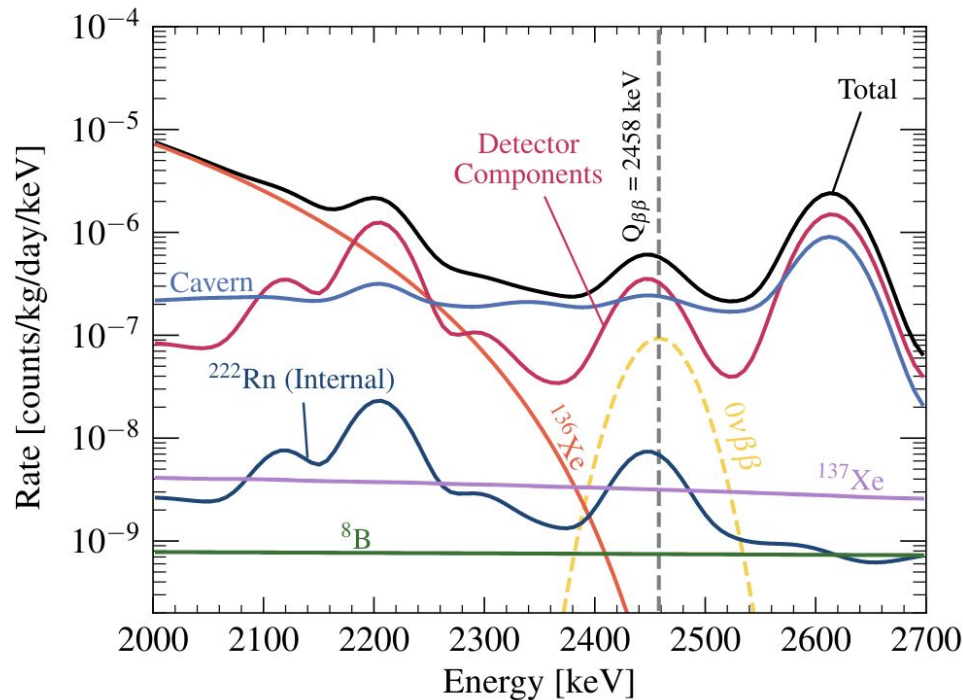




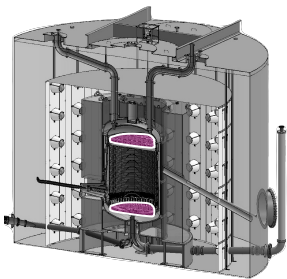
- Explore range of novel model accessible via pure electron recoils
- Backgrounds dominated by ^{222}Rn and ^{124}Xe $\nu\nu\beta\beta$
- Studies seven model, among others: Solar axions, axion-like dark matter, neutrino magnetic moment etc
- In all LZ is able to reach world leading sensitivities



[Phys. Rev. C 102, 014602 \(2020\)](#)

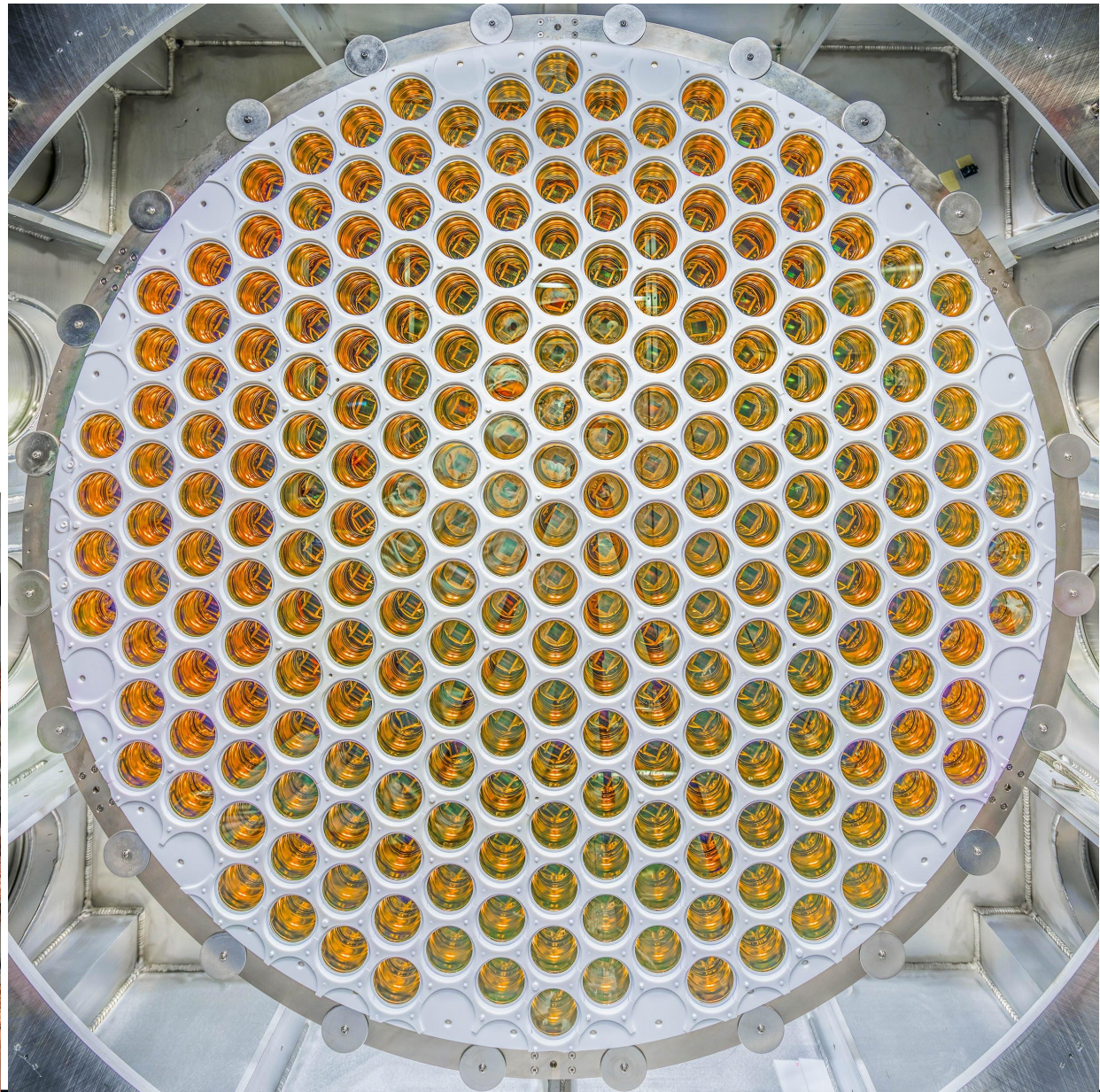


- Neutrinoless $0\nu\beta\beta$ only allowed if Neutrino is its own anti-particle (Majorana)
- Nominal 1% energy resolution at $^{136}\text{Xe } Q_{\beta\beta}$ value (2458 keV)
- $T_{1/2}$ (90% C.L.) $> 1 \times 10^{26}$ years in 1000 live days in 1 t fiducial volume

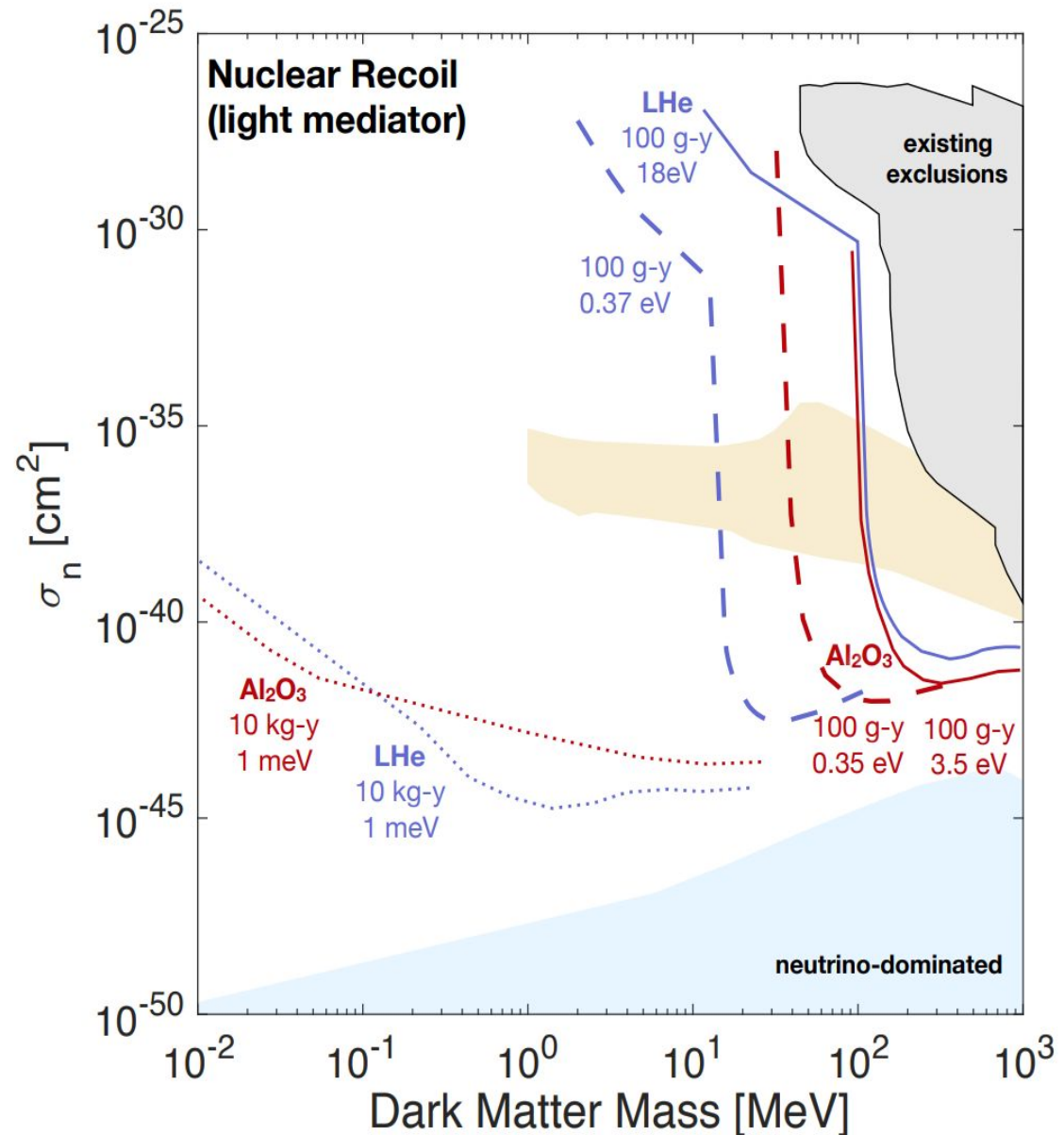


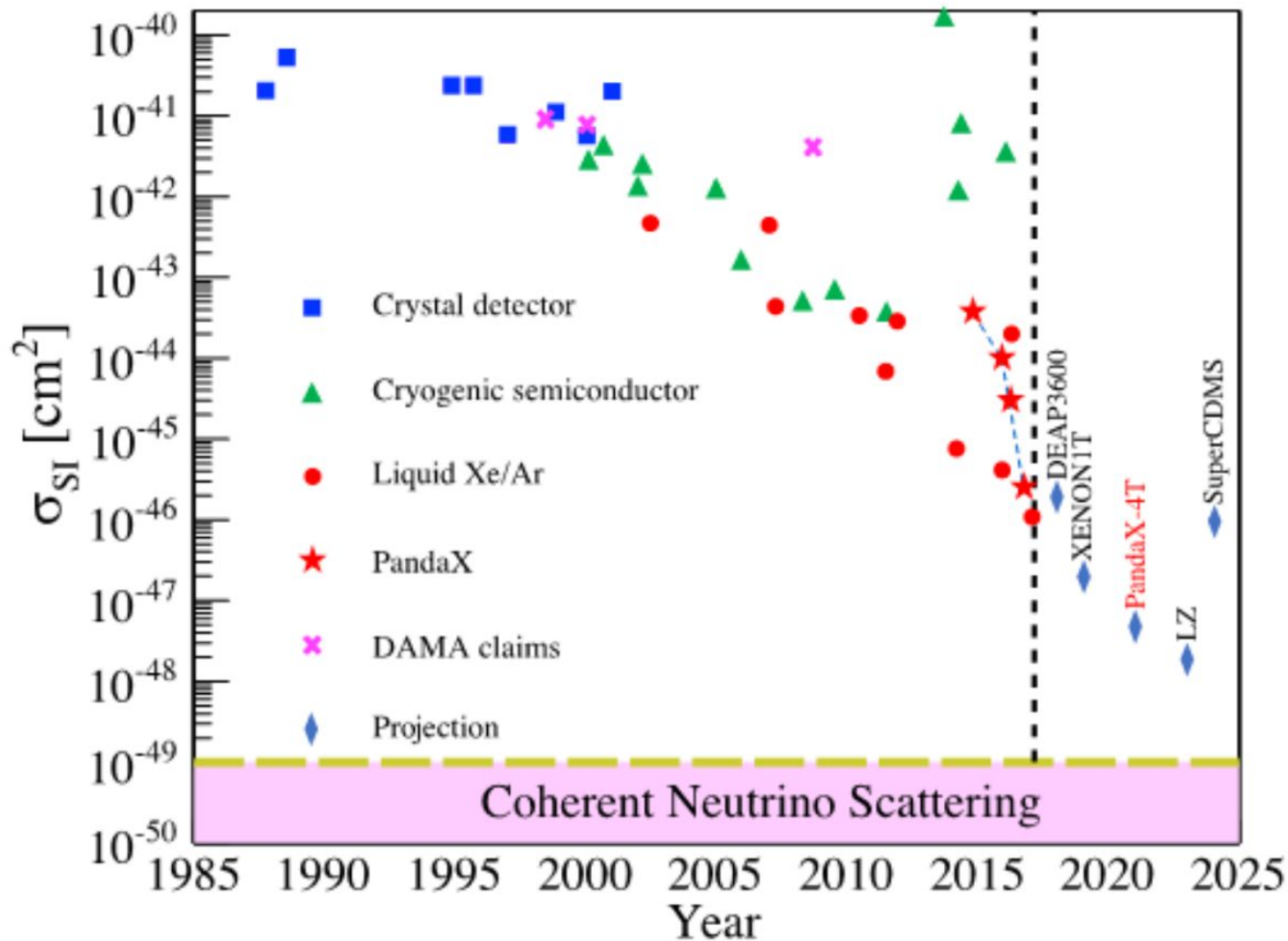
- **625 PMTs:**

- 253 x 3" top array
- 241 x 3" bottom array
- 93 x 1" and 38 x 2" skin



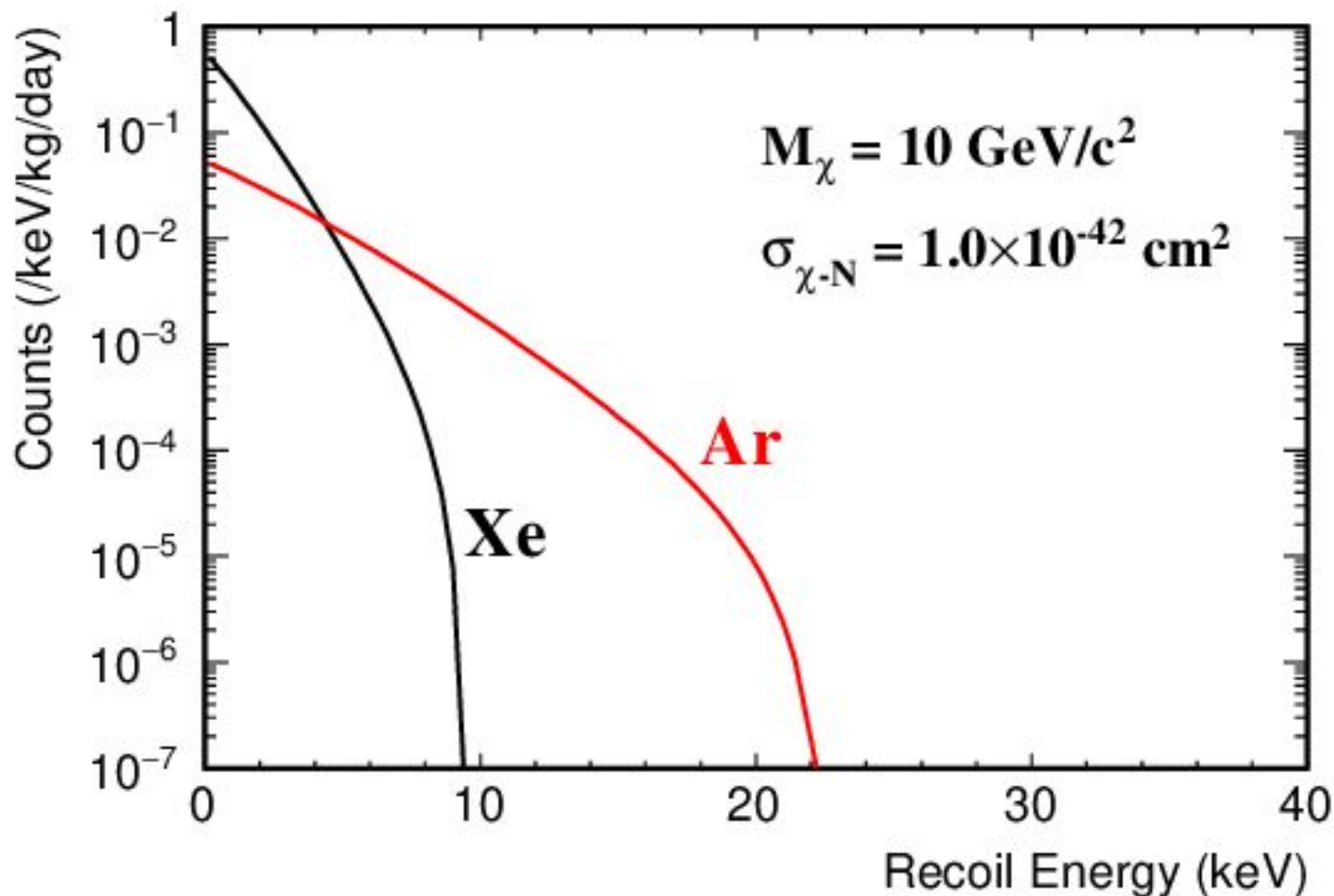
- Already producing **first papers**
- More projections [here](#)
- Expecting new DM limits from demonstrator setups soon



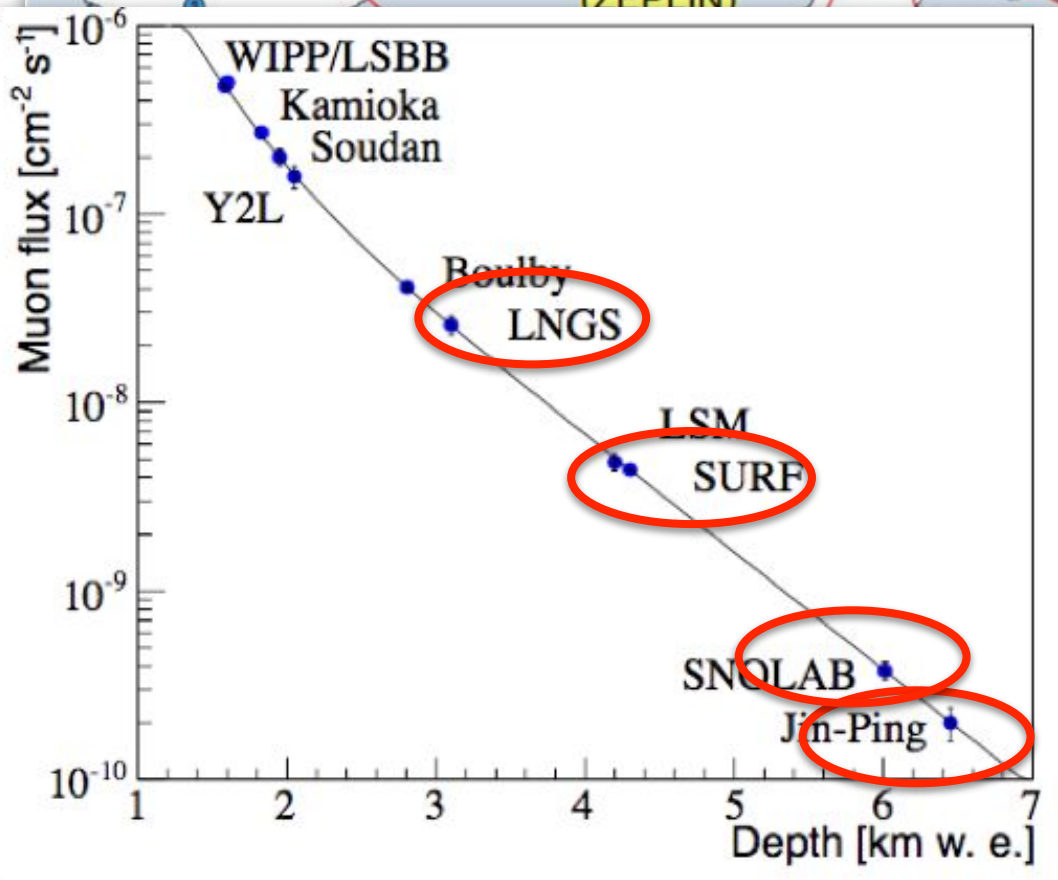
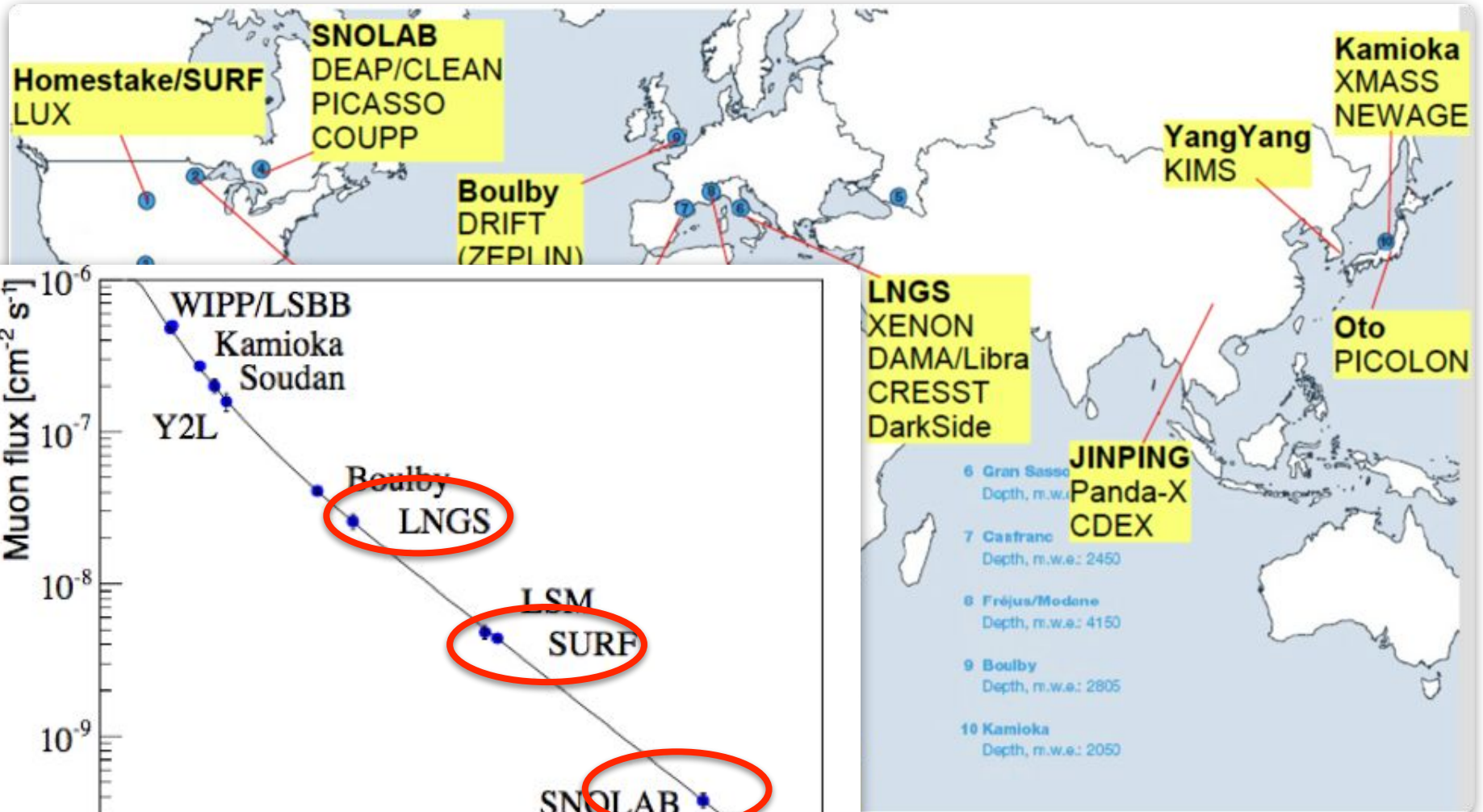


<https://arxiv.org/abs/1806.02229>

<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



- 6 Gran Sasso
Depth, m.w.e.: 2450
- 7 Castrane
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

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

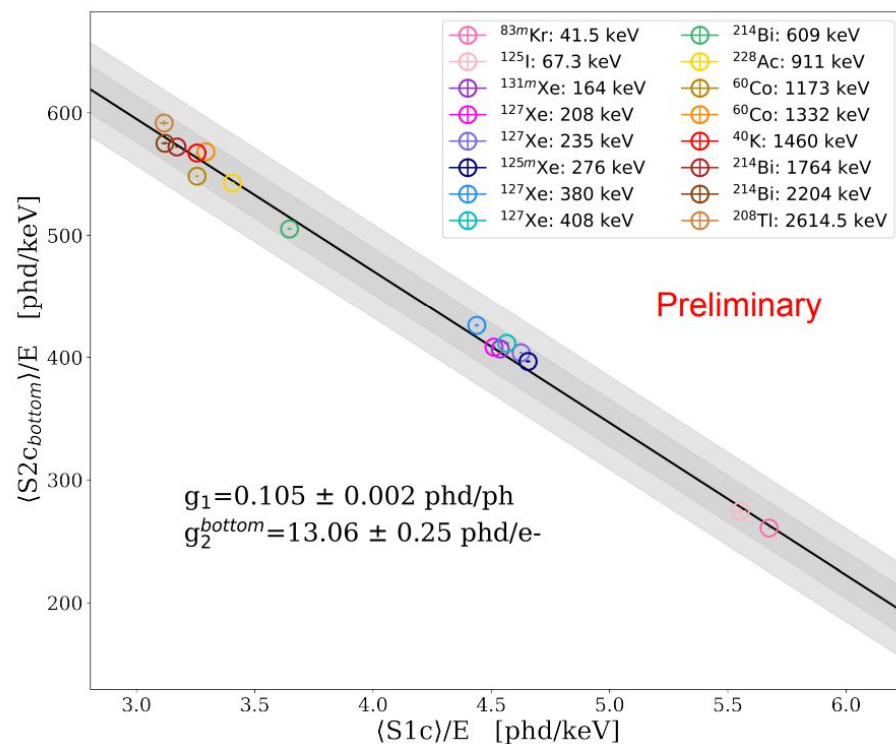
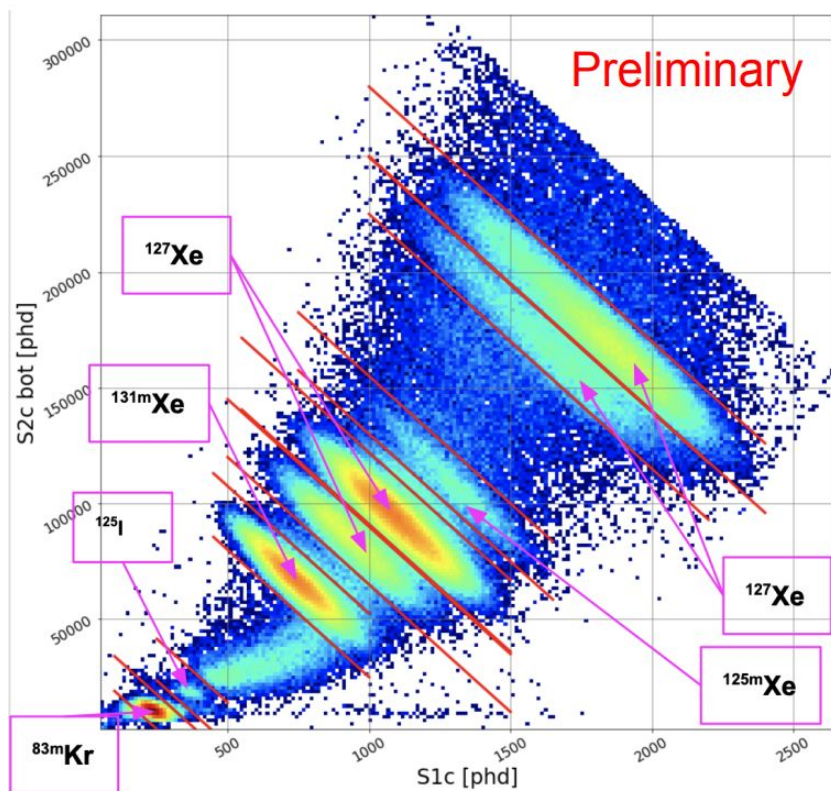
$$\sigma_{\text{SI}} = \sigma_n \frac{\mu^2}{\mu_n^2} \frac{(f_p Z + f_n (A - Z))^2}{f_n^2} = \sigma_n \frac{\mu^2}{\mu_n^2} A^2$$

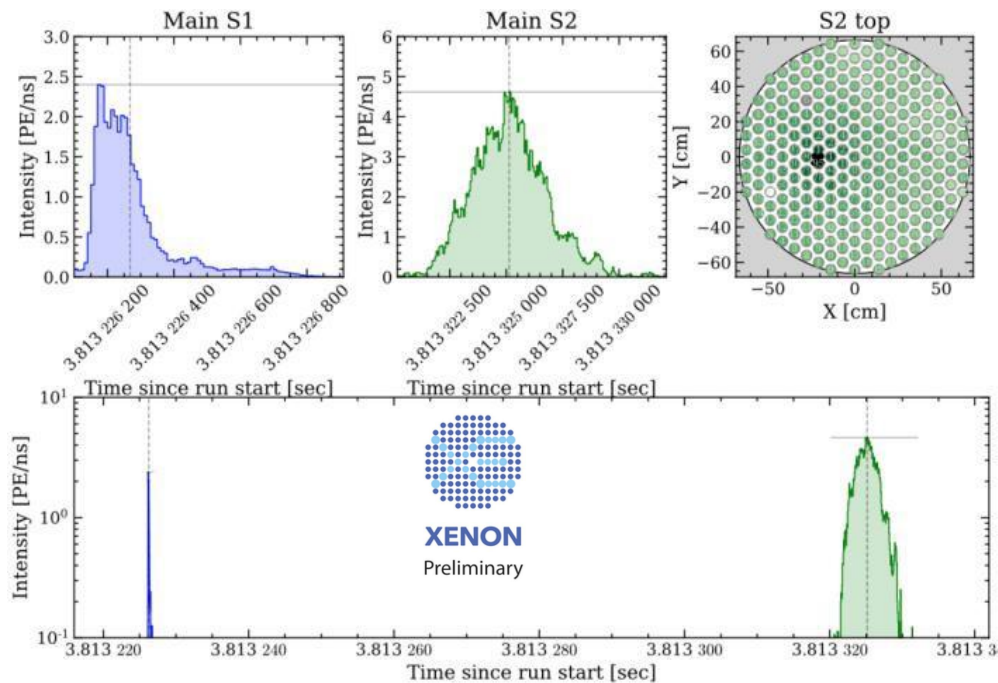
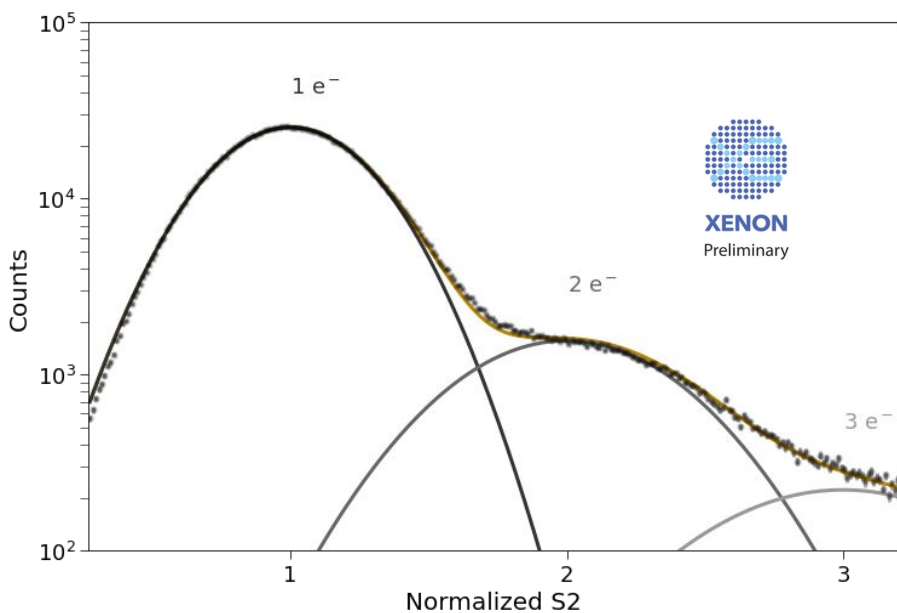
- Spin-dependent (SD), **axial-vector** particles
 - Favors targets with odd number of protons or neutrons (e.g. ${}^7\text{Li}$, ${}^{131}\text{Xe}$ respectively)

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

- Mono-energetic ER peaks used to find:
 - g_1 , photons detected (phd) per prompt scintillation photon
 - g_2 , phd per ionisation electron

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





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

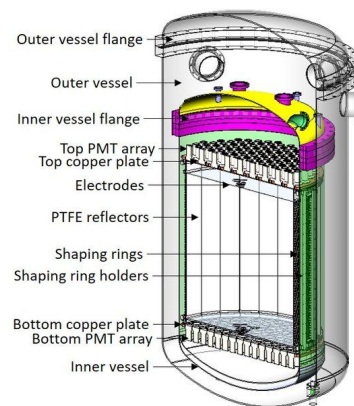
PandaX = Particle and Astrophysical Xenon Experiments



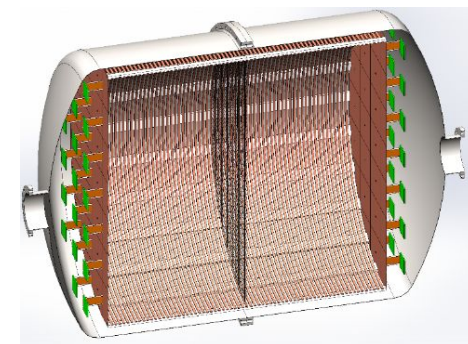
Phase I:
120 kg DM
2009-2014



Phase II:
500 kg DM
2014-2017



PandaX-4T:
multi-ton DM
2020-



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