Direct Search Experiments For Weak Scale Dark Matter

Numerous experiments, my apologies as I can't highlight them all …

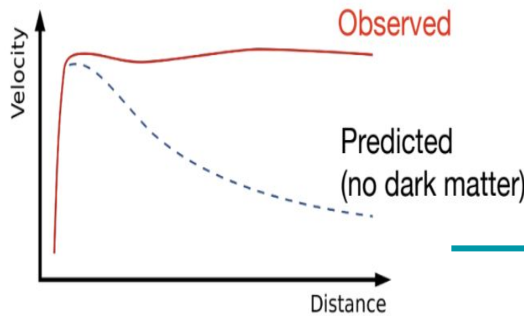
Alvine Kamaha
University of California, Los Angeles (UCLA)

Dark Interactions 2024, Vancouver, October 16-18, 2024

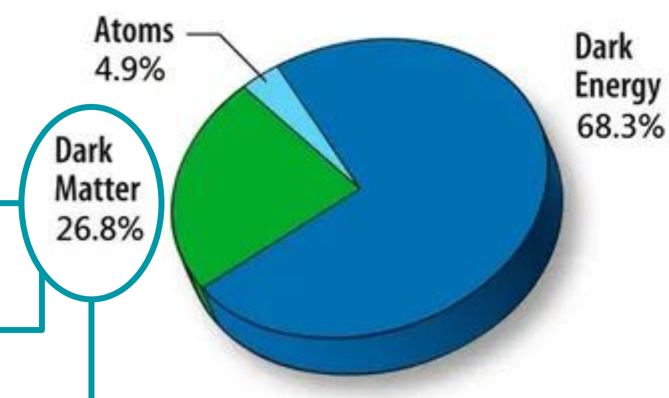
Dark Interactions 2024
Vancouver, Oct. 16-18

Multiple Lines of Evidence for Dark Matter

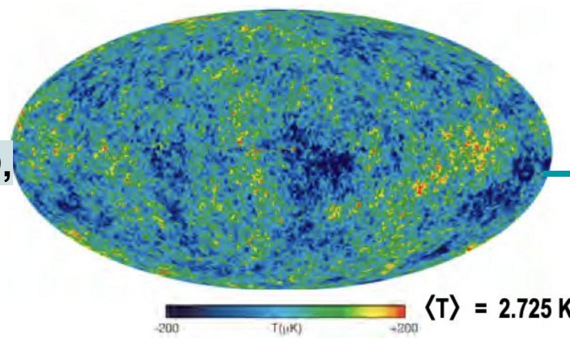
Motion of galaxies and galaxy clusters



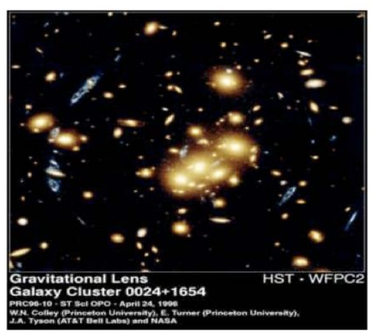
Mass-Energy distribution of the Universe

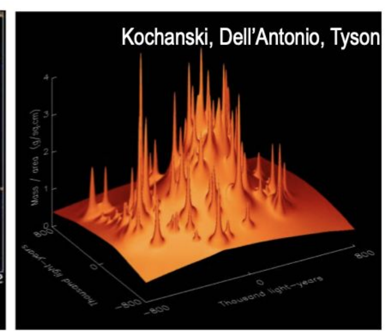


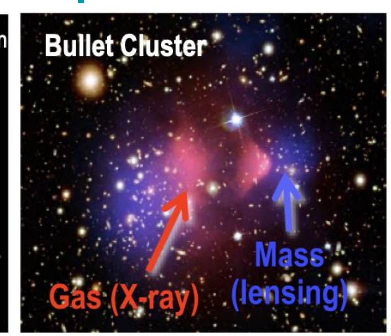
Cosmological Evidence (CMB, BAO, Supernovae...)



Gravitational Lensing (Weak/Strong)

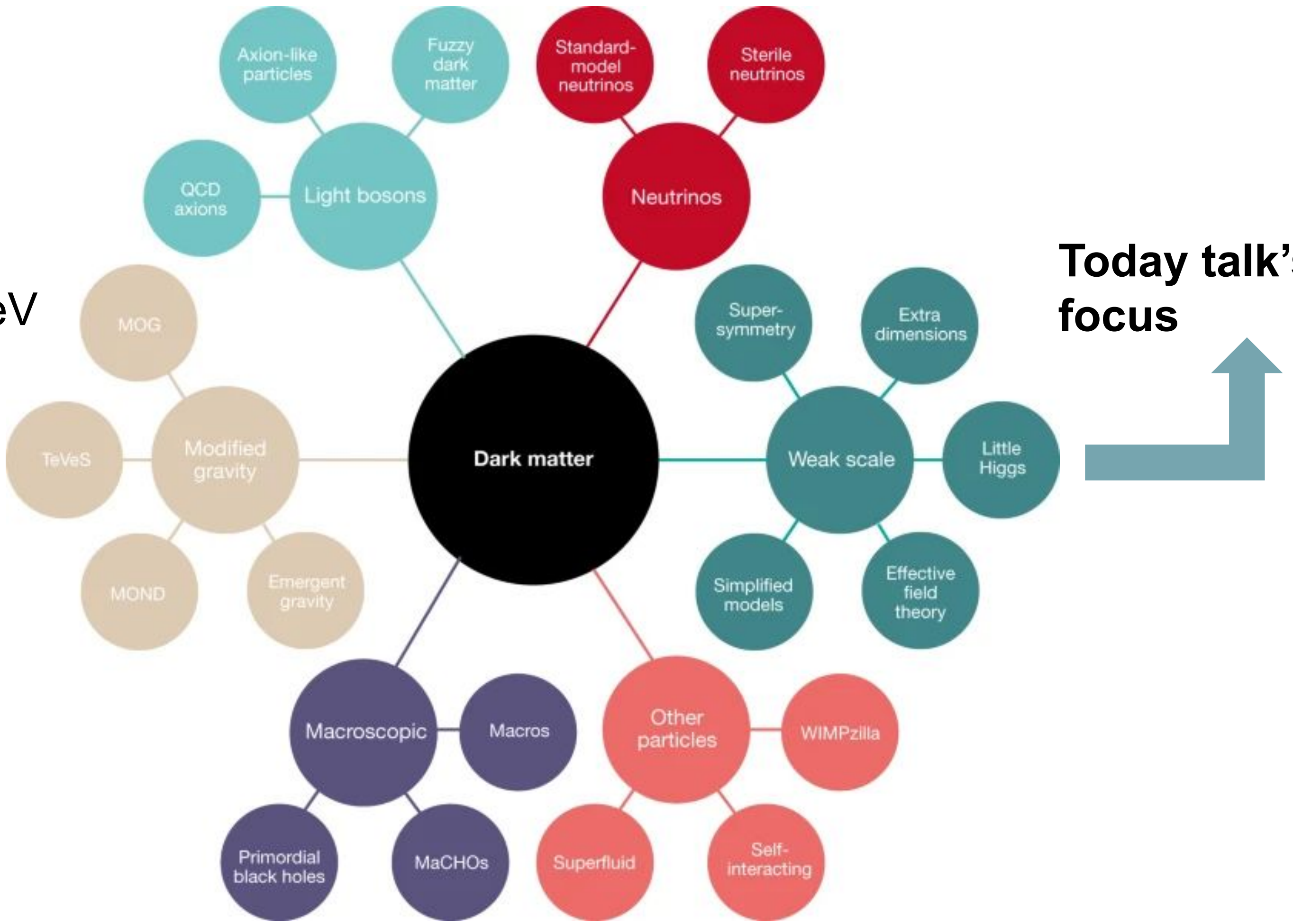






Numerous Dark Matter Candidates

Broad range of candidates from 10^{-22} eV - 10^{19} GeV [Nature.562, 51-56 (2018)]



Today talk's focus

Looking for non-luminous, non-baryonic, stable, and cold (non-relativistic) particles. Very broad landscape. **WIMPs ~(1-10,000 GeV)** are well motivated weak-scale candidates (right relic abundance …)

WIMP Direct Detection Principle

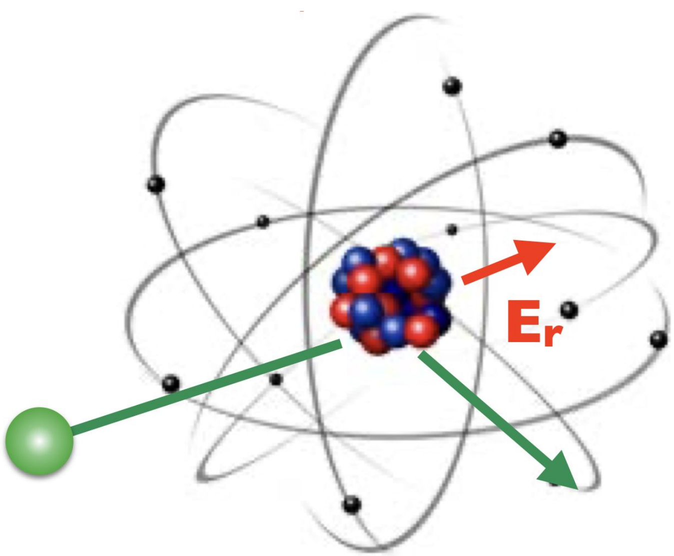
WIMPs scatter off nuclei

- Recoil energy <200 keV
- Event rate <1/100 kg/year

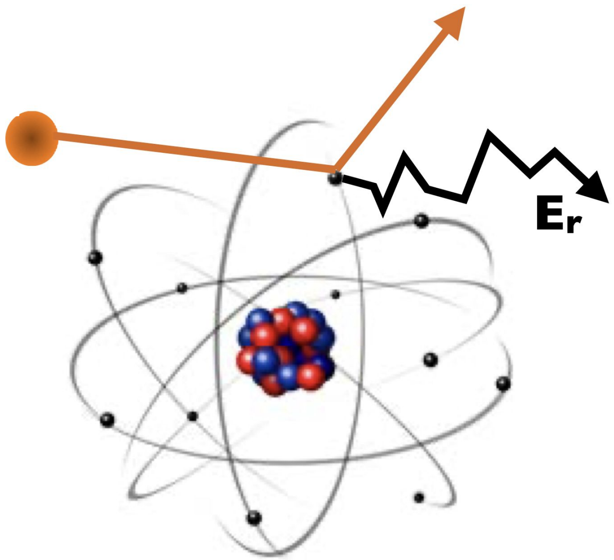
Requires both low-energy threshold & ultra-low background detectors ⇒challenging

Backgrounds

- Neutrons: scatter off nuclei
- Gammas and electrons: scatter off atomic electrons
- Neutrinos: scatter off nuclei (coherent elastic ν-N scattering) and also atomic electrons (ν-e)



Nuclear recoil

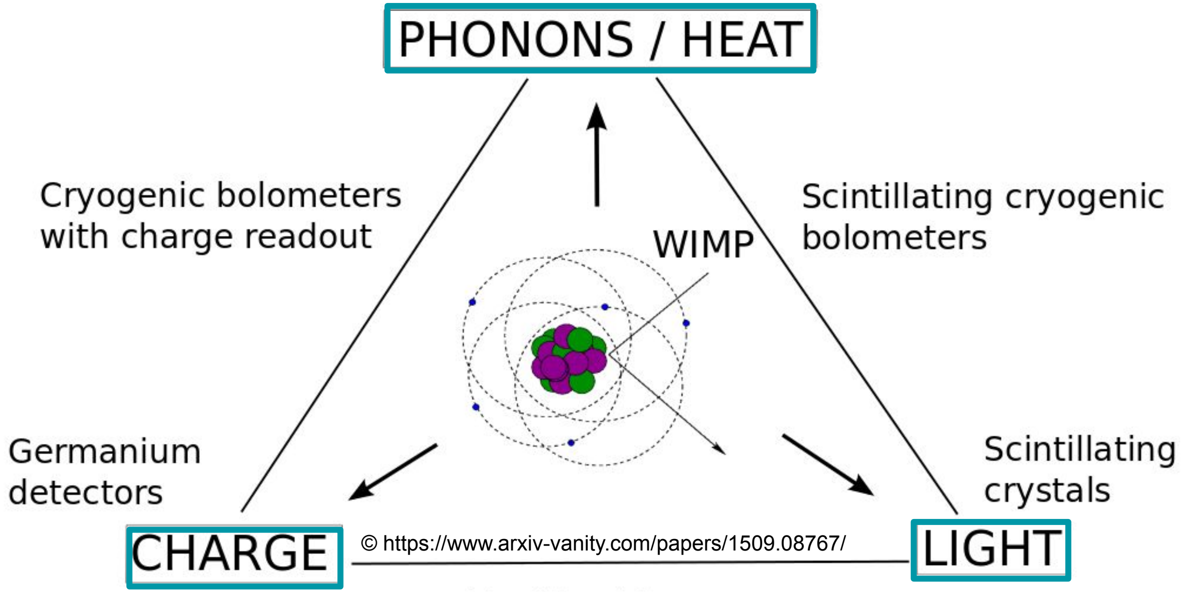


electron recoil

Direct Detection Technologies & Techniques

Rely on detecting signatures produced from energy deposited by recoiling nuclei

Background discrimination is crucial!



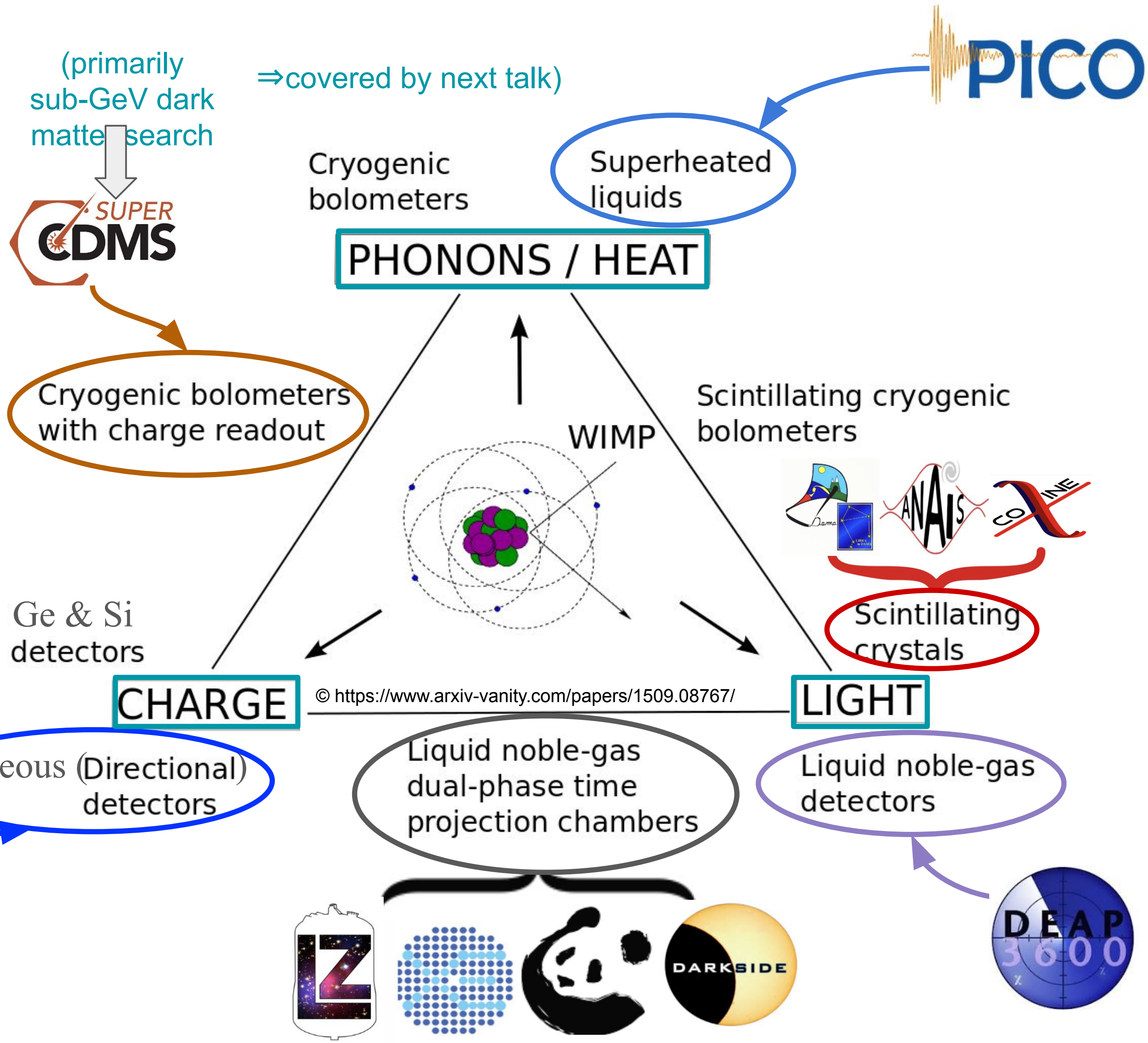
© https://www.arxiv-vanity.com/papers/1509.08767/

Direct Detection Technologies & Techniques

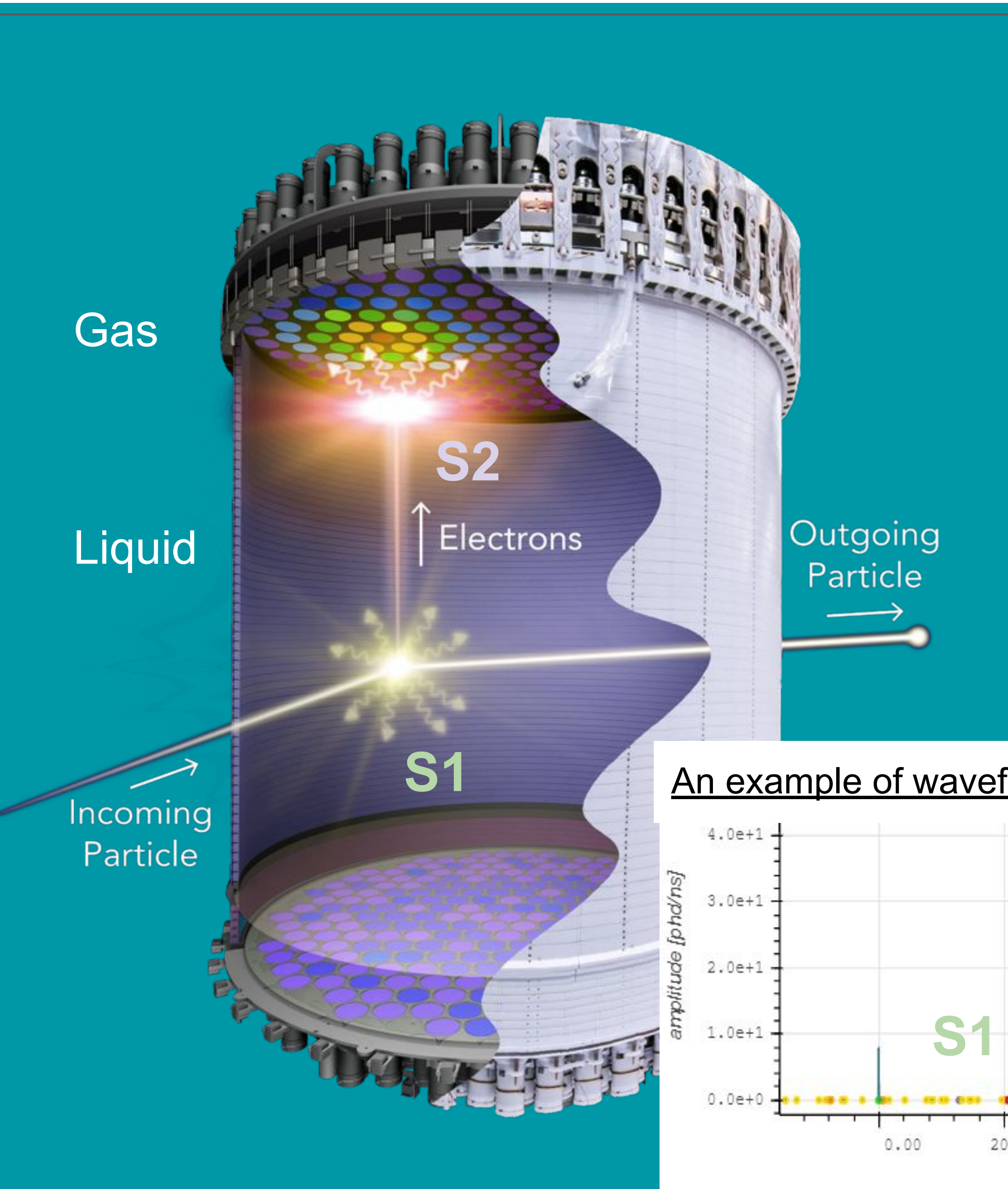
Rely on detecting signatures produced from energy deposited by recoiling nuclei

Background discrimination is crucial!

Only highlighting a few experiments...

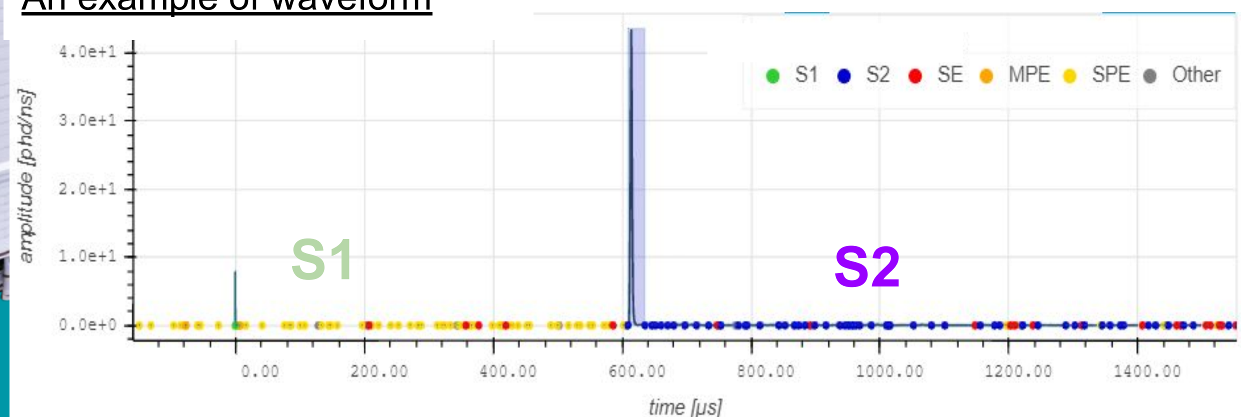


Dual-Phase Noble Liquid Time Projection Chamber (TPC)

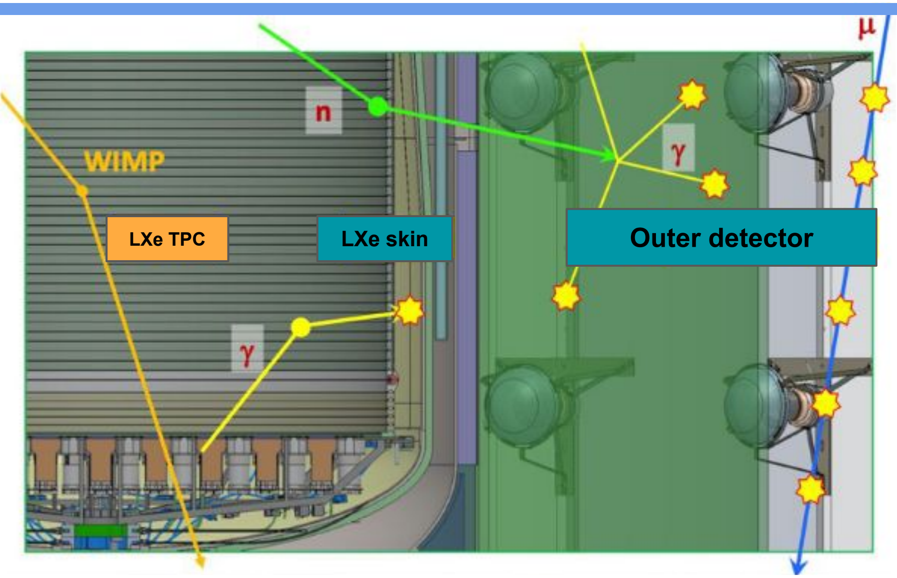


- PMTs record scintillation and charge (via electroluminescence) signals (S1 & S2)
  - Excellent 3D event reconstruction (position + energy)
  - S2/S1 ratio ⇒ signal (NR) to bckg (ER) discrimination

An example of waveform



Veto Detectors to enhance discovery Potential



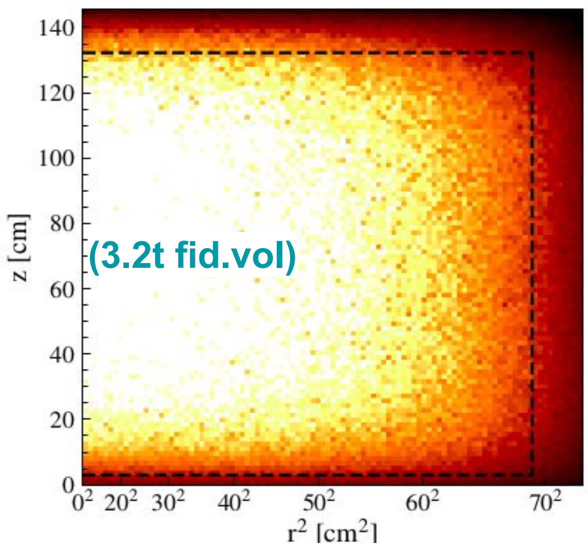
3 component systems: Xenon"skin", Water tank, GdLS

E.g. of LZ

Maximizes WIMP target mass (80% of active volume)

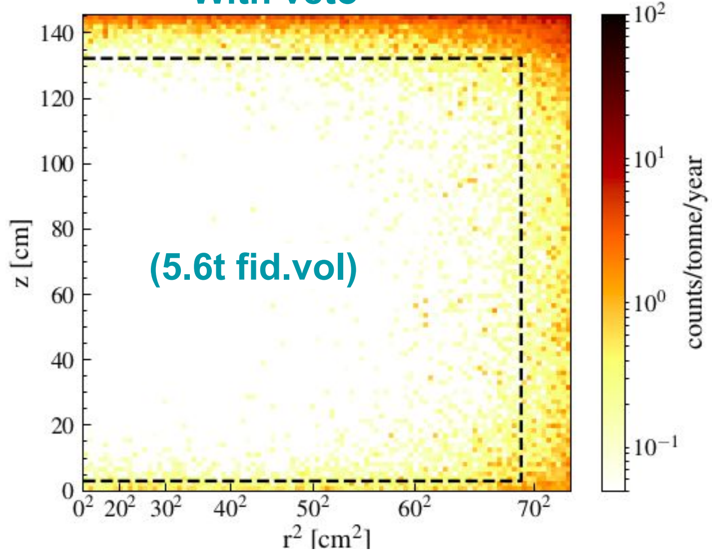
- Characterization, tagging and rejection of background (n,γ) events

Without veto



Impact of LZ vetoes [LZ projected WIMP Sensitivity: PRD.101.052002]

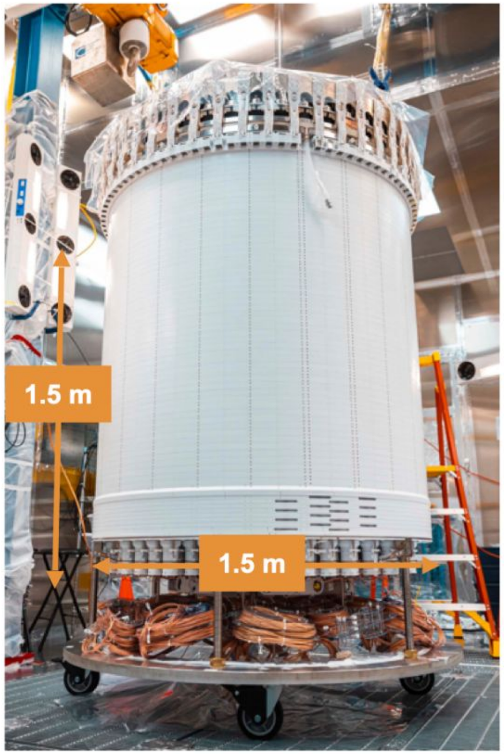
With veto



Distributions of single-scatter nuclear recoils in 40 GeV WIMP ROI (6-30 keV) for 1000 live-days

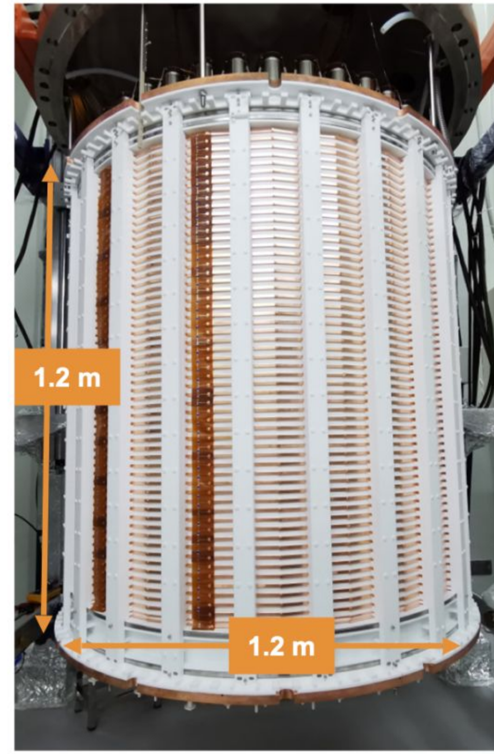
Current Xenon TPCs

LUX-ZEPLIN (LZ)



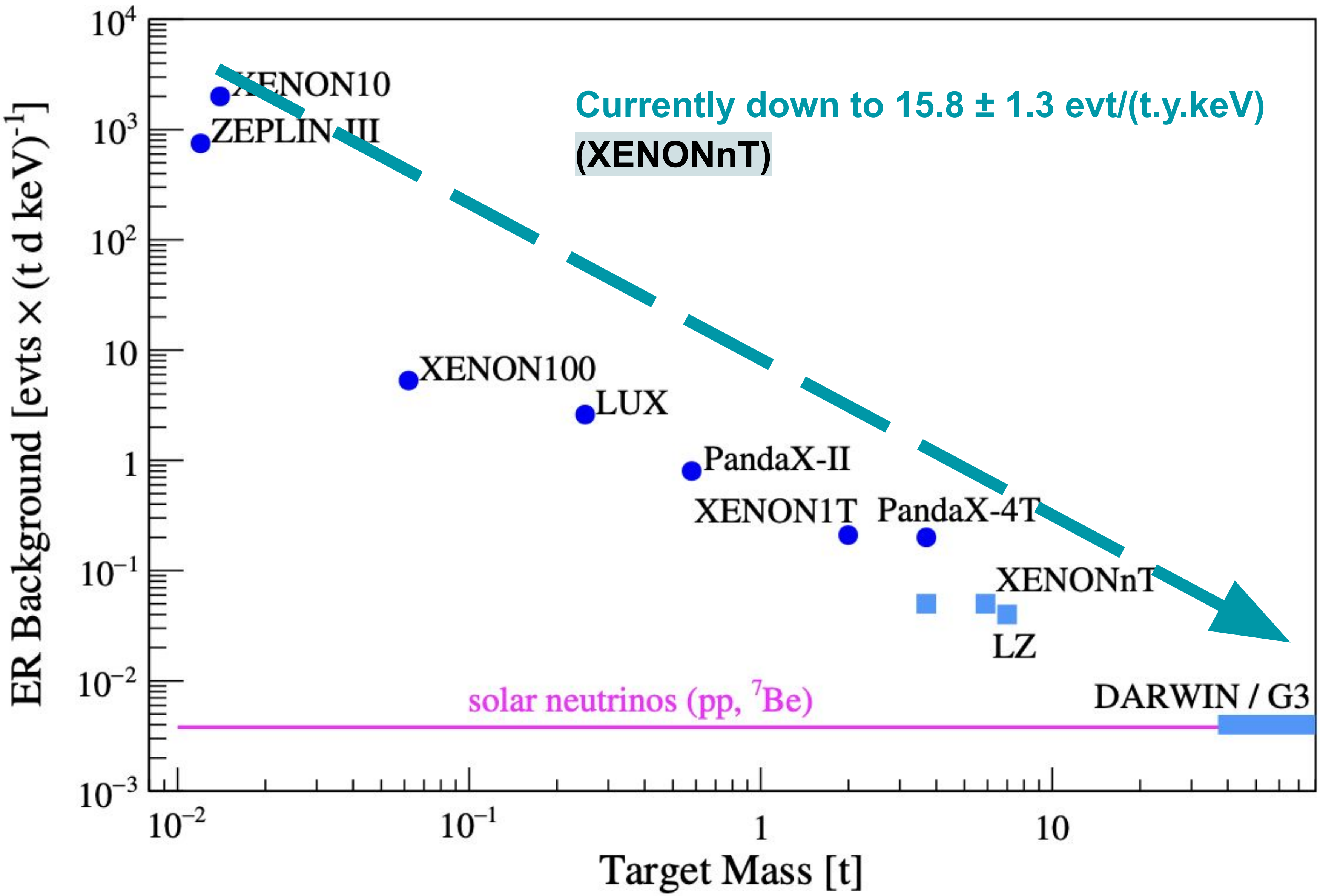
XENON

PandaX



Total (Active) mass	10 (7) tonnes	8.5 (5.9) tonnes	5.6 (3.7) tonnes
# PMTs (3-inch)	494	494	368
Drift field (SR1)	193 V/cm	23V/cm	93 V/cm
Operating T, P	Stable to sub-percent level over many years at about 175K and 2 bar(a)		

Significant Background Reduction Over the Years



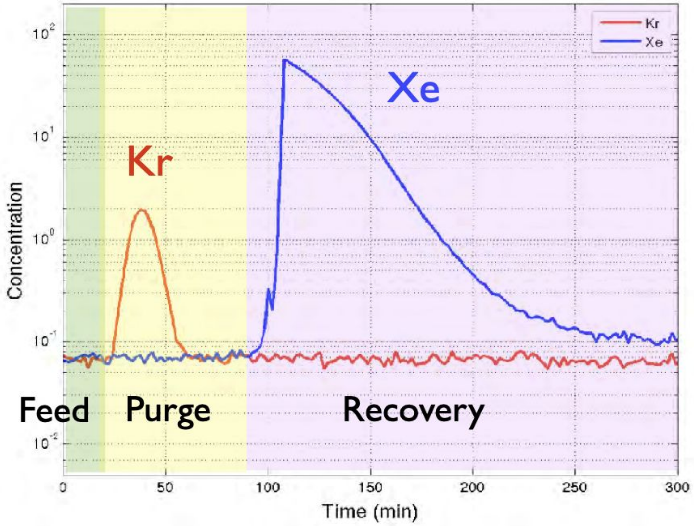
Xenon TPC Purification

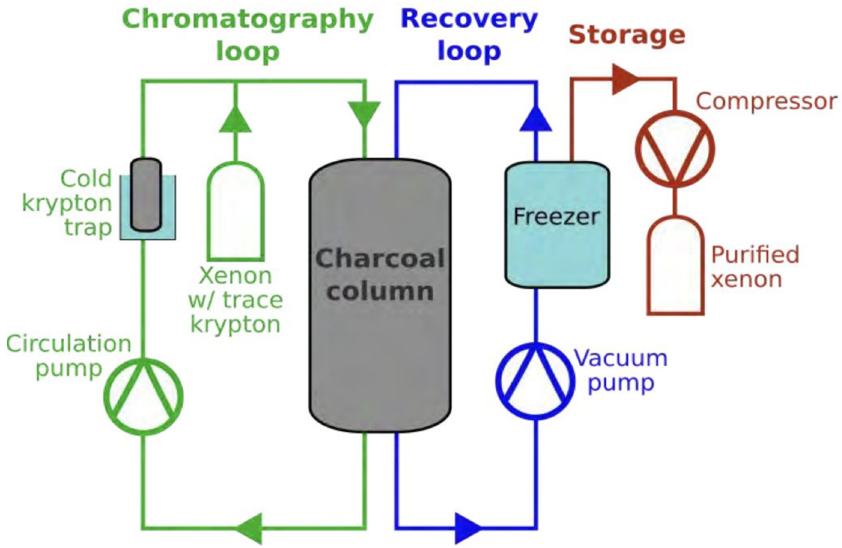
Removal of intrinsic noble gas contaminants (e.g. ^{85}Kr)

- ^{85}Kr originating from xenon extraction from air only needs to be removed once.
    - Kr-nat/Xe>1 ppb in commercial xenon with Kr-nat/Xe ~2*10^{-11}
    - Requirement: Kr-nat/Xe<0.2ppt

- **E.g.: LZ Kr Removal (Gas Chromatography)**
- Concentration reduced to Kr/Xe ~0.14ppt ⇒Naked β-decay ^{85}Kr no longer a limiting background

E.g. LZ Kr removal



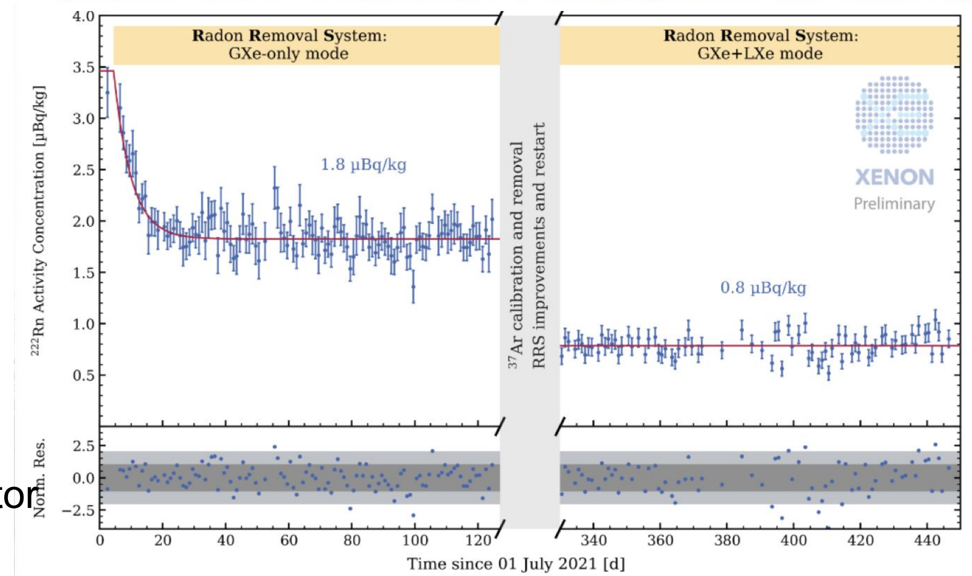


Xenon TPC Purification

Removal of intrinsic noble gas contaminants (e.g. ^{222}Rn)

- ^{222}Rn emanating from internal TPC surfaces are tackled in two ways:
  - Selecting best radio-pure materials via extensive material screening campaign is required [e.g Eur.Phys.J.C 80 (2020) 11, 1044]
  - Continuous "online" Rn removal by gas chromatography (LZ) or by cryogenic distillation (PandaX, XENONnT)

E.g. XENONnT Rn removal



XenonNT achieved 0.8uBq/Kg GXe+LXe mode

^{214}Pb (^{222}Rn daughter) currently the largest contributor

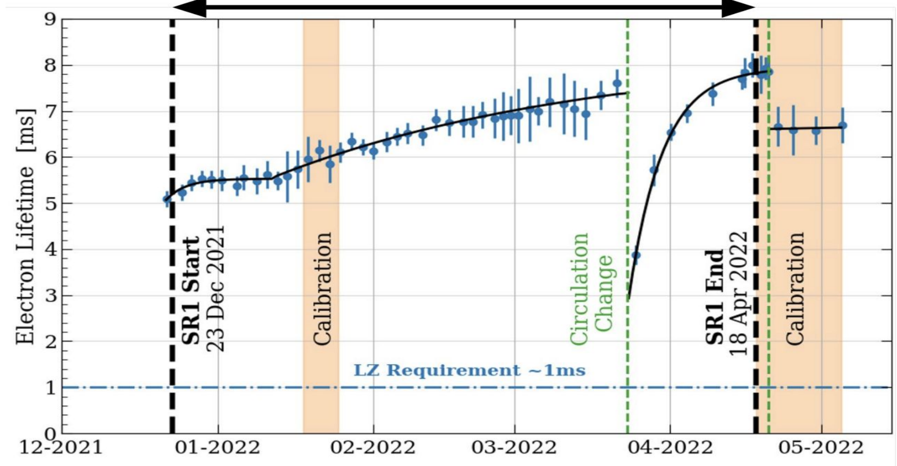
In LZ SR1: 3.26 ± 0.13(stat) ± 0.57(sys)

Xenon TPC Purification

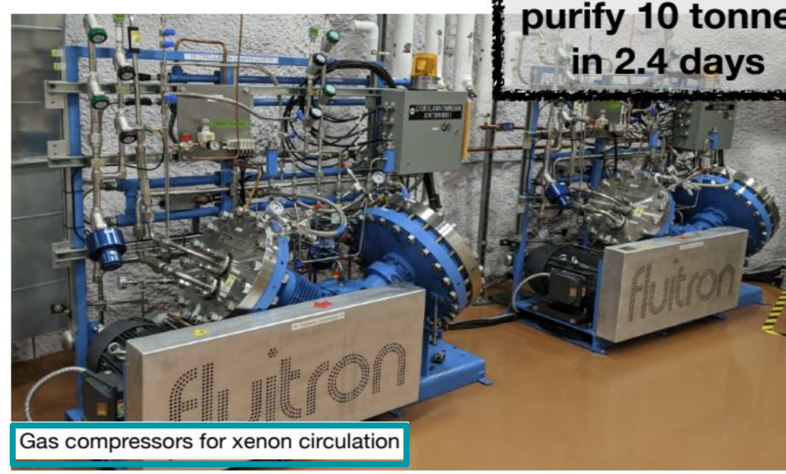
Removal of electro-negative Impurities (e.g O_2)

- Continuous purification in gas (LZ, PandaX) and/or in liquid (XENON)
  - LXe purity monitored by electron lifetime “the mean time a drifting electron can live before being trapped by electro-negative impurities”

Electron lifetime monitoring in LZ SR1: 5-8 ms



- **E.g. LZ Gas-phase purification:**
  - Uses hot SAES getter
  - 5000 SLPM flow rate ⇒ purify all xenon in ~2.4 days



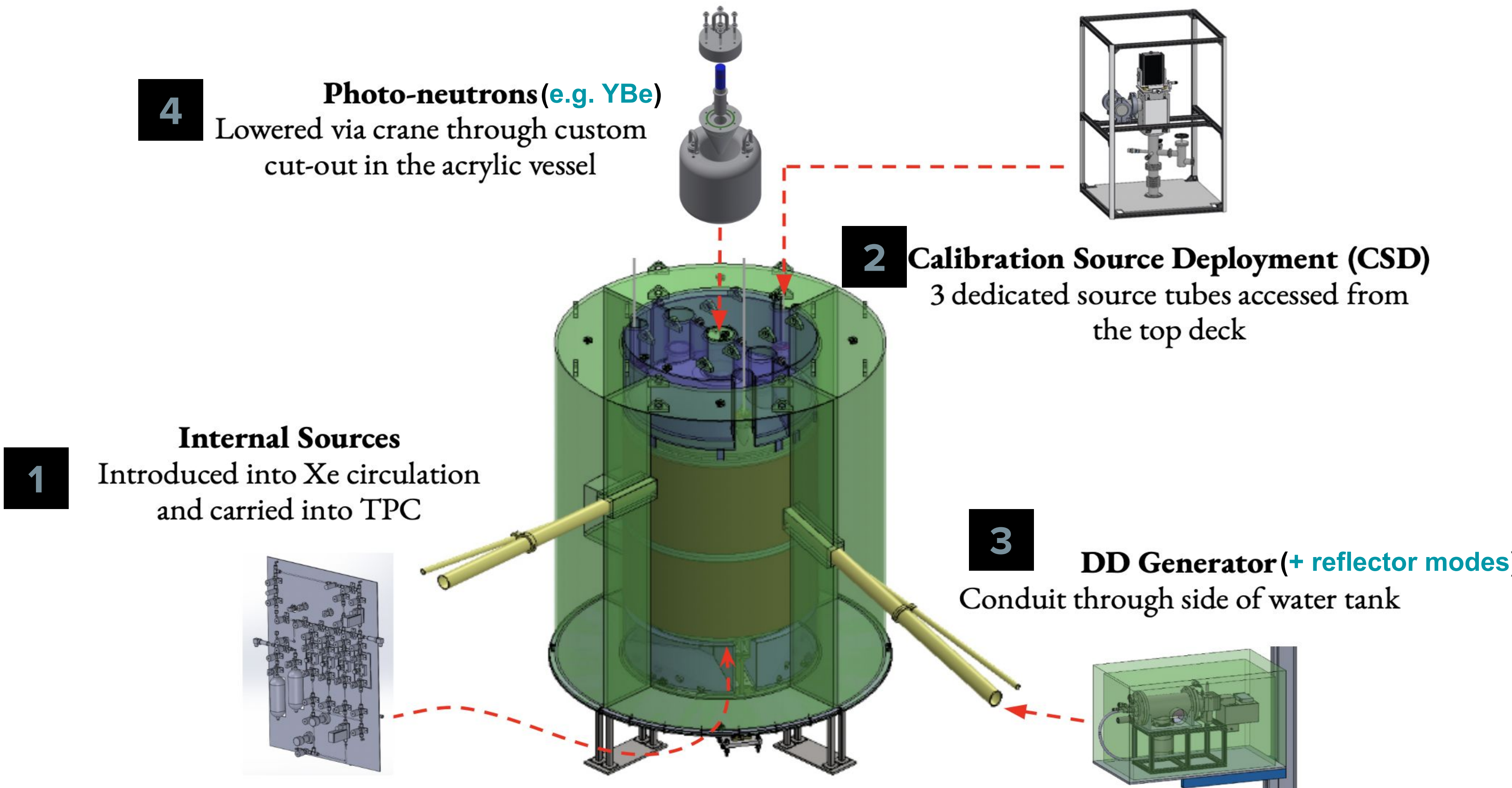
Gas compressors for xenon circulation

500 SLPM flow - purify 10 tonnes in 2.4 days

Xenon purification unit from SAES using hot zirconium getter

Xenon TPC Calibrations & Recent Development

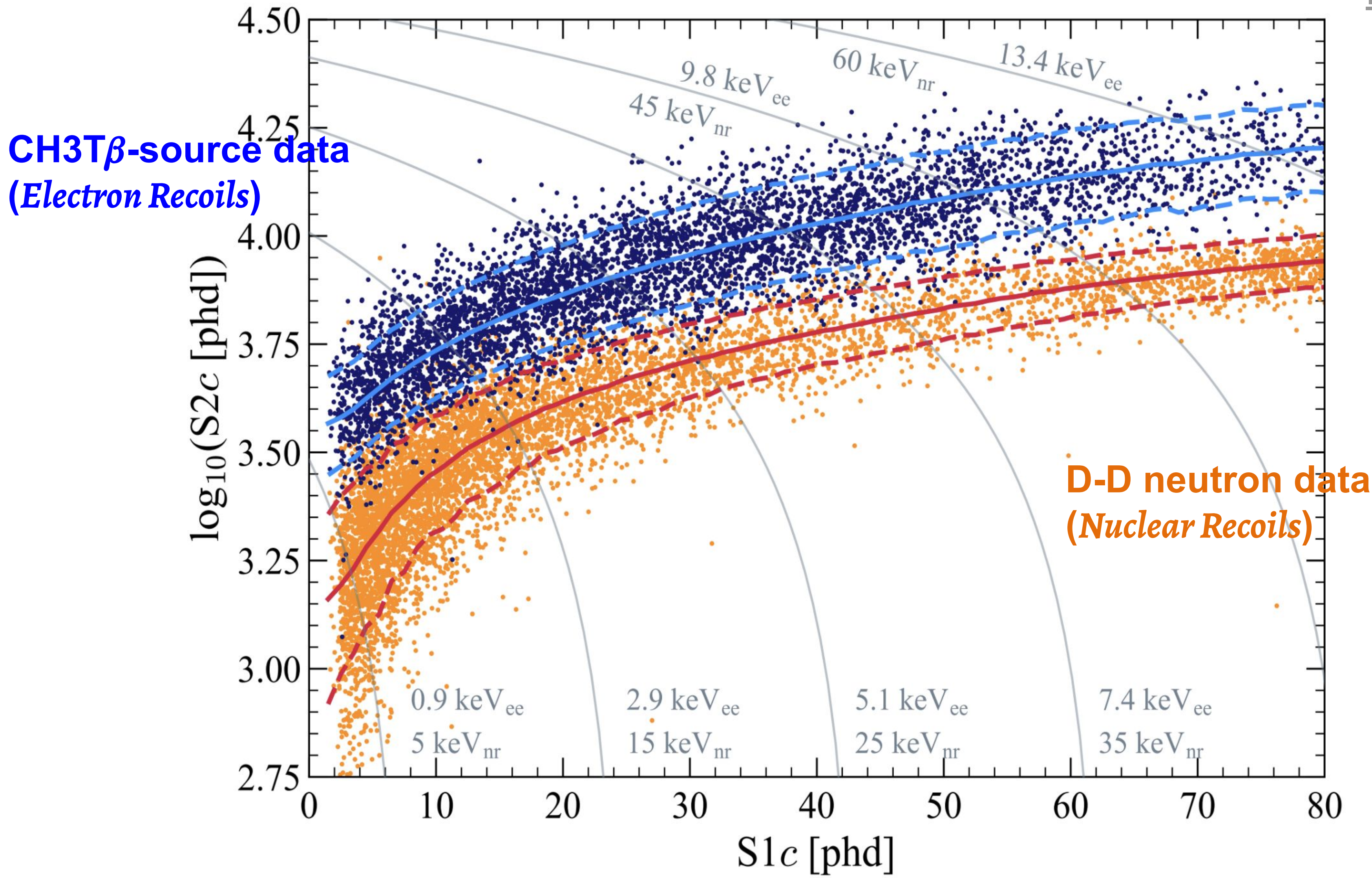
Calibrating these large LXeTPCs is a challenge ⇒ careful design and implementation of state-of-the-art calibration systems (**e.g. from LZ detector**)



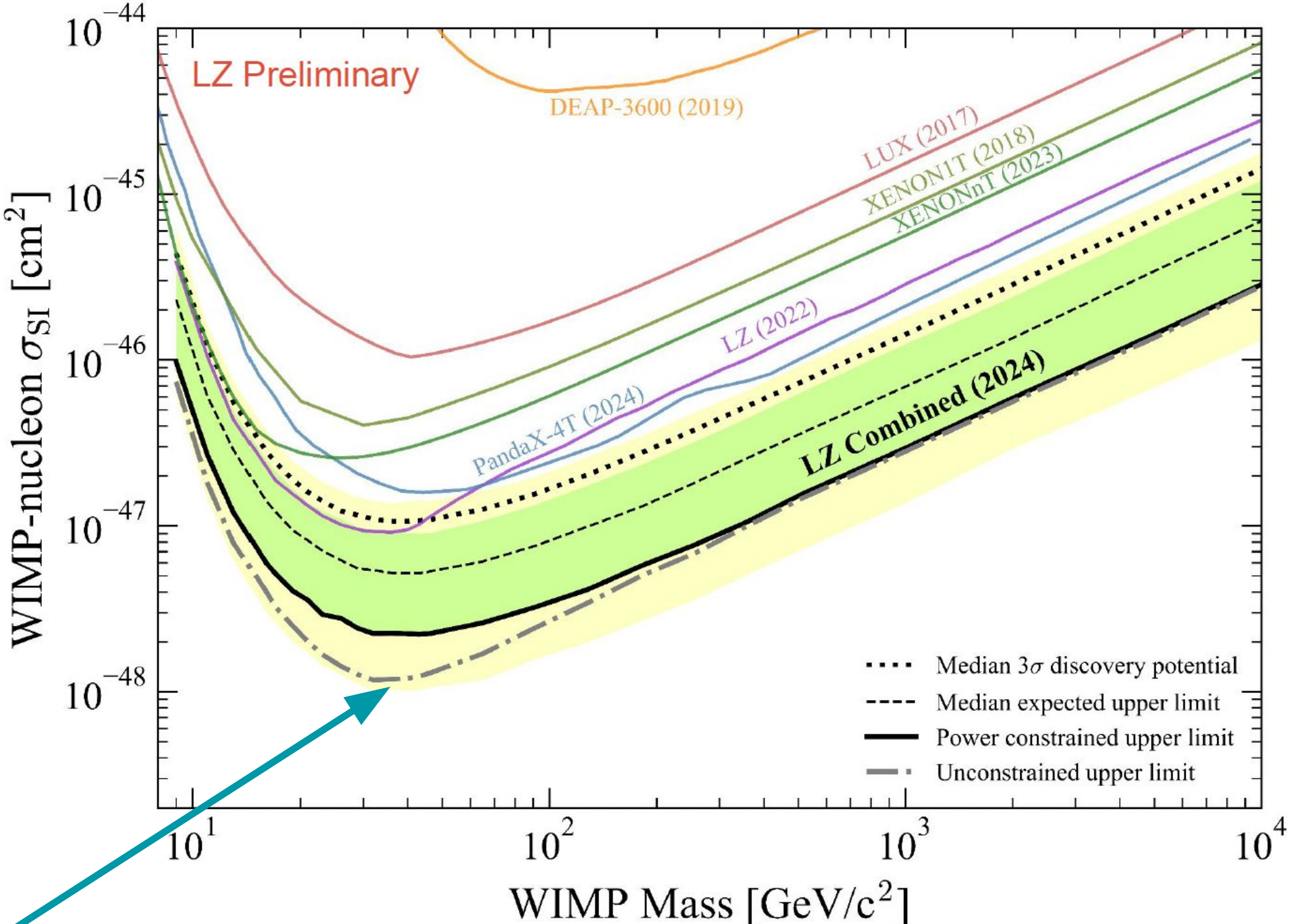
[JINST 19.08 (2024): P08027]

Xenon TPC ER & NR Calibration: End Goal

*NEST



Current Status: Leading The high mass Field (LUX-ZEPLIN)



LZ: 90% CL minimum of 2.2×10^{-48} cm^2 @ 43 GeV/c^2

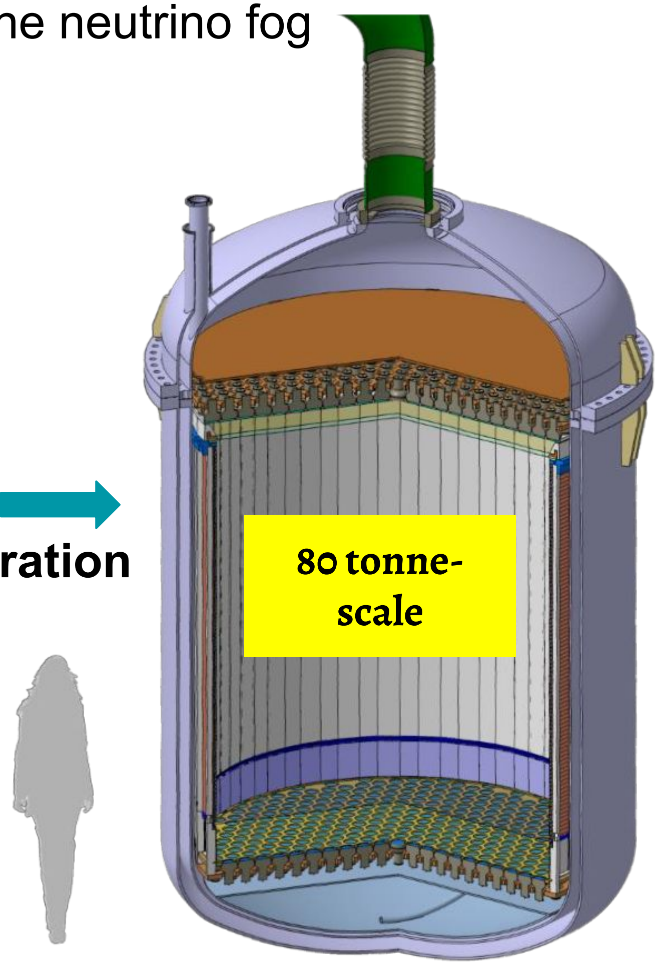
- **Larger size**
- **Lower background (99.9% ER rejection)**

Outlook: Short and Long Term

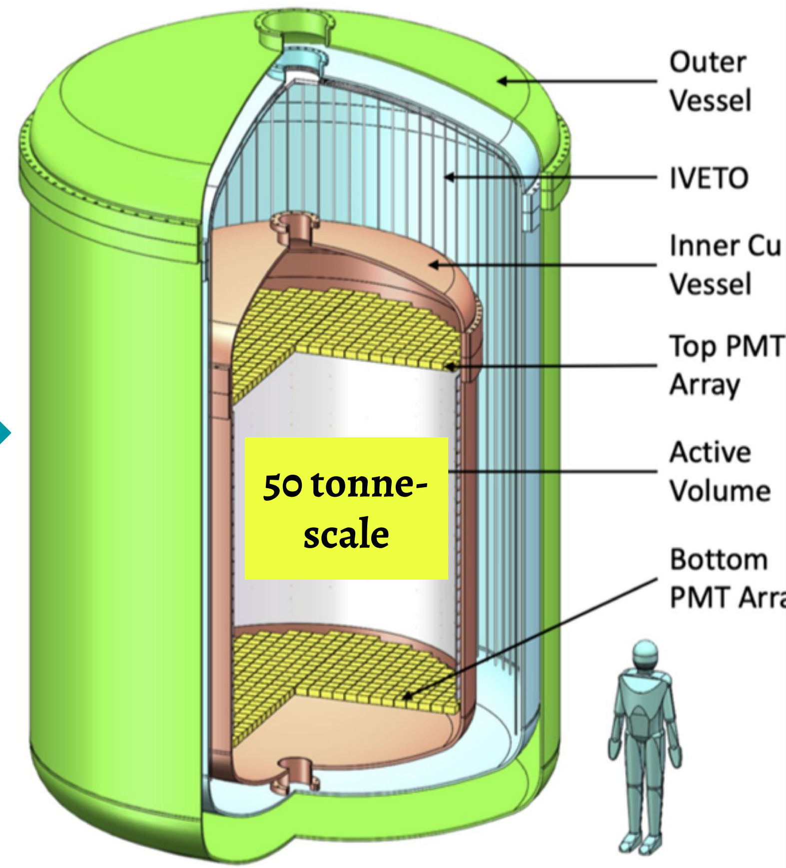
Short term: Reaching some milestone (e.g. 1000 livedays for LZ) + potential upgrades

Long term: Merging to generation-3 (G3) xenon TPCs in 2030s with ultimate goal to reach the neutrino fog

XLZD collaboration →



PandaX collaboration →

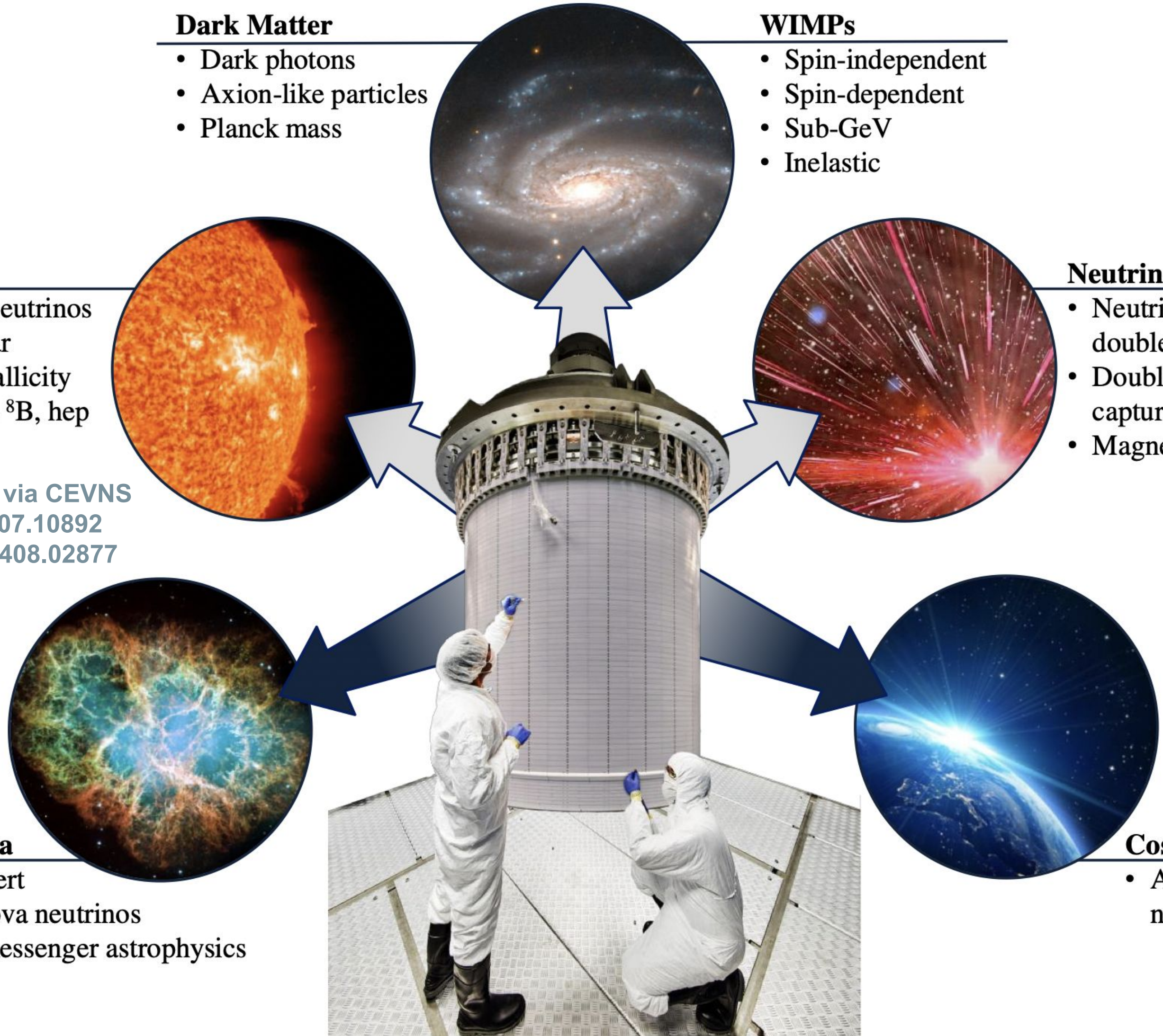


[XLZD (XENONnT/LZ/DARWIN) detector]

[PandaX G3 detector]

Xenon TPCs: Outlook

WIMPs + many more physics …



First measurement of 8B via CEVNS
- PandaX: arXiv:2407.10892
- XenonNT: arXiv:2408.02877

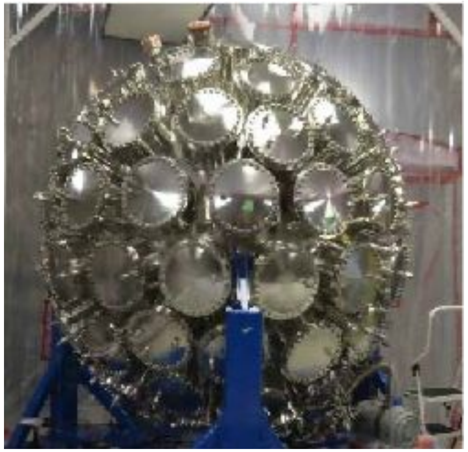
XLZD science case [arxiv 2203.02309]

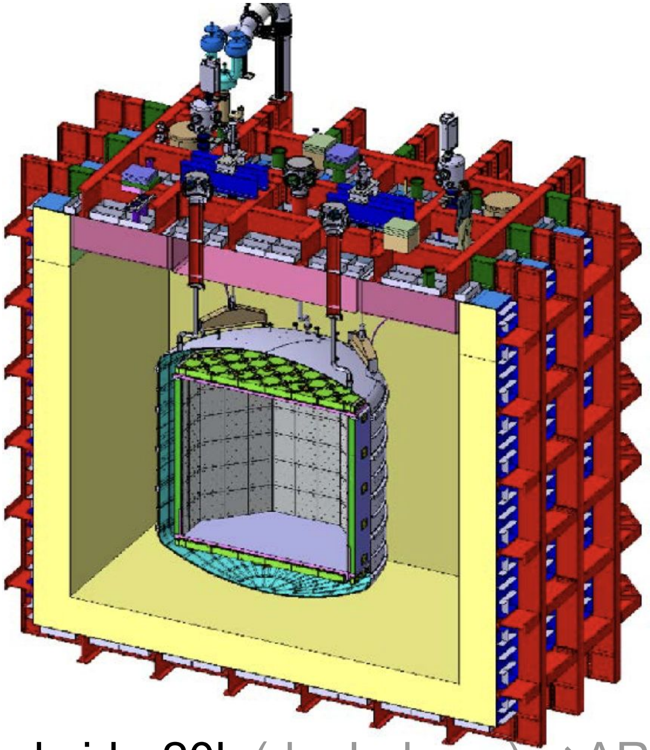
XLZD.org

Noble Liquid Argon Detectors (GADMC)

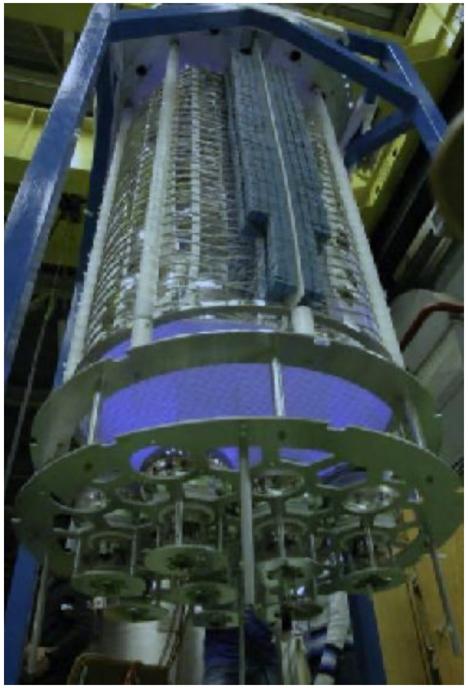
Deap-3600
(single-phase)

MiniCLEAN
(single-phase)





Darkside-20k (dual-phase) ⇒ARGO

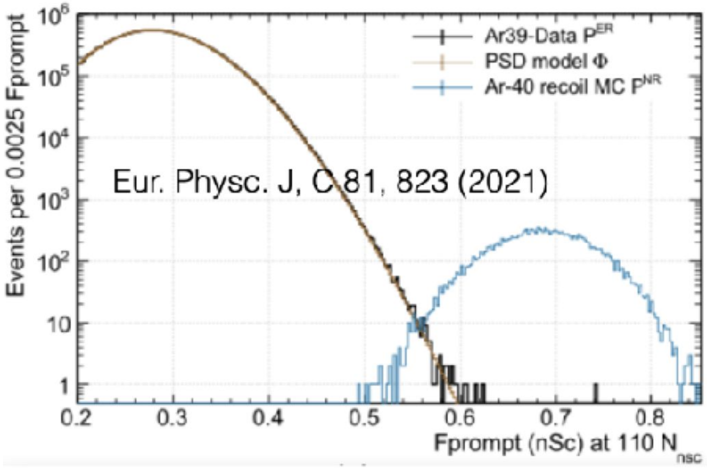


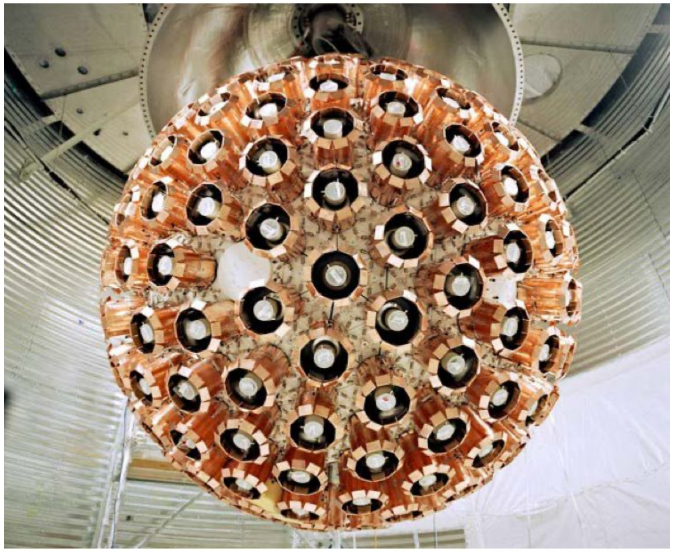
ArDM
(dual-phase)

DarkSide-50
(dual-phase)

Argon Detectors: Deap-3600

- Single-phase liquid argon (no E-field)
- 3.6 tonnes (~1t fid), 255 PMTs
- Higher energy threshold relative to xenon detectors
- High ^{39}Ar (β) background when using ^{nat}Ar (~1Bq/kg)
- But excellent discrimination using pulse shape (PSD)
- **Current Status:**
  - DEAP-3600 "neck" upgrade nearly complete ⇒better α tagging to understand neck events leaching into main volume



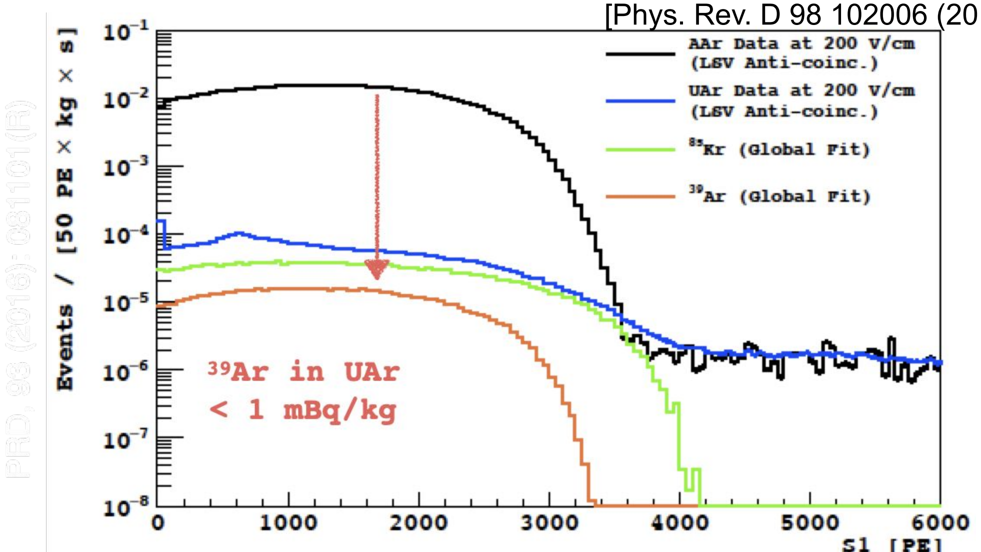


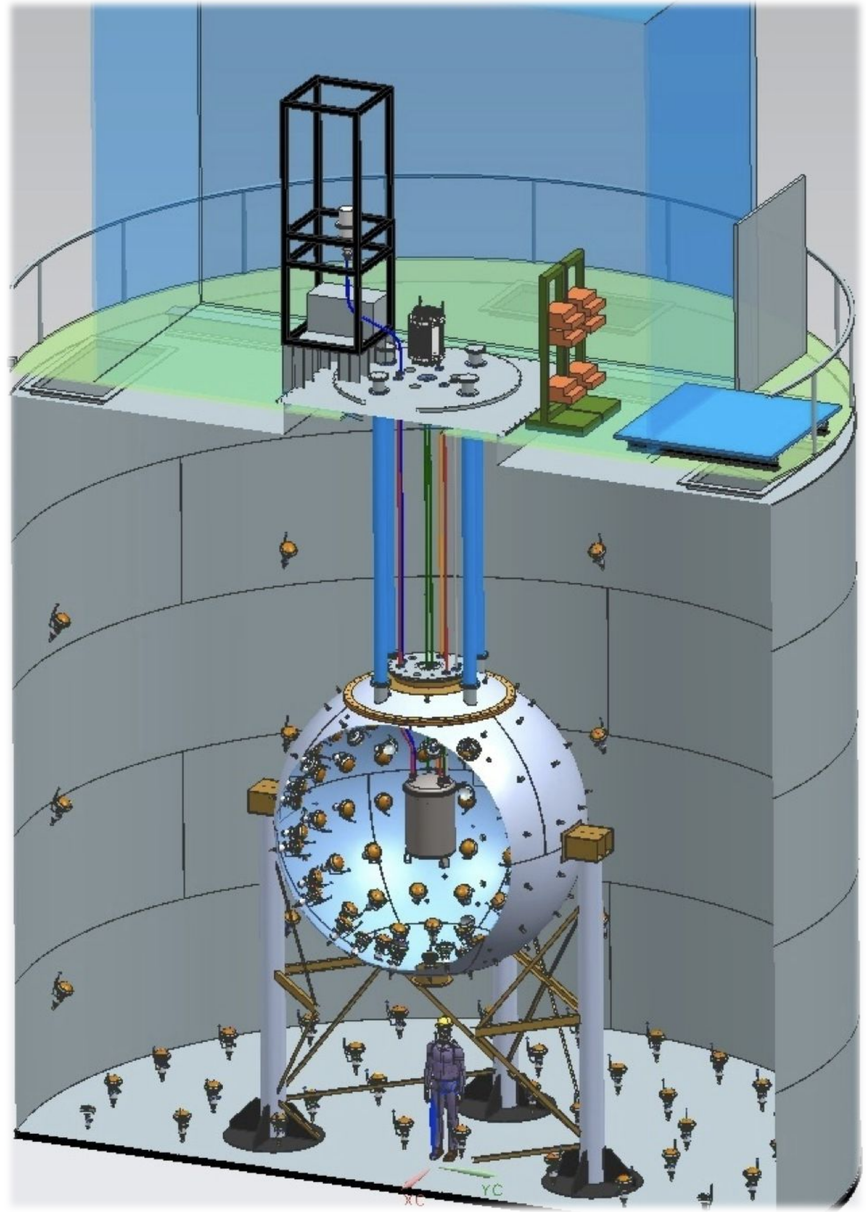
Argon Detectors: DarkSide-50

Two-phase argon: 150 kg underground argon (UAr), 50 kg fiducial,

- Pioneered the use of UAr
  - ^{39}Ar depletion factor >1400
  - ⇒Demonstrate the feasibility of tonne-scale low-background UAr TPCs ⇒Darkside-20k (20t fid.) & ARGO (300t fid., planned)

[J.CAP12(2018)011]
[Phys. Rev. D 98 102006 (2018)]



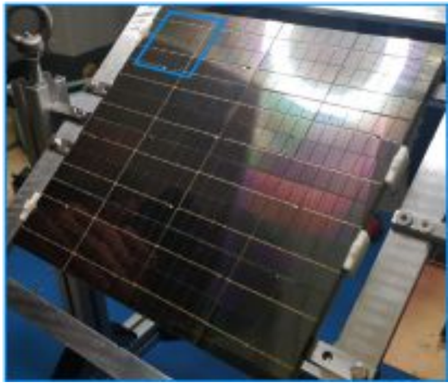


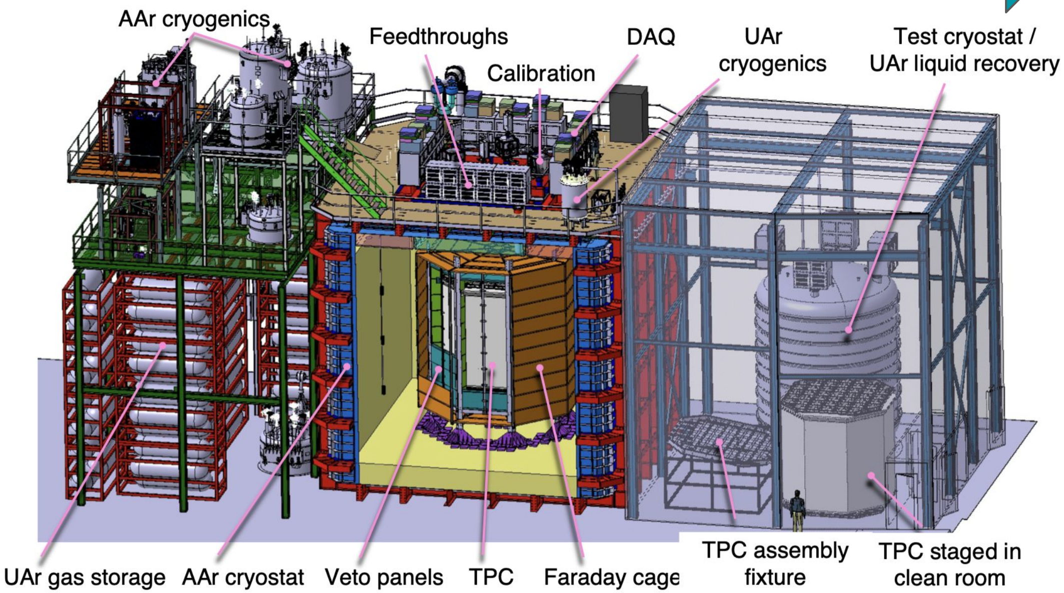
Thanks to Shawn Westerdale!

Argon Detectors: DarkSide-20 Currently in Construction

- A 20-tonnes fiducial argon detector filled with UAr (~700 tonnes total)
- Large area (21 m^2) of Cryogenic Silicon based Photo Multipliers (PDU)
- TPC acrylic vessel surrounded by AAr + Gd-loaded acrylic shell as a neutron veto
  - Coupled to UAr +excellent PSD ⇒ zero instrumental background
- Currently under construction at LNGS

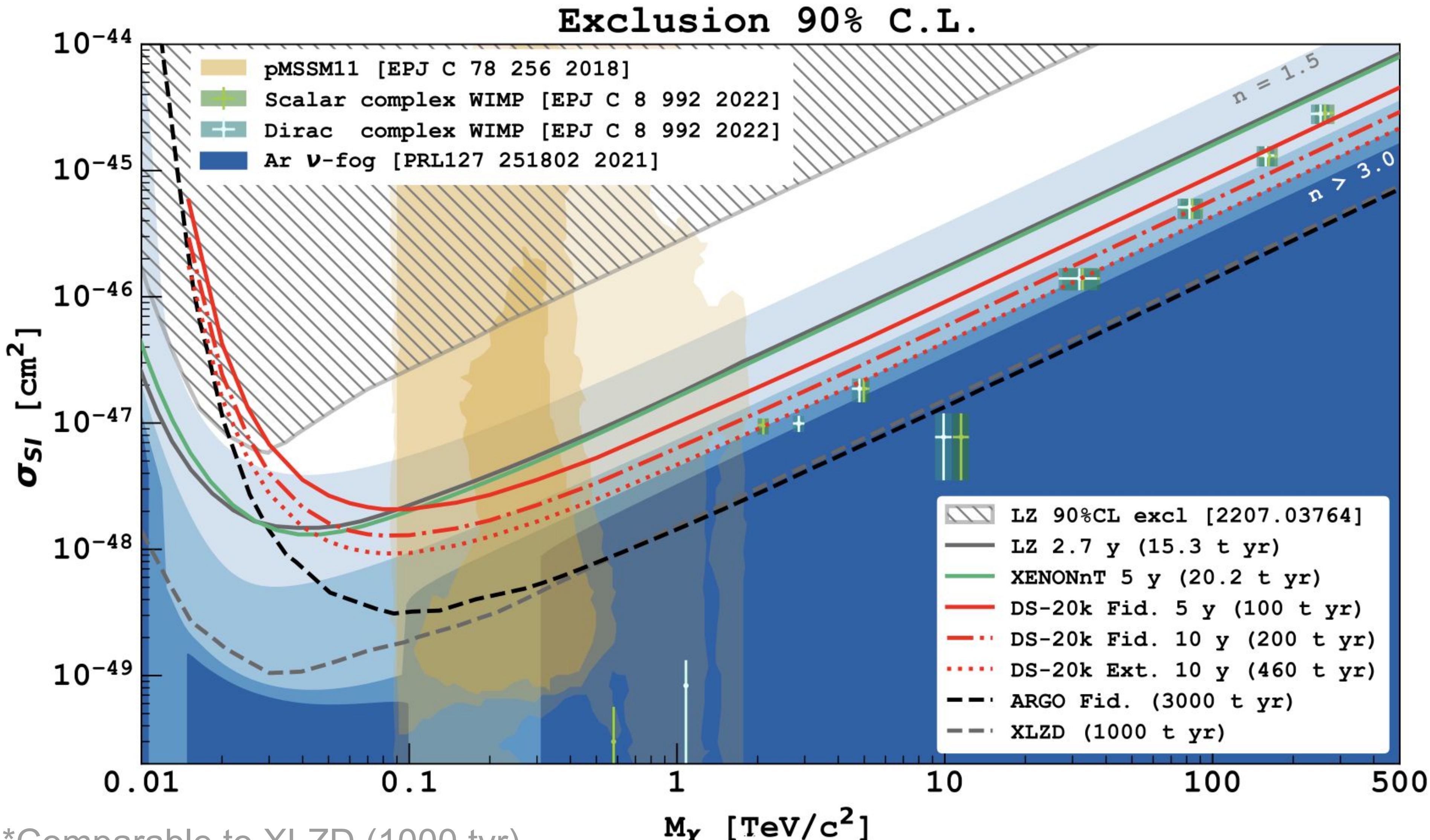
Picture of a SiPM PDU (photon detector unit)





Projected Sensitivity with ARGO (3000 tonne years)

C. Galbiati's, GADMC

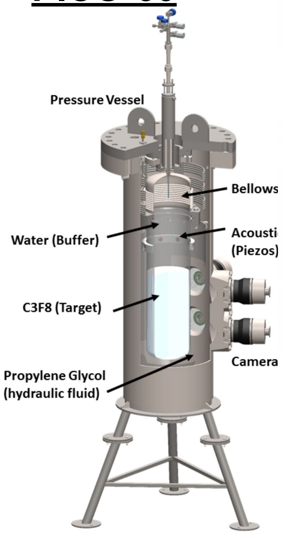


*Comparable to XLZD (1000 tyr)

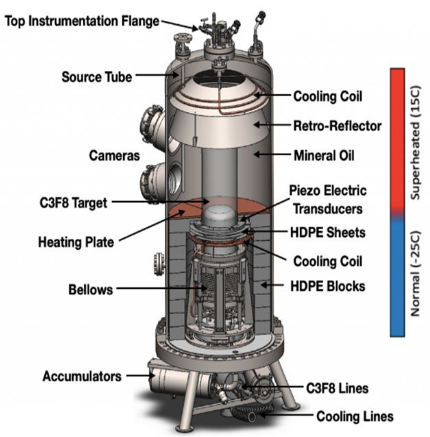
Bubble Chambers: PICASSO + COUPP ⇒PICO

- Low threshold detectors (~3keVNR) filled with superheated fluorocarbons
- ^{19}F abundance ⇒sensitivity to **Spin Dependent** (SD) interaction
- A suite of detectors operating for >15 years pre-merger
  - Beginning 2016 with PICO-60 (after PICASSO & COUPP merger)
    - World most sensitive SD WIMP-proton result!
  - ⇒PICO-40L (currently operating) ⇒PICO-500 (under-construction)
- Projected sensitivity 10^{-46} cm^2 @ 100 GeV/c^2

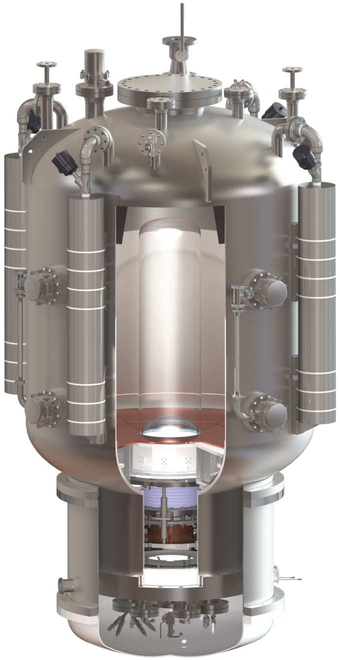
PICO-60

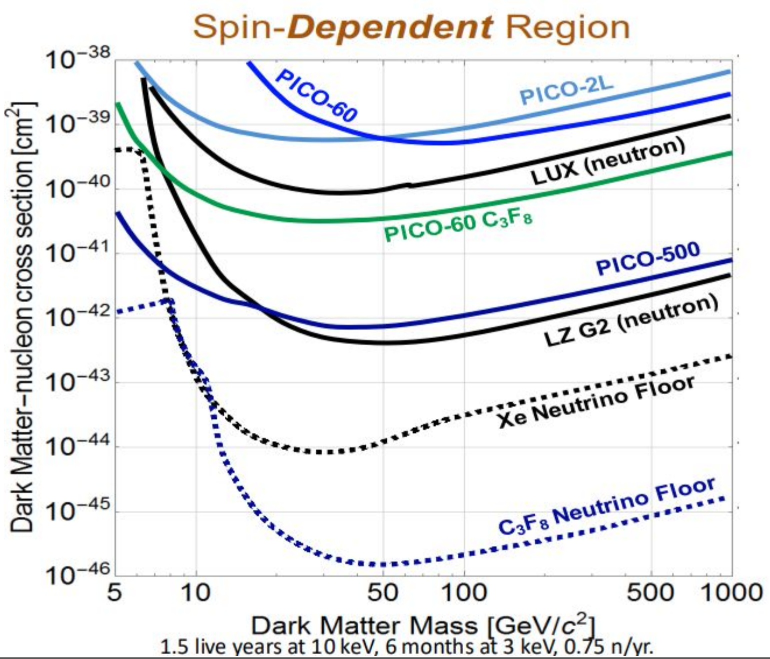


PICO-40L



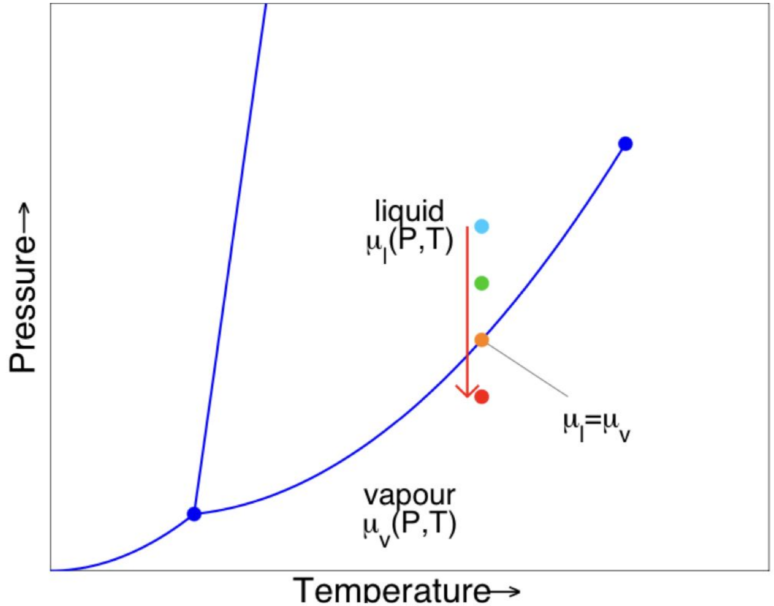
PICO-500



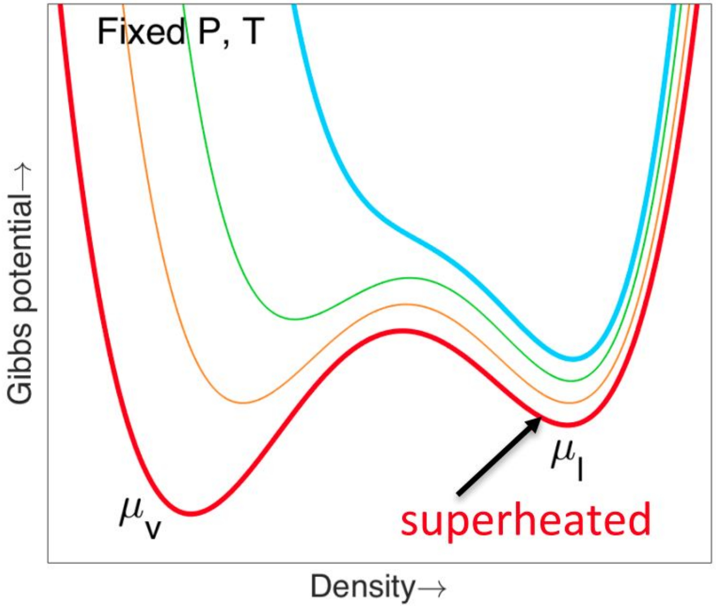


Thanks to Derek Cranshaw !

Bubble Chamber Operating Principle



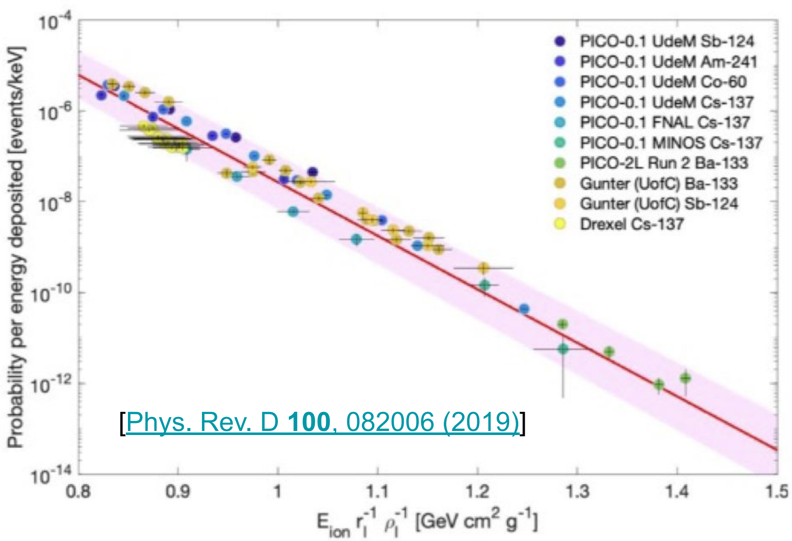
On the saturation curve, two minima exist on the Gibbs potential (vapour and liquid)



Lowering the pressure modifies the Gibbs potential ⇒superheated liquid state

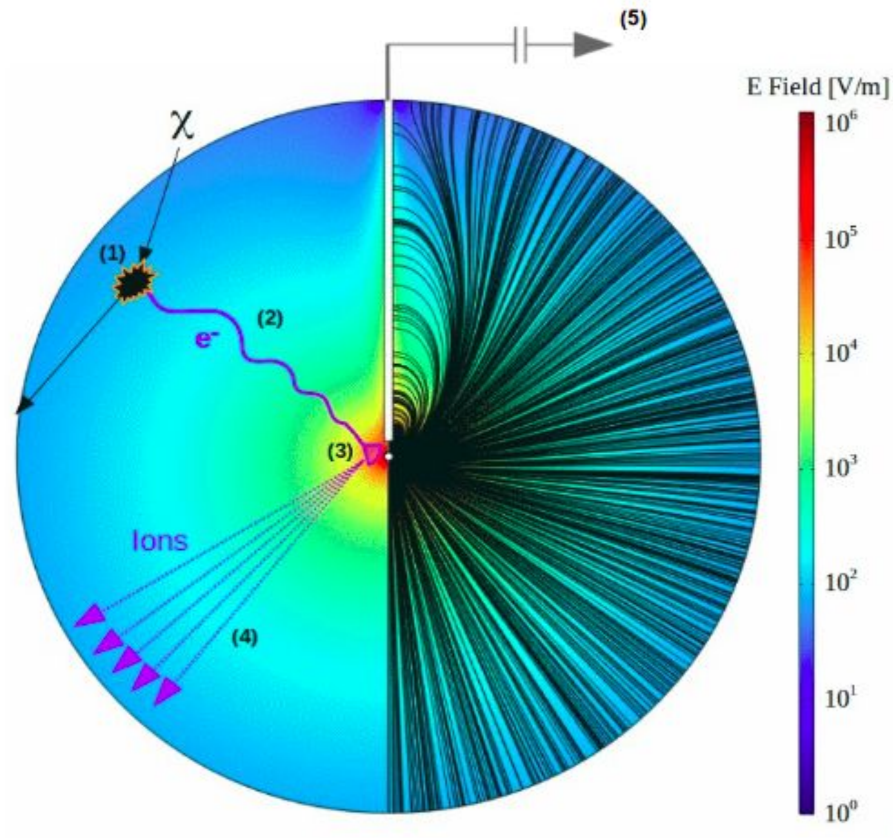
Sufficient energy deposition within a critical radius can overcome the energy barrier ⇒ **bubble formation**

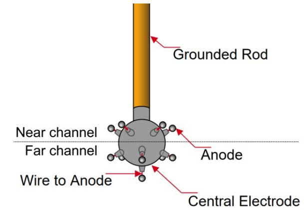
After bubble forms, target is rapidly re-compressed in preparation for next event



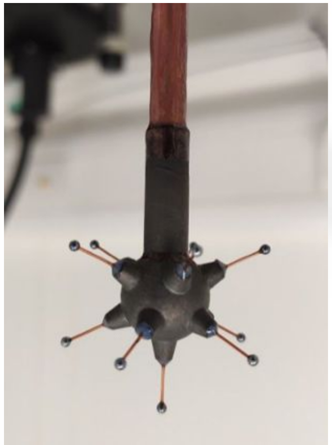
[Phys. Rev. D **100**, 082006 (2019)]

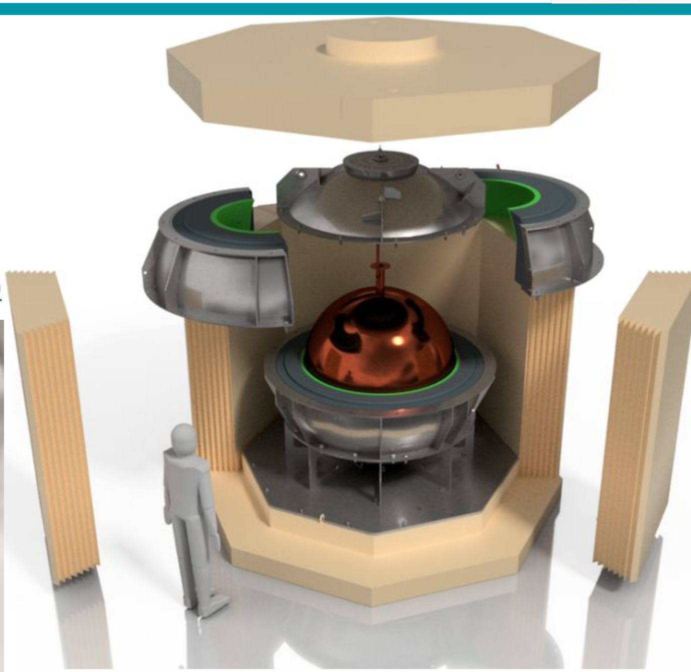
Ionization Detectors: NEWS-G



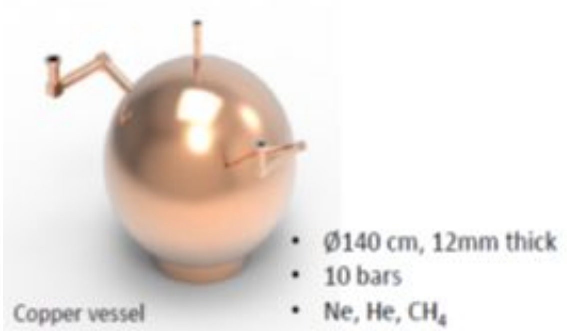


doi: 10.1016/j.nima.2019.162390





CAD drawing of NEWS-G detector & shielding

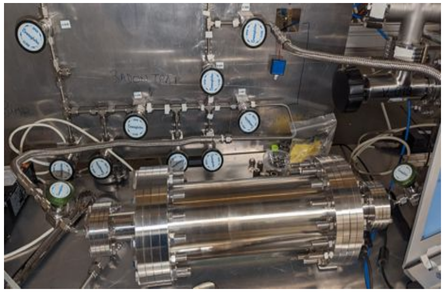


doi:10.1088/1748-0221/18/02/T02005
doi: 10.1088/1748-0221/15/11/P11023

- Very low threshold **single phase** spherical proportional counters (SPC) filled with light gas (e.g. He, Ne) to search **for low mass DM** (0.1 - ~10 GeV).
- Various size: S30, S60, S140. S140 taking data since 2022 @ SNOLAB

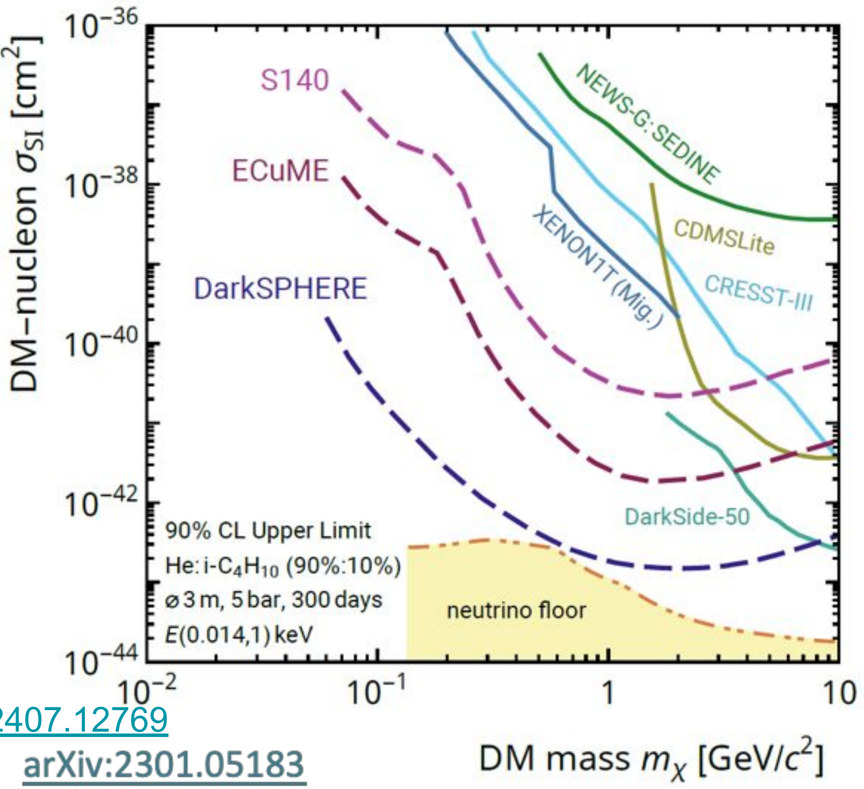
NEWS-G Current Status & Outlook

- New results with S140, CH4 run @LSM
- Improvements since LSM
  - DAQ/Trigger
  - Better gas purity for lower backgrounds
    - E.g. Silver zeolite radon trap, oxygen removal
- Current R&D
  - Preparing new gases (Ne + 7%CH_4, He + CH_4 pure CH_4)
  - New sensor geometry & materials
- Future R&D
  - Fully underground electroformed 140 cm of diameter copper sphere in SNOLAB (tests ongoing at PNNL)
  - Fully electroformed 3m of diameter sphere in a water shield
  - (under consideration)
  - Modified Shielding for CEvNS detection at nuclear reactors



Gas urifier

Radon trap



arXiv:2407.12769

arXiv:2301.05183

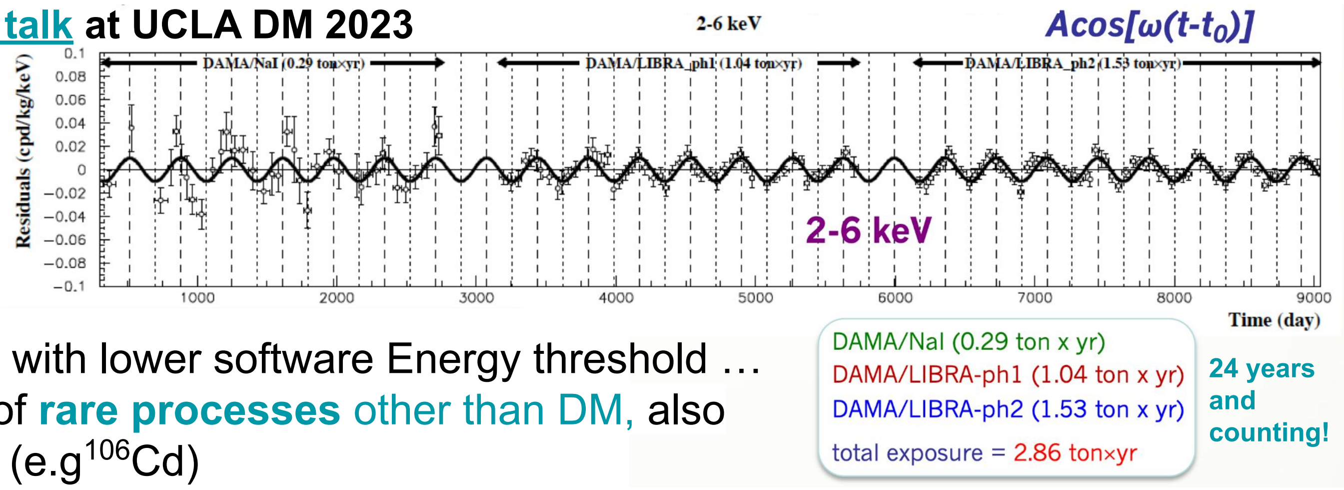
Thanks to Jean-Marie Coquillat!

Scintillating Crystals: Sodium Iodine Detectors

© P. Belli's talk at UCLA DM 2023

DAMA/LIBRA

experimental residuals of the single-hit scintillation events rate vs time and energy



Outlook: continue data taking with lower software Energy threshold … and continuing investigations of **rare processes** other than DM, also using the other DAMA set-ups (e.g. ^{106}Cd)

Scintillating Crystals: Sodium Iodine Detectors

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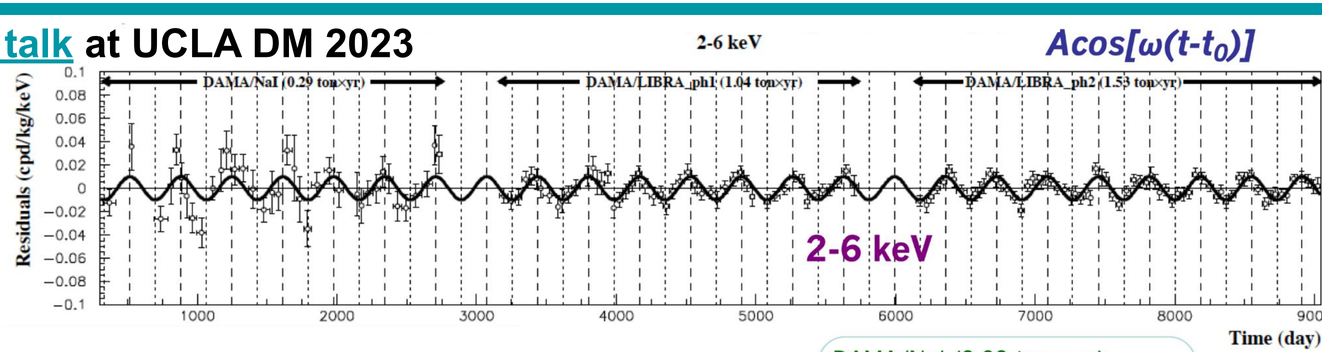


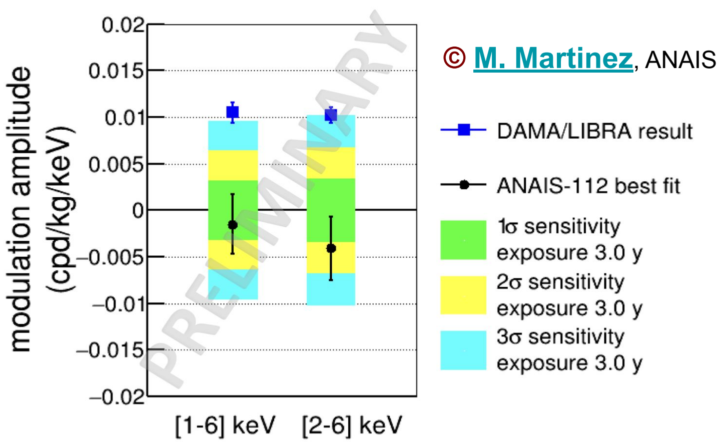
DAMA/NaI (0.29 ton x yr)
DAMA/LIBRA-ph1 (1.04 ton x yr)
DAMA/LIBRA-ph2 (1.53 ton x yr)
total exposure = 2.86 ton×yr

24 years and counting!

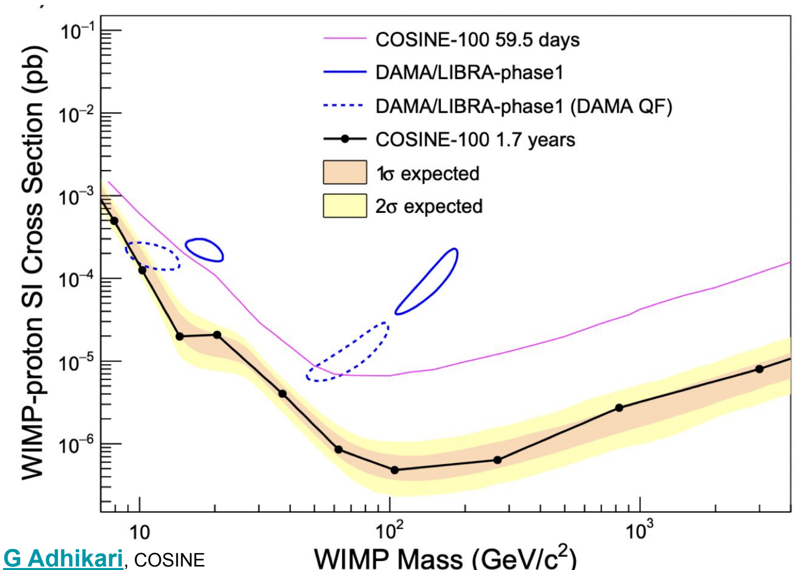
Outlook: continue data taking with lower software Energy threshold … and continuing investigations of **rare processes** other than DM, also using the other DAMA set-ups (e.g.^{106}Cd)

SABRE, ANAIS, COSINE, SABRE, PICO-LON, DM-ICE also investigating …

© M. Martinez, ANAIS



best fit modulation amplitudes compatible with zero at ~1σ
Best fit incompatible with DAMA/LIBRA at 3.75 (4.2) σ for [1-6] ([2-6]) keV
Sensitivity with 3 years data: 3.3 (3.0) σ for [1-6] ([2-6]) keV

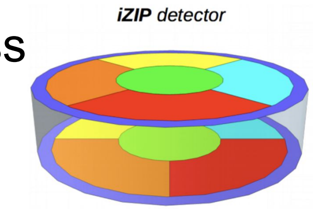


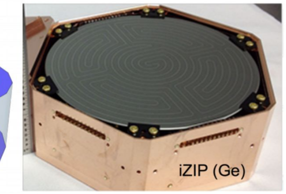
© G Adhikari, COSINE

Cryogenic Bolometers: SuperCDMS

Low threshold heat & ionization detector primarily for low mass

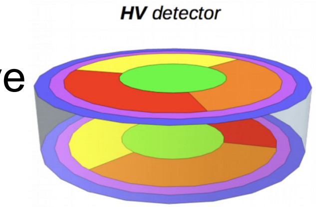
- Phonons read out via Transition edge sensors (QETs)
- Charge read out via interleaved electrodes





Currently in construction @SNOLAB (plan for 30 kg total)

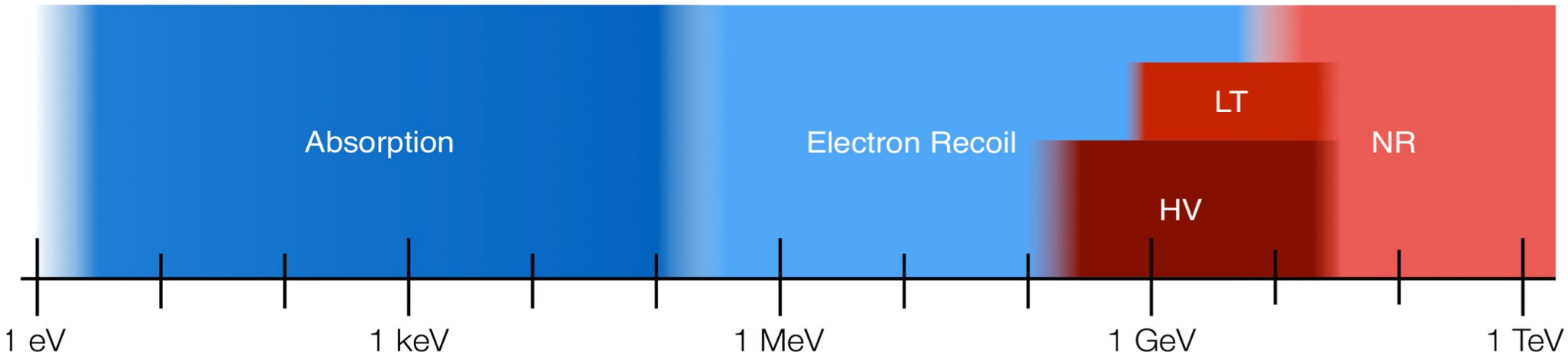
- Bigger (more fiducial volume) and higher purity (fewer radioactive impurities) crystals than CDMS
- Ge (1.4 kg crystals): larger exposure
- Si (0.6 kg crystals): lower mass reach



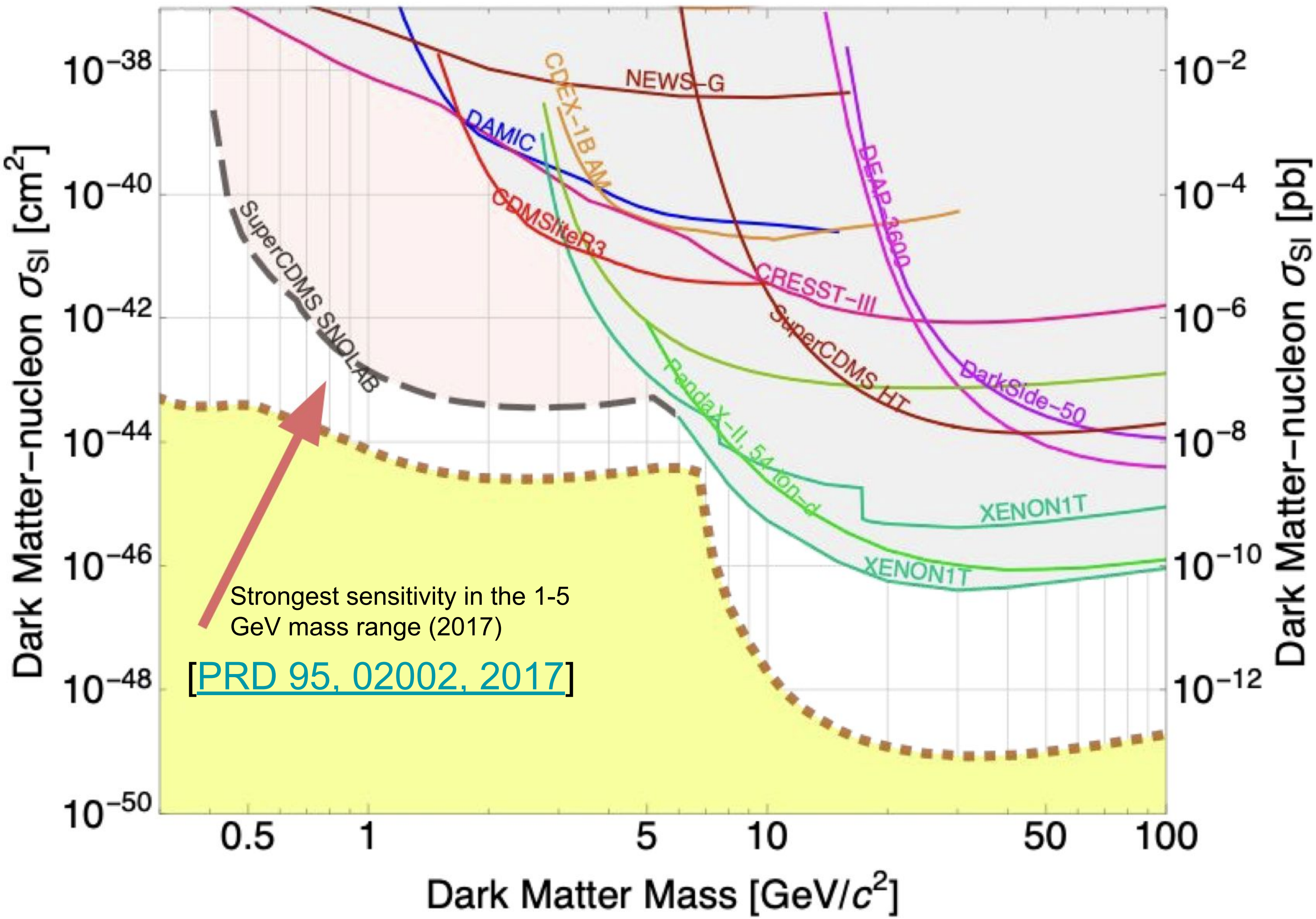
A broadband DM search experiment

Traditional Nuclear Recoil:	iZIP, Background free	>5 GeV
Low Threshold NR:	iZIP, limited discrimination	>1 GeV
HV mode:	HV, no discrimination,	~0.3 - 10 GeV
Electron recoil:	HV, no discrimination,	~0.5 MeV - 10 GeV
Absorption (Dark Photons, ALPs):	HV, no discrimination,	~1 eV - 500 keV ("peak search")

Mostly sub-GeV search ⇒ **talk by J. Cooley**

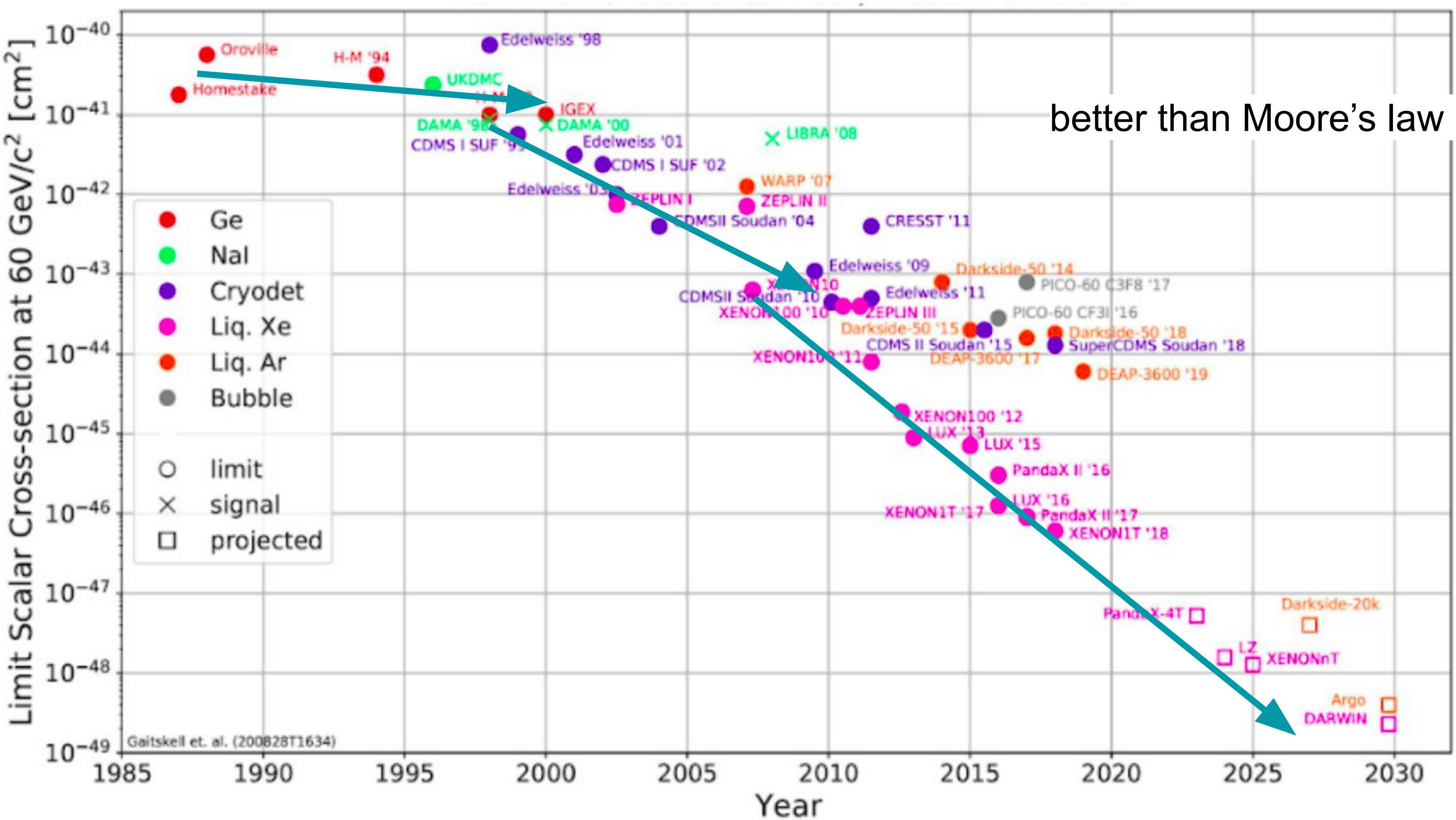


SuperCDMS@SNOLAB Projected Sensitivity



[PRD 95, 02002, 2017]

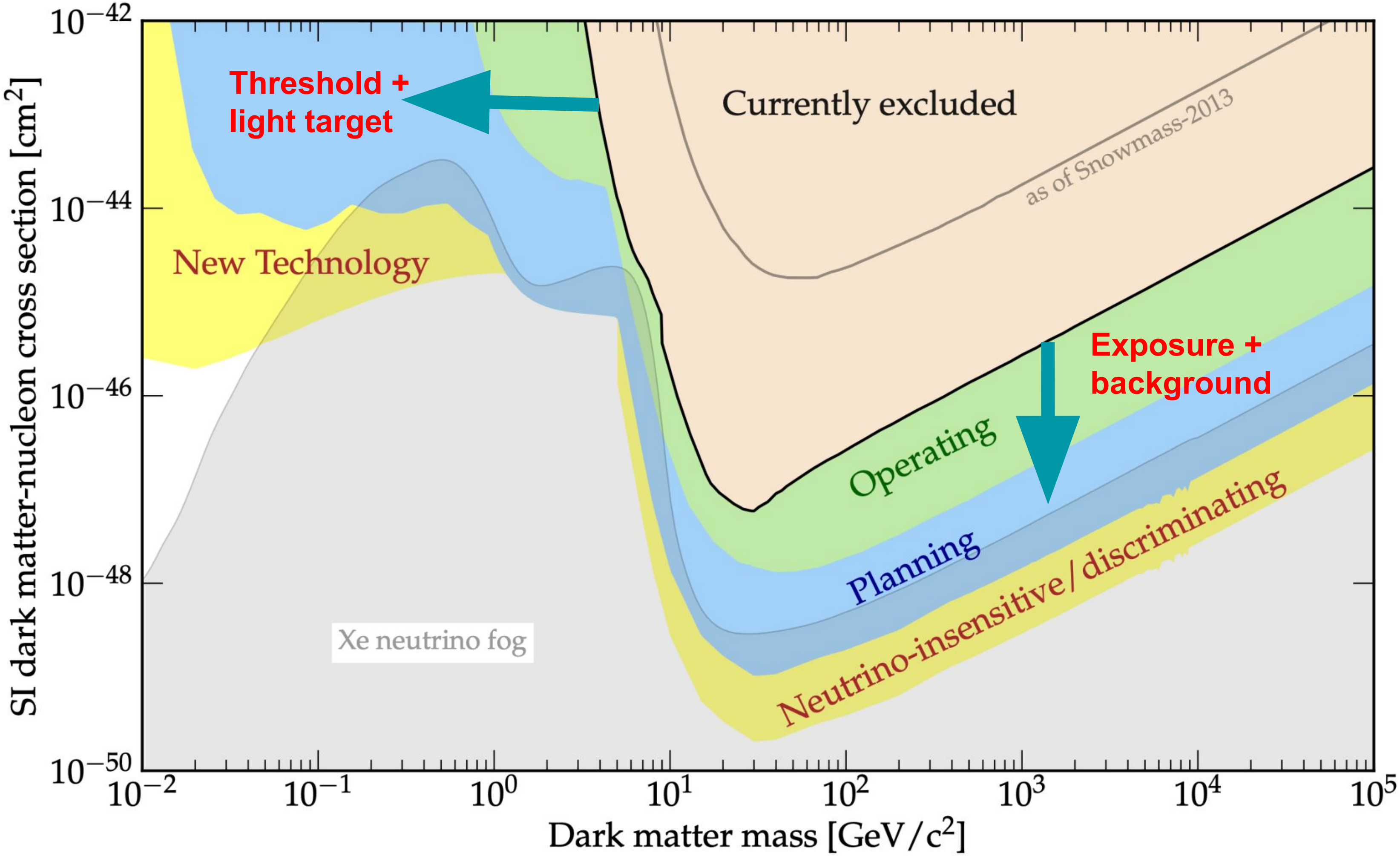
Weak Scale Search: Past, Present and Future



better than Moore's law …

- Current sensitivity <10^{-47} cm^2 in 2024 compared to a few x 10^{-41} cm^2 in ~1998
    - Dominated by dual-phase noble liquid detectors at *high mass*

Weak Scale Search: Past, Present and Future



Key message from the SNOWMASS'2021 particle physics community study:

Delve Deep and **look left**

Weak Scale Search: Past, Present and Future

[DOE-HEP Response to P5]

G3 Dark Matter

- From P5 Recommendation 2, Priority 4 out of 5 :
  - An **ultimate Generation 3 (G3) dark matter** direct detection experiment reaching the neutrino fog, in coordination with international partners and **preferably sited in the US**.
- DOE response and actions:
  - At the present time, based on the Snowmass Community Summer Study, there have been two proposals for G3 Dark Matter detectors : XLZD and ARGO
  - P5 recommended a **domestic site for the experiment in the higher funding scenario** and an international site in the lower funding scenario.
  - Start with site independent R&D as we understand the funding that will be available.
    - Engage with partners who are interested in hosting.
  - DOE will entertain proposals by U.S. groups for pre-project R&D.

New challenges await: scaling of the detector, tackling new backgrounds, active material procurements, etc … but it is doable …**so exciting time lies ahead!**

Key message from the SNOWMASS'2021 particle physics community study:

Delve Deep and **look left**

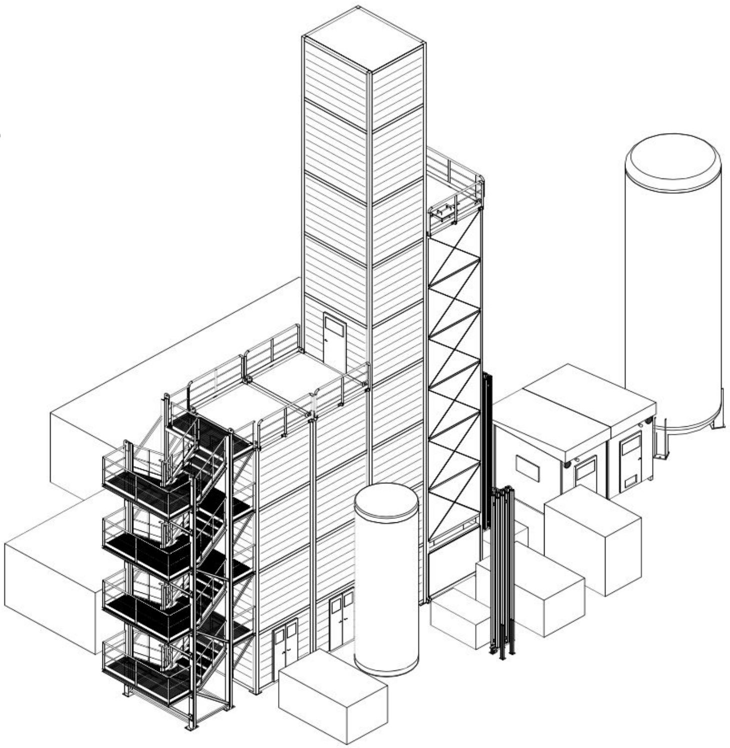
Thank you!

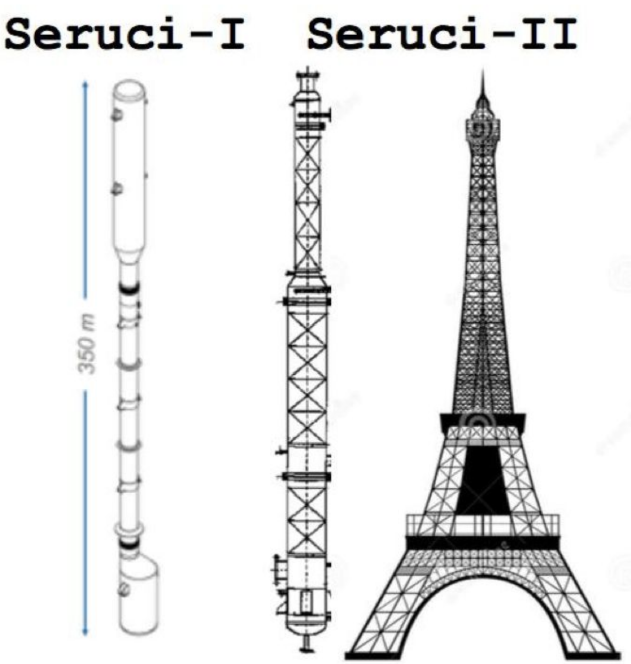
Back-up

GADMC Low Radioactivity Argon Acquisition

Urania

- Procurement of 50 tonnes/year of UAr from same CO_2 well in Colorado as for DS-50
- Extraction of 250 kg/day, with 99.9% purity
- UAr transported to Sardinia for final chemical purification at Aria





Aria

- Big cryogenic distillation column in Seruci, Sardinia
- Final chemical purification of the UAr
- Can process O(1 tonne/day) with 10^3 reduction of all chemical impurities
- Ultimate goal is to isotopically separate ^{39}Ar from ^{40}Ar (at the rate of 10 kg/day in Seruci-I)

Xenon Acquisition Market

- Industrial commodity ~ 60 tonnes/year and increasing
- Many demand from particle astrophysics (XLZD, PandaX, nEXO) and industry (electronics, aerospace)
    - Xe procurement for XLZD may take 8 – 10 years