School and Workshop on Dark Matter and Neutrino Detection

Dark Matter — Direct Detection
Lecture 2

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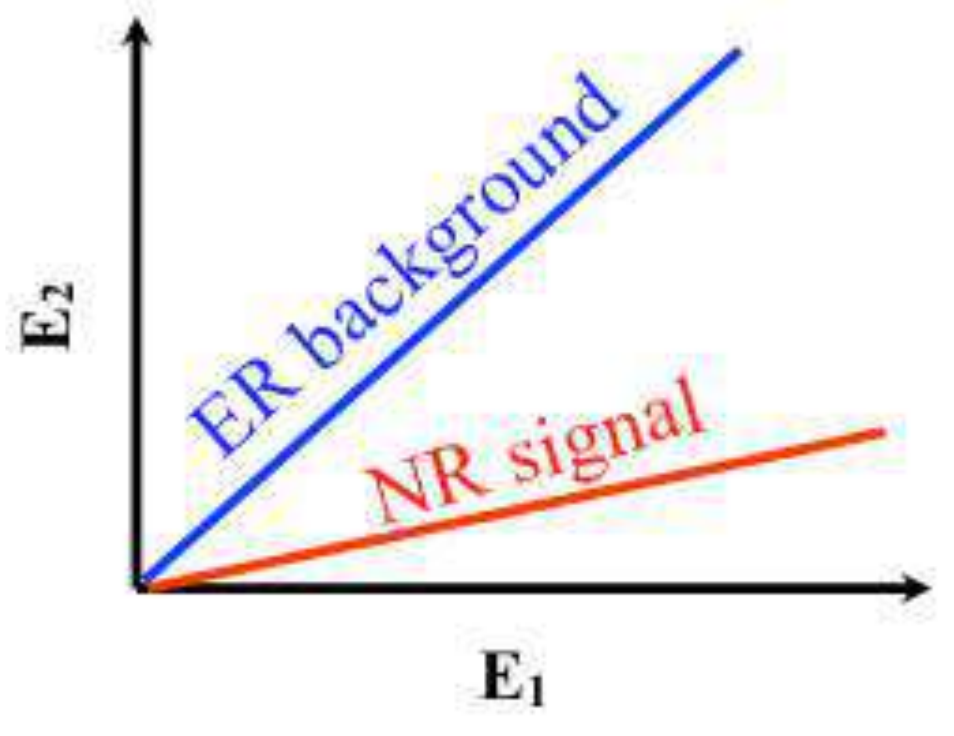
COLEGIO DE FISICA FUNDAMENTAL E INTERDISCIPLINARIA DE LAS AMERICAS

Outline

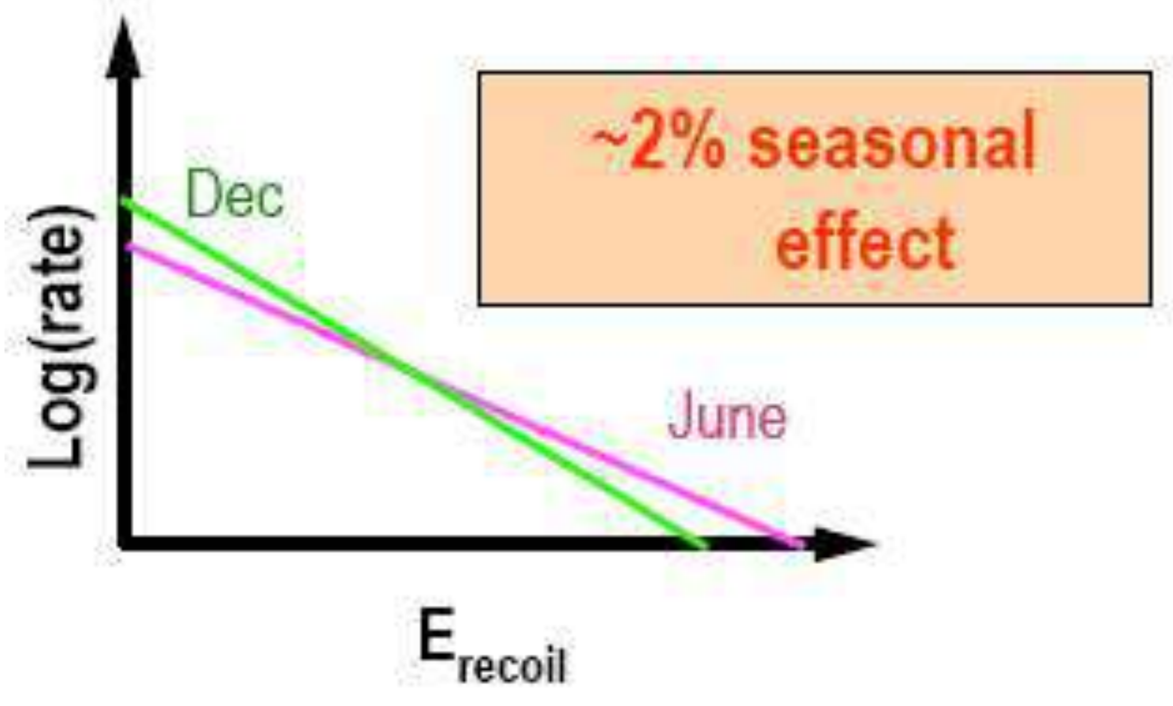
- Lecture 1:
  - The dark matter problem
  - WIMP and WIMP-like DM detection
- Lecture 2:
  - WIMP detection technologies
  - Current and future limits
- Lecture 3:
  - More 1-10 GeV DM detection technologies
  - To the Neutrino Floor, and beyond!
- Lecture 4:
  - The SuperCDMS Experiment
  - meV - 1GeV direct detection
- Lecture 5:
  - Indirect sterile neutrino detection

Last Time: Separating Signal from Background…

- By Detector **Response**
  - Obtain particle identification from the physics of the detector response to different types of particle interactions.

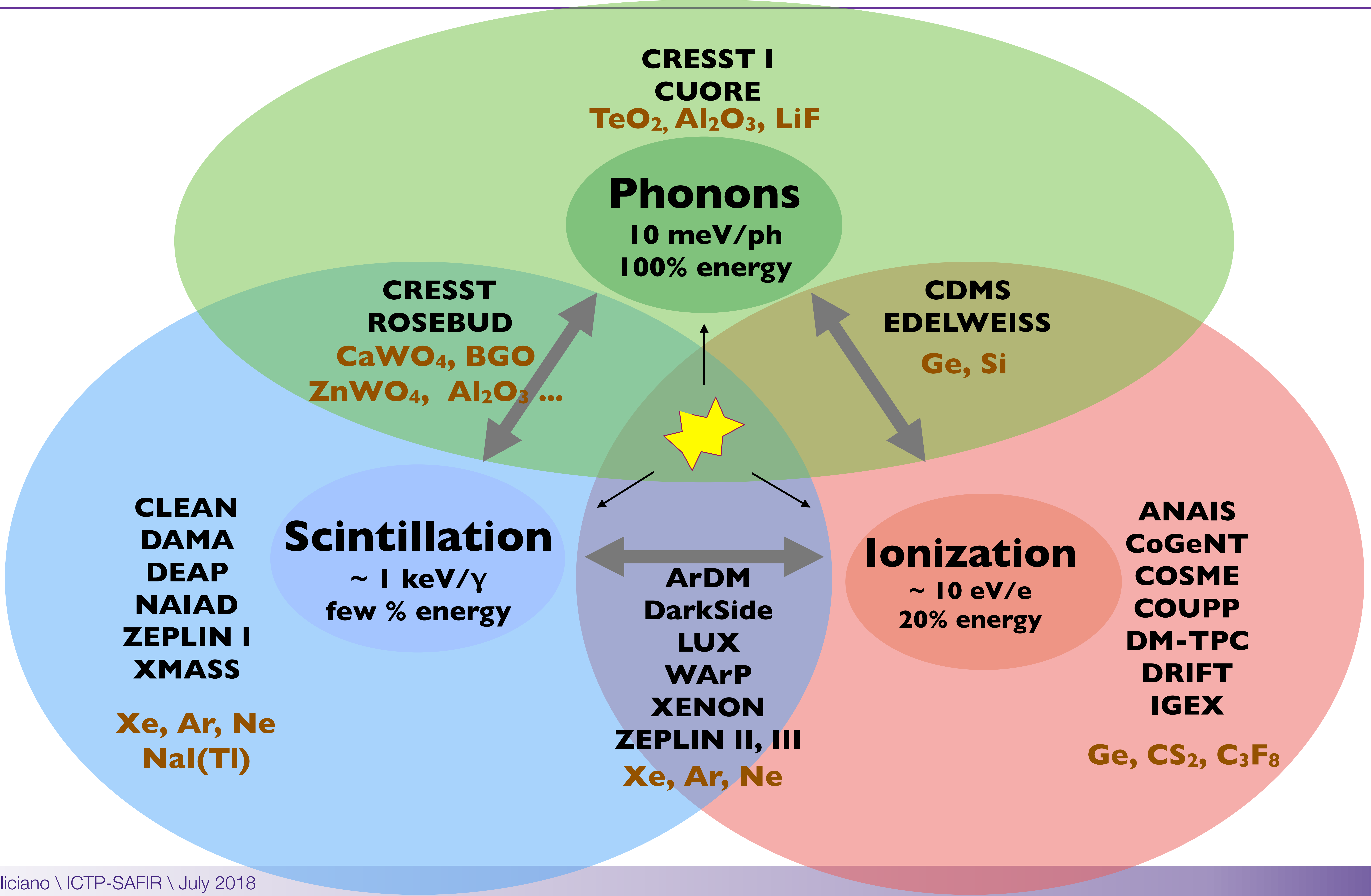


- By **Astrophysical** Modulation
  - Annual Modulation in the WIMP recoil spectrum. Earth's velocity through the galactic halo is max in June, min in December (DAMA/LIBRA).
  - Daily modulation of the incident WIMP direction. Measure the direction of the short track produced by nuclear recoil. (DM-TPC)



- Can be Event-by-Event or Statistical

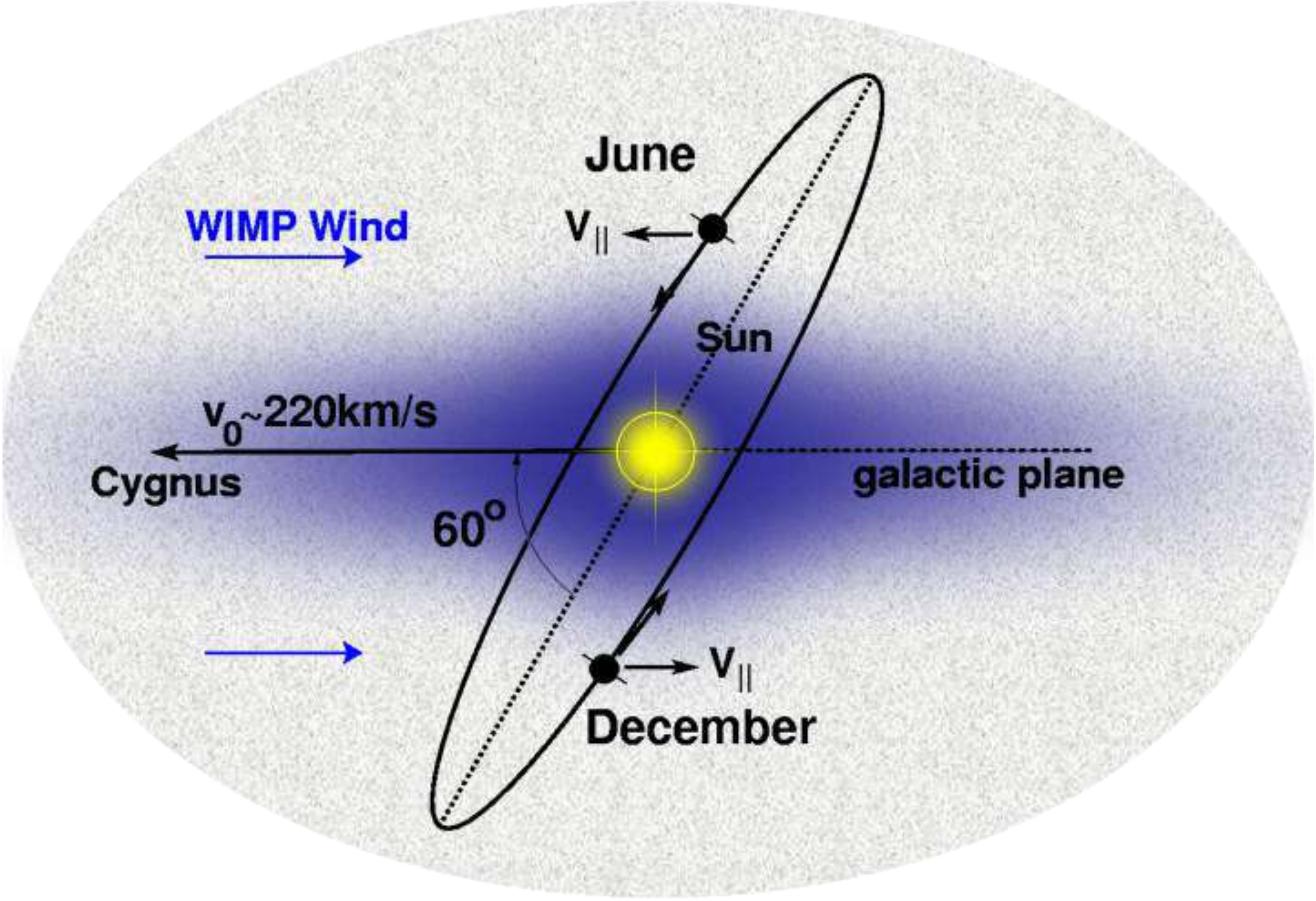
Last time: Particle ID Through Detector Response



Annual Modulation

Earth's motion about the Sun produces small changes in velocity relative to the dark halo

➔ Modulates expected rate of dark matter interactions detected on Earth



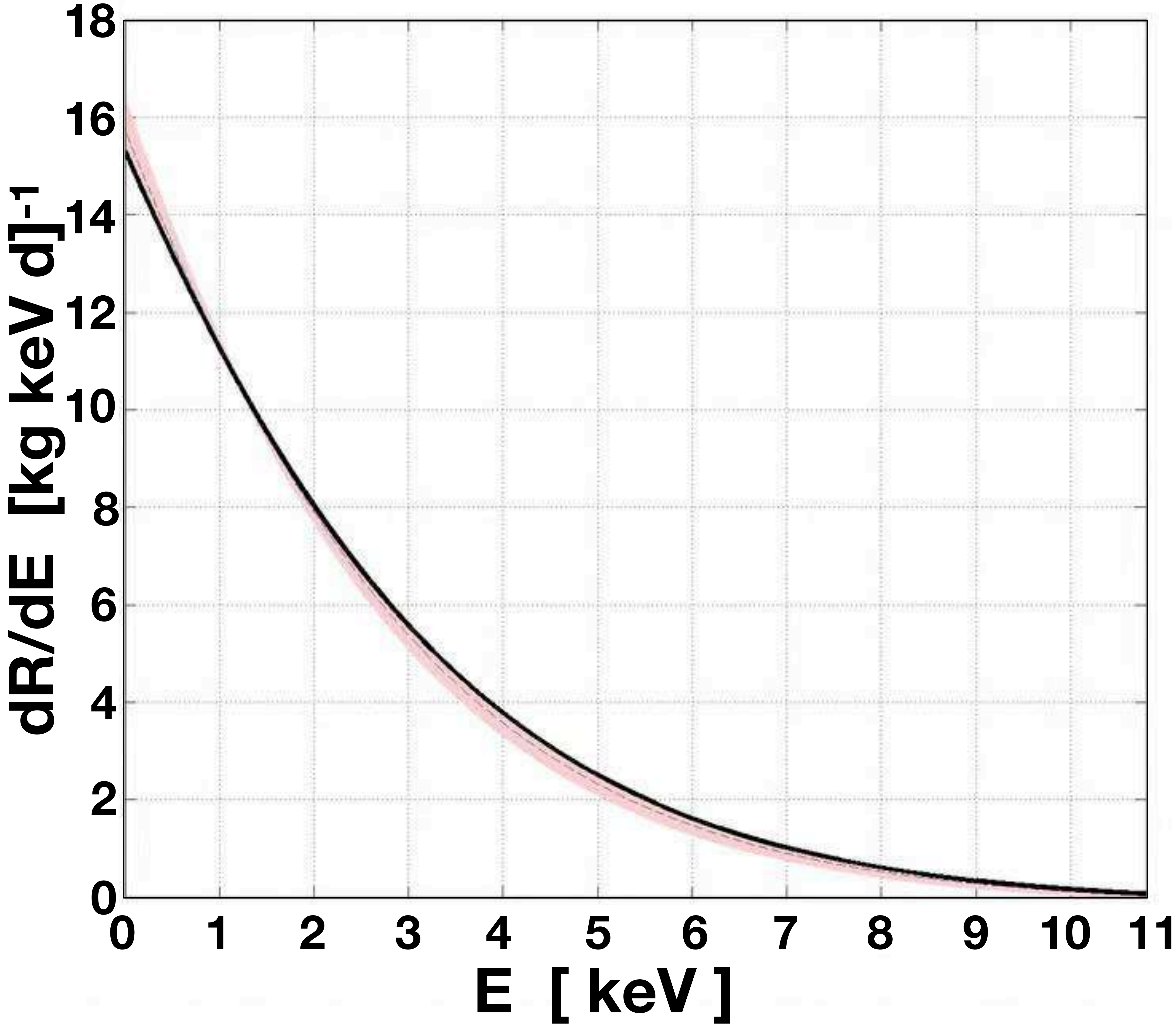
If you see a signal, check for an annual modulation

OR

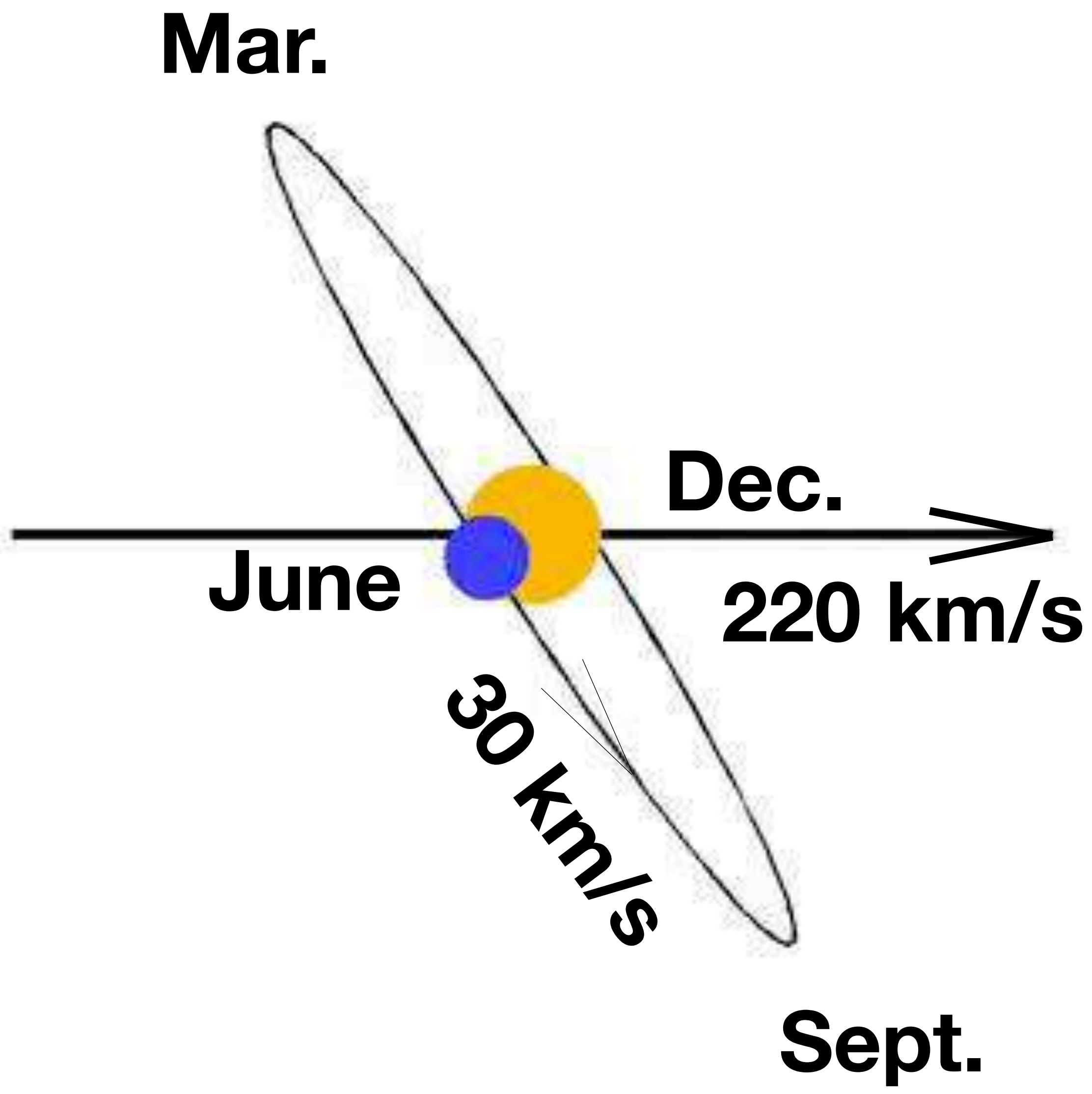
If you have irreducible backgrounds, use the modulation to pick out a signal

A dark-matter-induced modulation will have extrema in June and December (whether it's max or min depends on target and threshold)

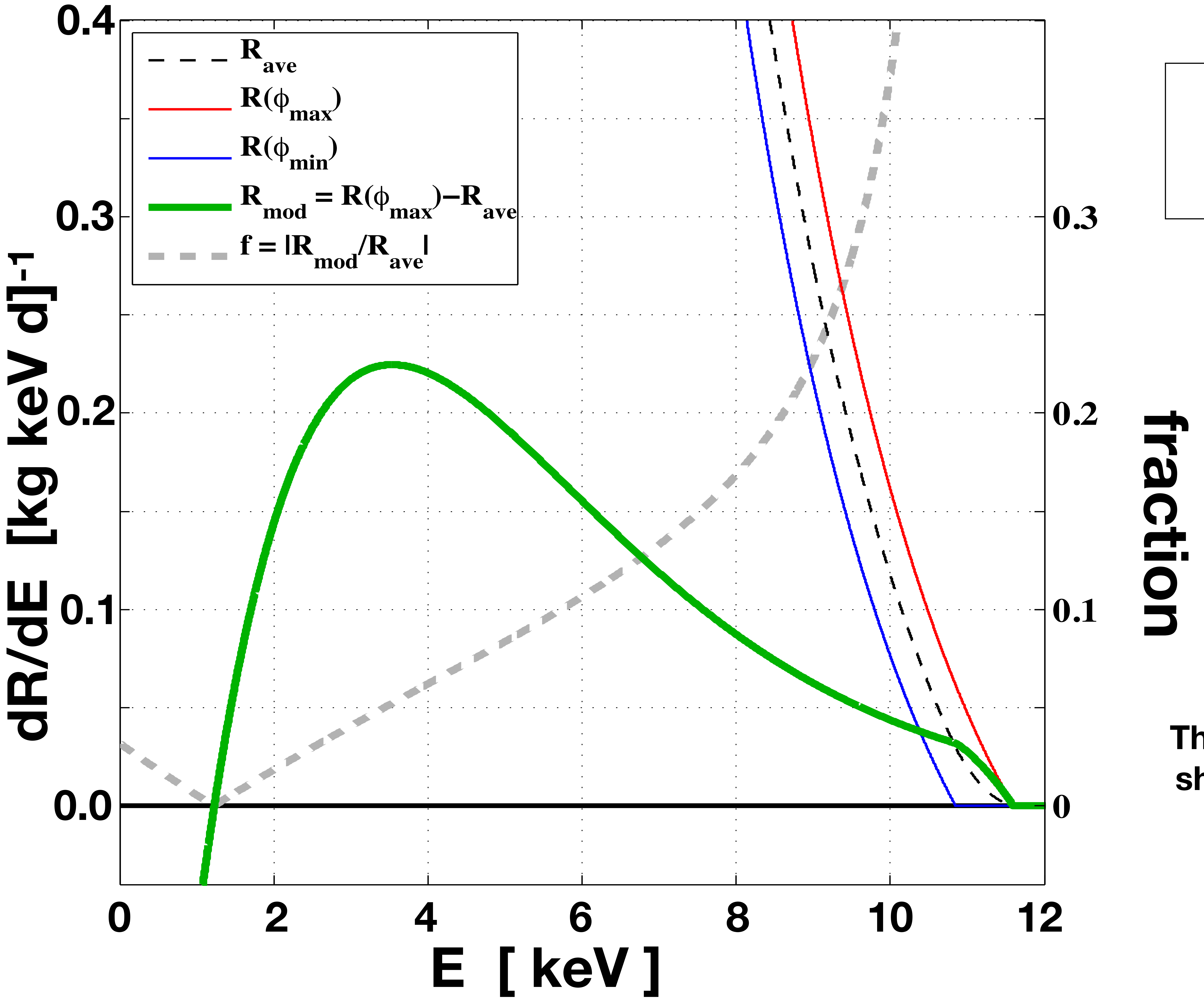
Annual Modulation



Target: Ge
σ_{SI} = 1x10^{-4} pb
M_X = 10 GeV/cm^2



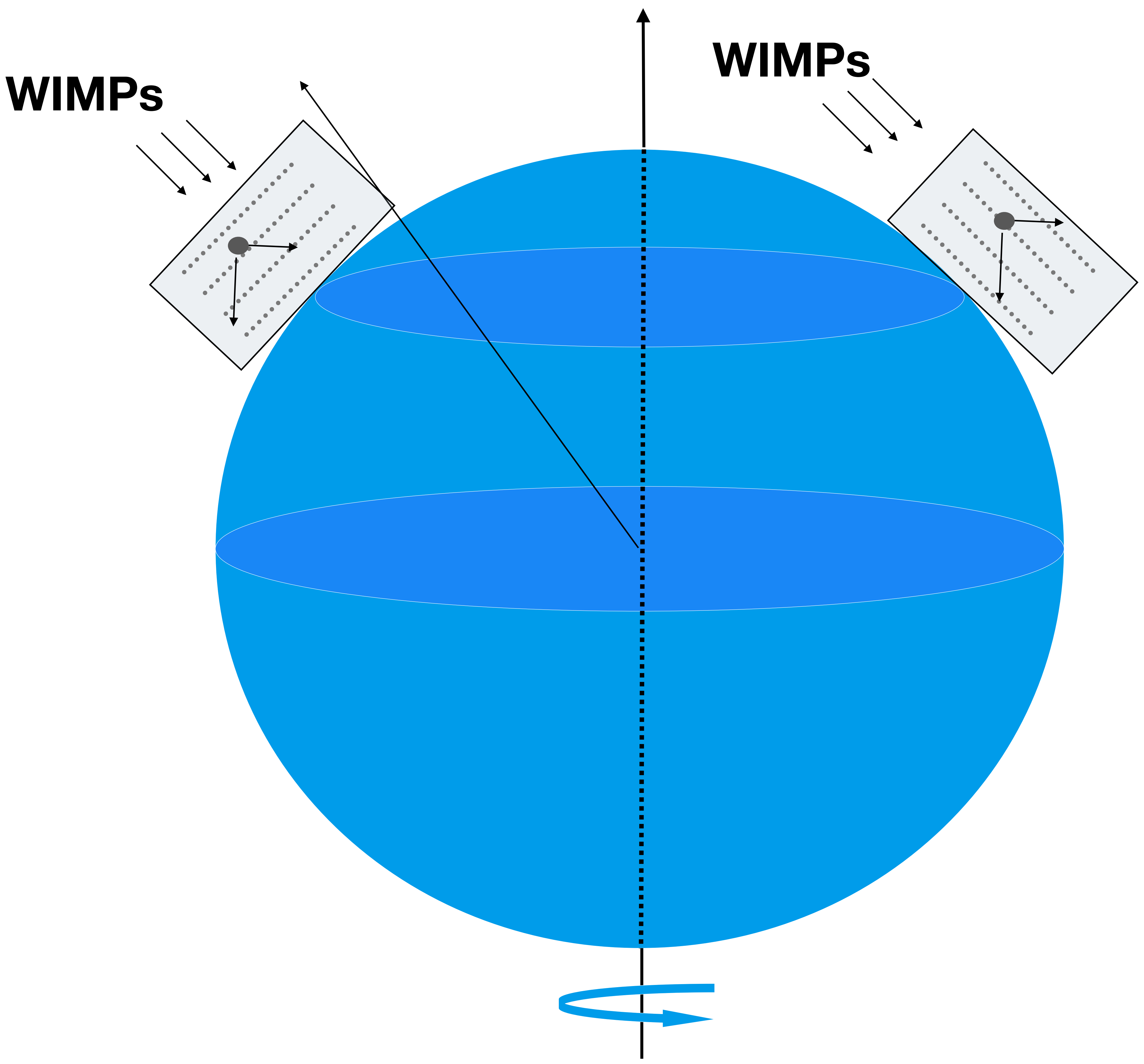
Modulation Signal



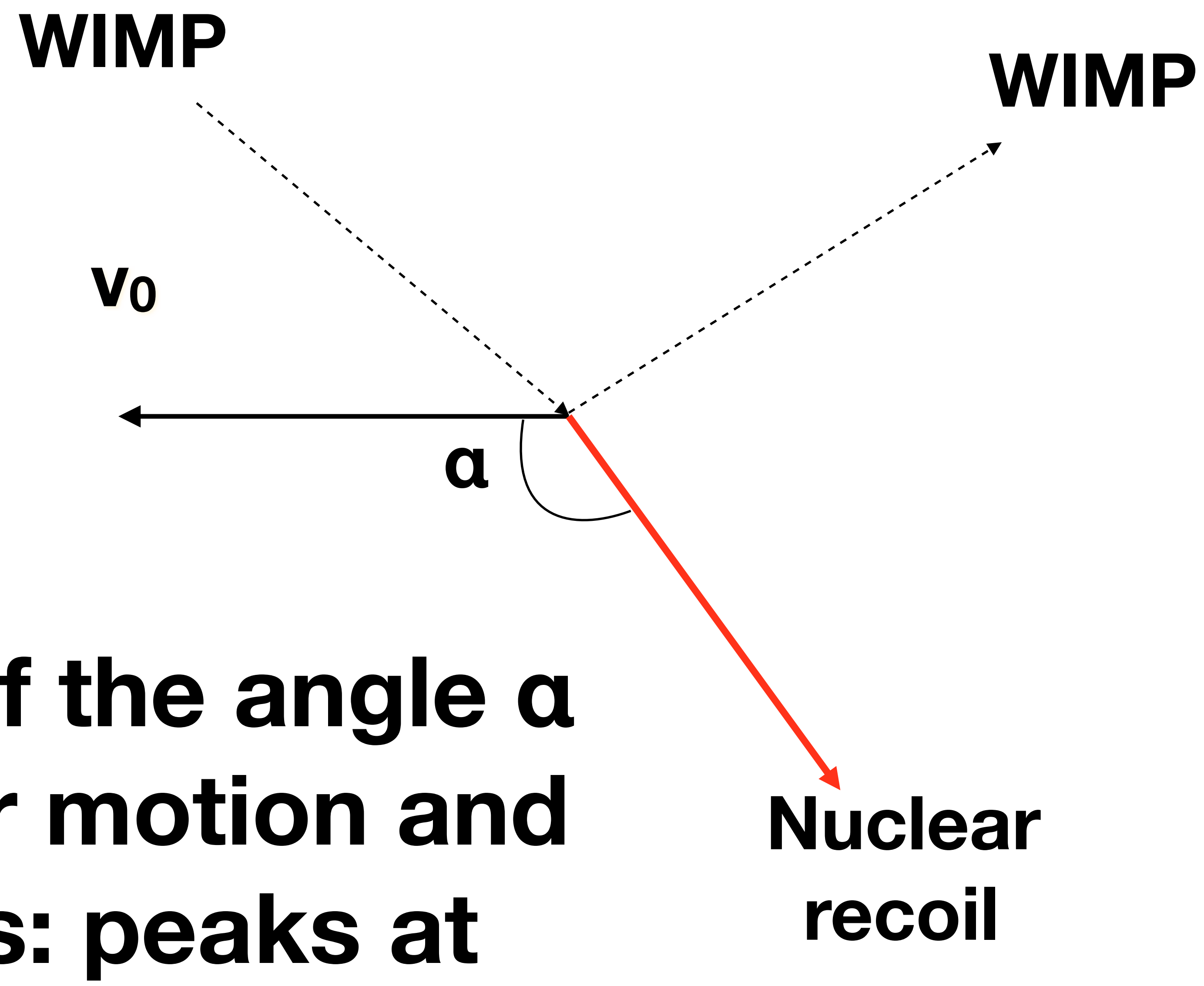
Target: Ge
$\sigma_{SI} = 1\text{x}10^{-4}$ pb
$M_X = 10$ GeV/cm^2

The modulation shape is target dependent!

Diurnal Modulation (a.k.a. Directional Detection)

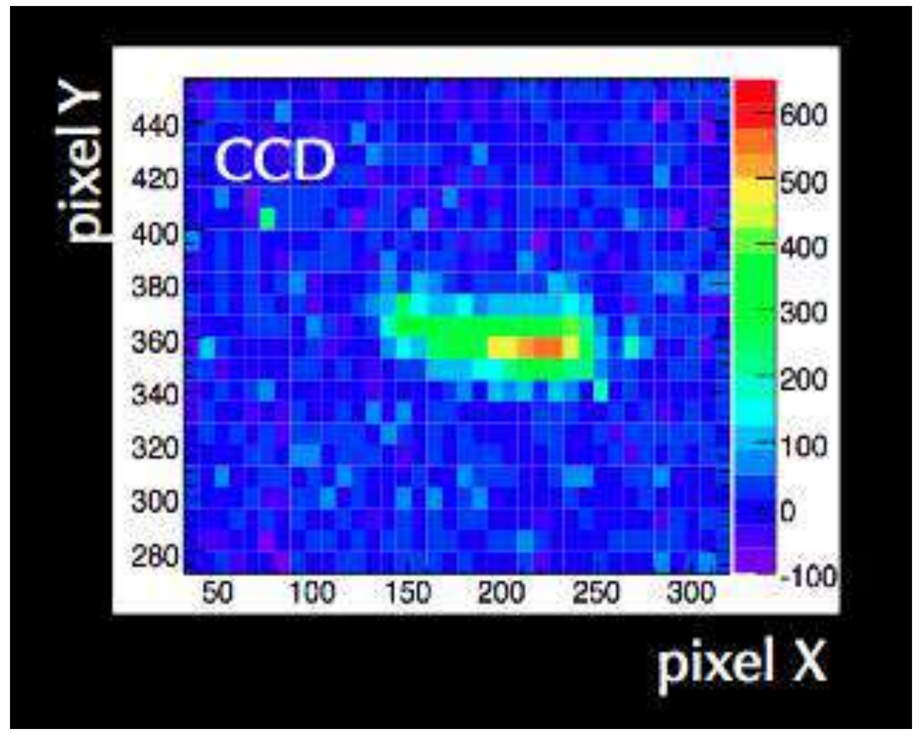


The mean recoil direction rotates over one sidereal day



The distribution of the angle α between the solar motion and recoil directions: peaks at α=180°

Low pressure TPC's preserve dE/dx profile such that "head to tail" measurement can be made



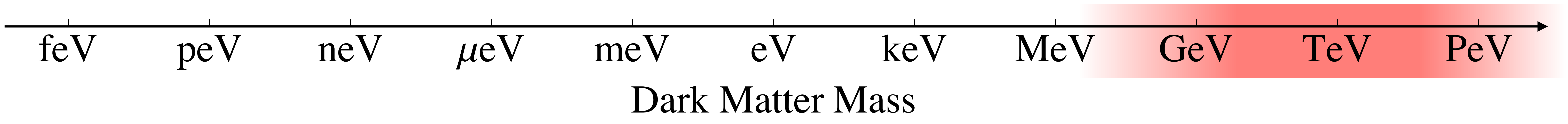
Summary of Nuclear Recoil Direct Detection Requirements

1: Large Exposure (Mass x Time)

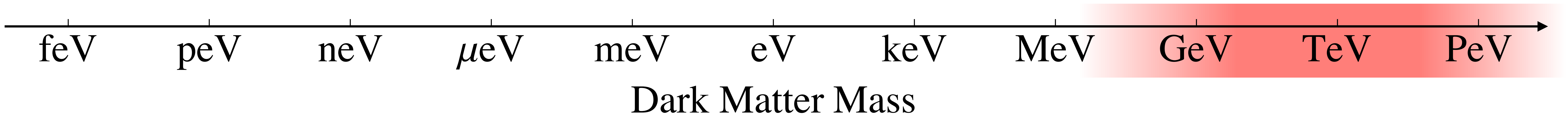
2: Low Energy Threshold

3: Low Backgrounds

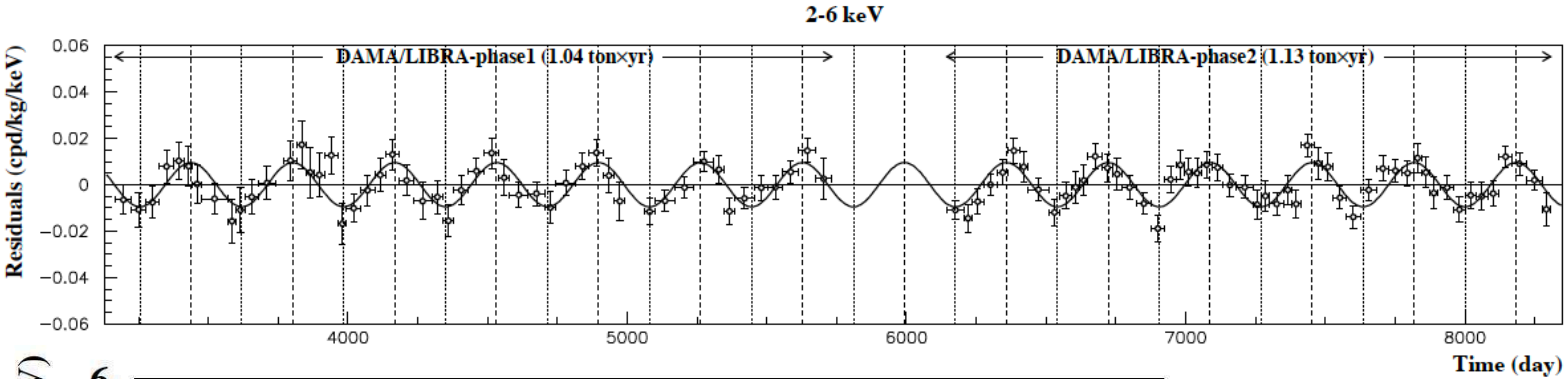
4: Discrimination between Signal and Backgrounds

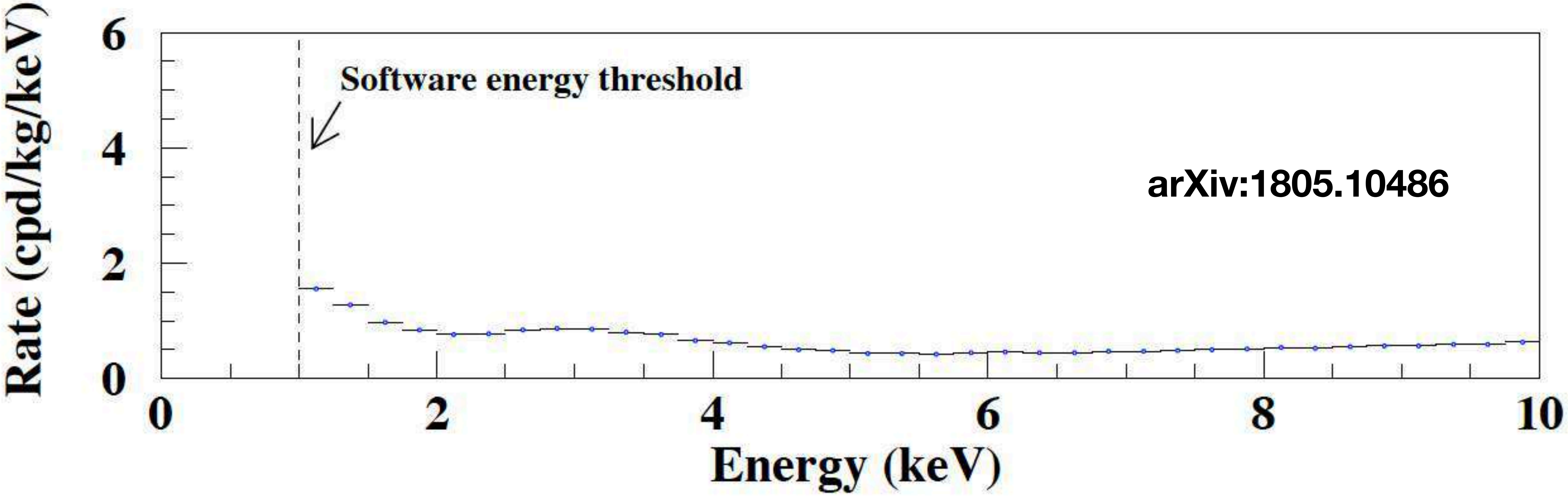


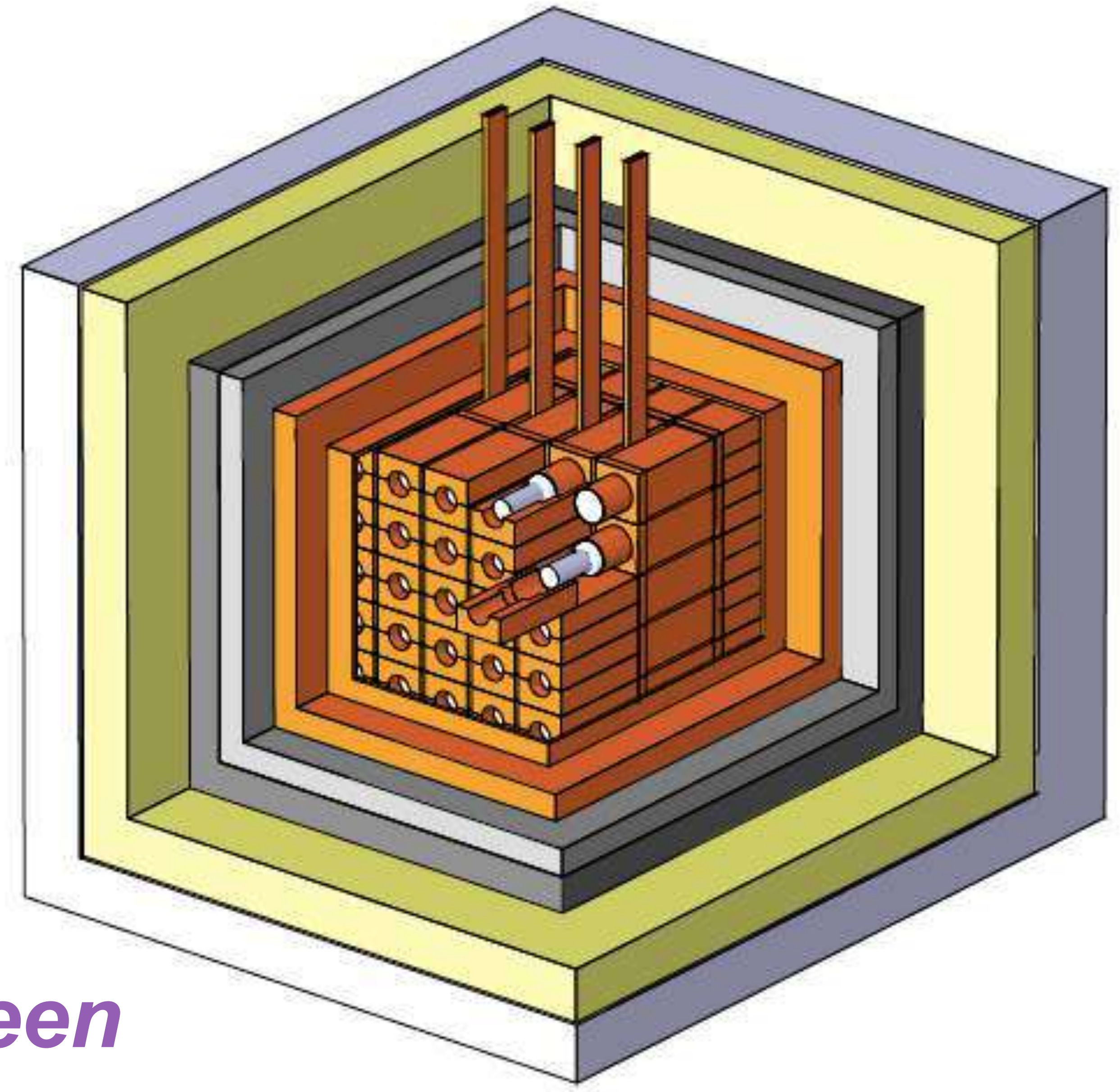
WIMP Direct Detection Technologies, Experiments, and Current Results



DAMA/LIBRA: a Model-Independent Signal







DAMA/NaI and successor DAMA/LIBRA operate large arrays of NaI detectors. Their combined data yield a 12.9σ modulation consistent with dark matter. It has never been verified by another experiment, yet no one has a really good alternative explanation.

Non-dark matter explanations for the modulation

- Alternative sources of modulation have been proposed
  - DAMA has addressed some of these

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5\times10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1\text{-}2\times10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured at LNGS	$<3\times10^{-5}$ cpd/kg/keV

Slide taken from DAMA/LIBRA

Further discussed in:
EPJC 56:333 (2008),
EPJC 72:2064 (2012),
EPJC 74:3196 (2014)

Modulation Amplitude in Signal is ~ 1×10^{-2} cpd/kg/keV

Checking DAMA with NaI Detectors

Northern Hemisphere	Gran Sasso **DAMA/LIBRA** 250 kg running	Boulby **DM-Ice North** 37 kg R&D 250 kg planned	Canfranc **ANAIS** 37 kg R&D 250 kg planned	Y2L **KIMS** 45 kg R&D 200 kg planned	Gran Sasso **SABRE** R&D	Kamioka **PICO-LON** **KamLAND-PICO** R&D
Southern Hemisphere		South Pole **DM-Ice** 17 kg running 250 kg planned			Stawell **SABRE** Lab completion 2017	rock ice

Ultra-pure crystal development underway by DM-Ice, KIMS, ANAIS, SABRE, and PICO-LON collaborations

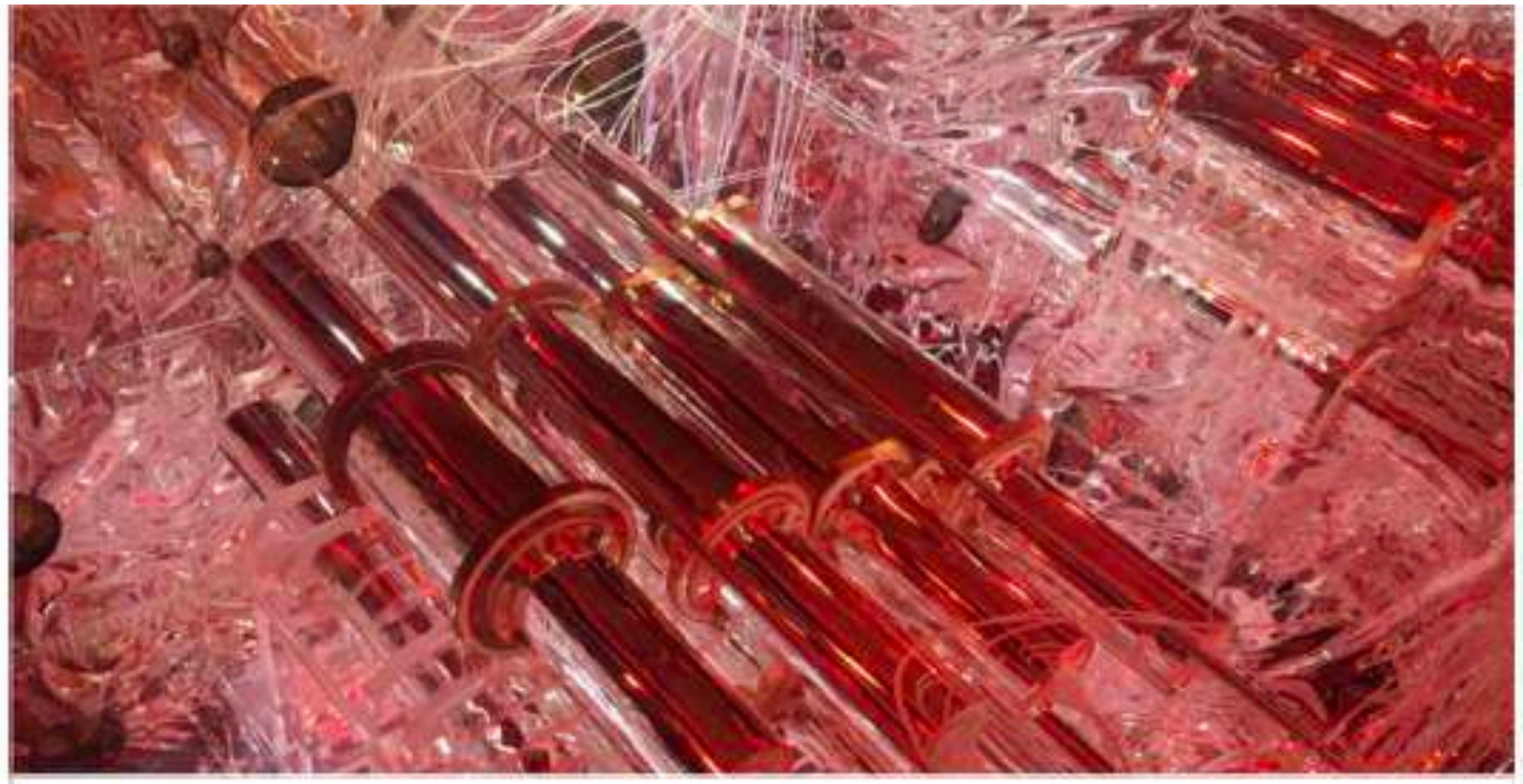
South Pole offers:

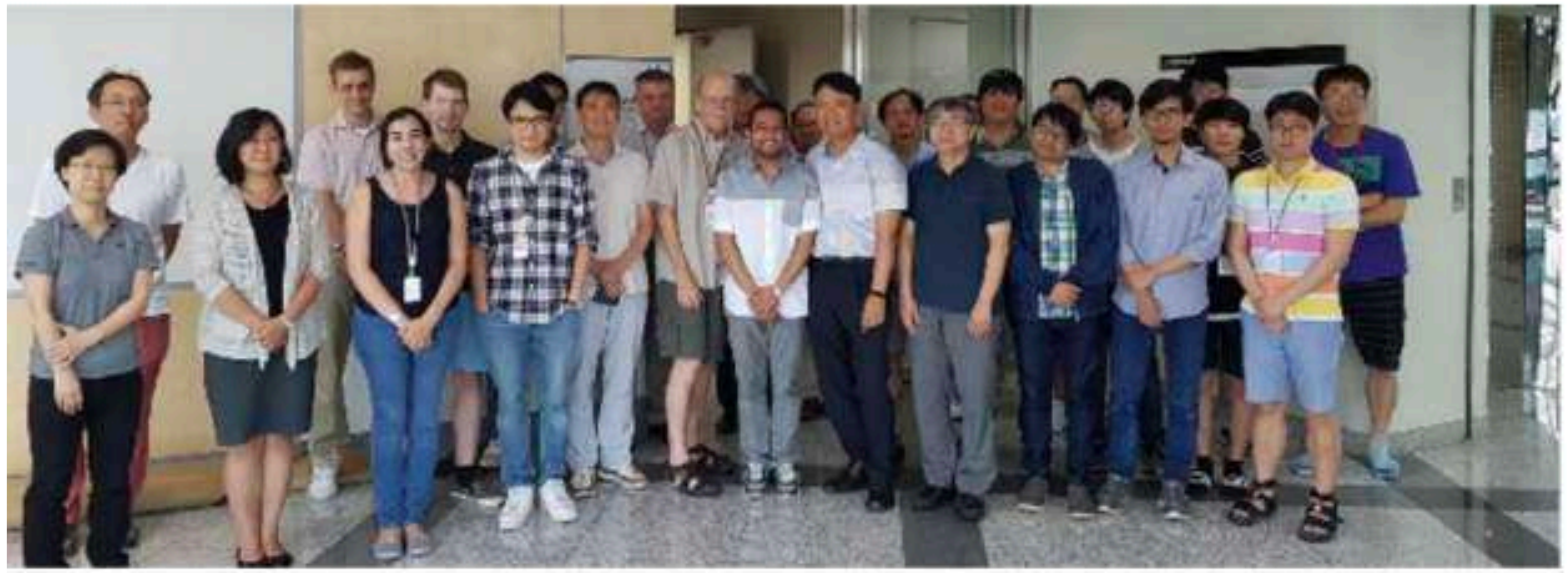
- Ultra-clean and ultra-stable environment
- Seasonal variation unambiguously different from dark matter modulation
- IceCube offers muon monitoring and veto as well as experience
- NSF-run South Pole Station for logistical support

Note: Annual Modulation is also being looked for with other detector technologies!

The COSINE-100 Experiment @ Yangyang

- Model-independent test of DAMA's result
- 106 kg of same target material (NaI(Tl))
- Located 700 m underground at Yangyang Underground Lab in Korea
- Physics run began Sept. 2016





KIMS Korea Invisible Mass Search Experiment + DM-ICE

KiSTi KRISS

The University Of Sheffield.

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Yale

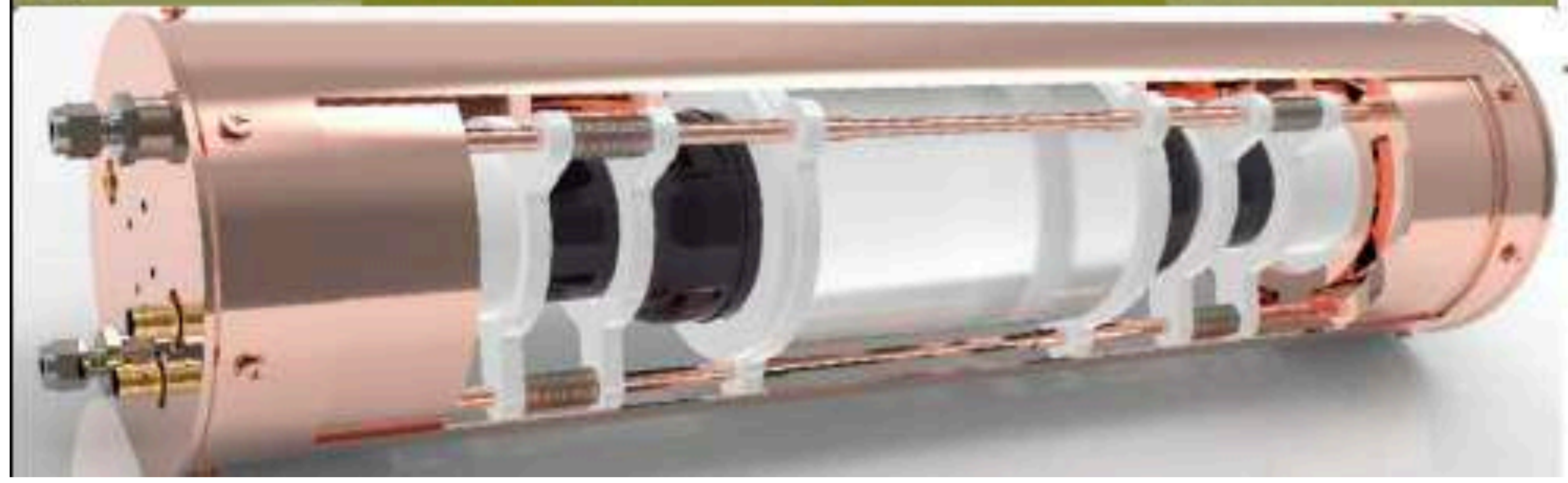
The SABRE Experiment @ LNGS & Stawell

Ultrapure NaI:Tl Target Detector

Intrinsic radioactivity limits WIMP sensitivity.
SABRE has made the most radiopure NaI:Tl to date.

- 'Astrograde' powder (Sigma Aldrich).
- Carefully-developed powder preparation and growth protocols (Princeton + RMD).

Lower radioimpurity than DAMA.
Production growth underway.
High QE + low background PMTs: 1 keV threshold design.



Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal [ppb]
K	100	~13	9	9
Rb	n.a.	<0.35	<0.2	<0.1
U	~0.02	0.5-7.5$\times 10^{-3}$	$<10^{-3}$	$<10^{-3}$
Th	~0.02	0.7-10$\times 10^{-3}$	$<10^{-3}$	$<10^{-3}$

The ANAIS Experiment @ Canfranc

ANAIS-112:

- Commissioning in March-April 2017
- Calibration and general assessment from April to July 2017
- **Dark matter run** is underway since **3rd, August 2017**: first year of data taking is about to be successfully completed

DM-ICE 17

Location: South Pole, Antarctica

Depth: 2457 m (2200 m.w.e)

Deployment: Dec. 2010

Science Run: Jun. 2011 – Jan. 2015

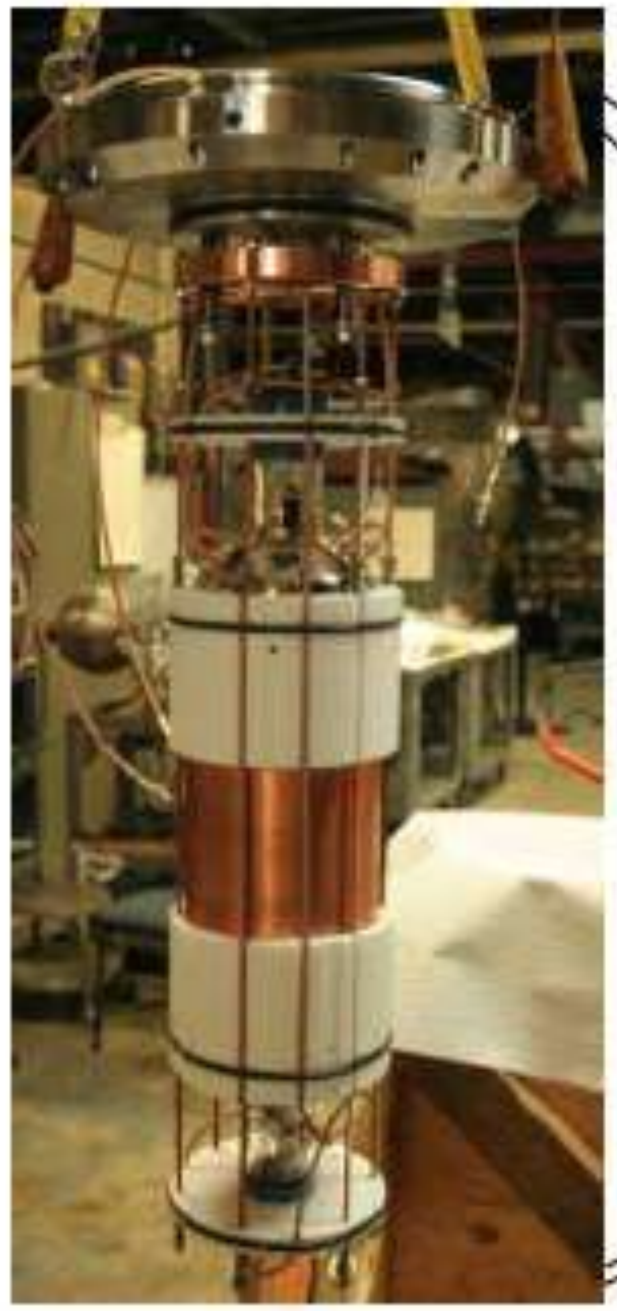
Uptime: > 99%

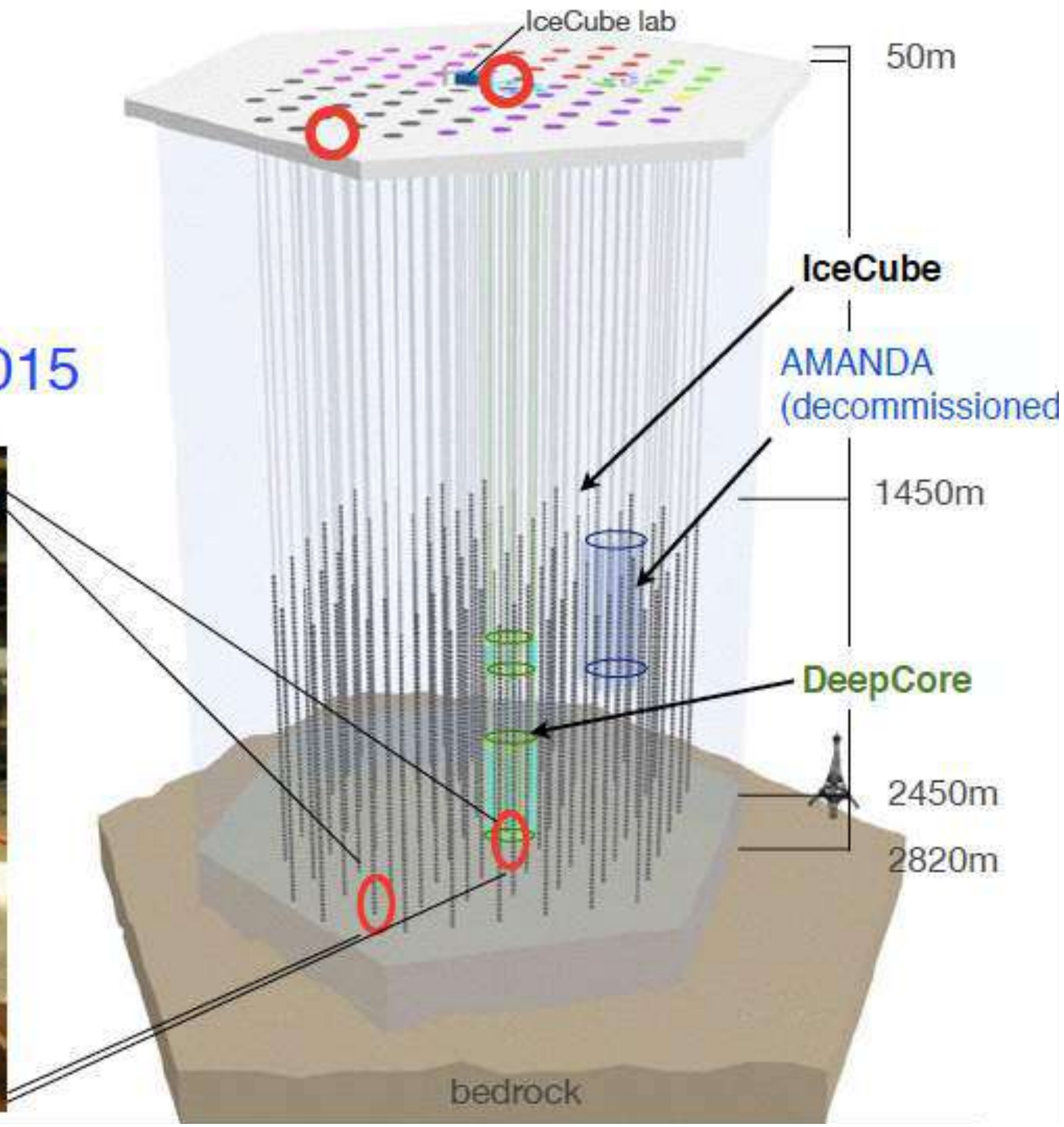
Exposure: 60.8 kg-yr

Target: NaI(Tl)

Mass: 2 x 8.5 kg

Still going…

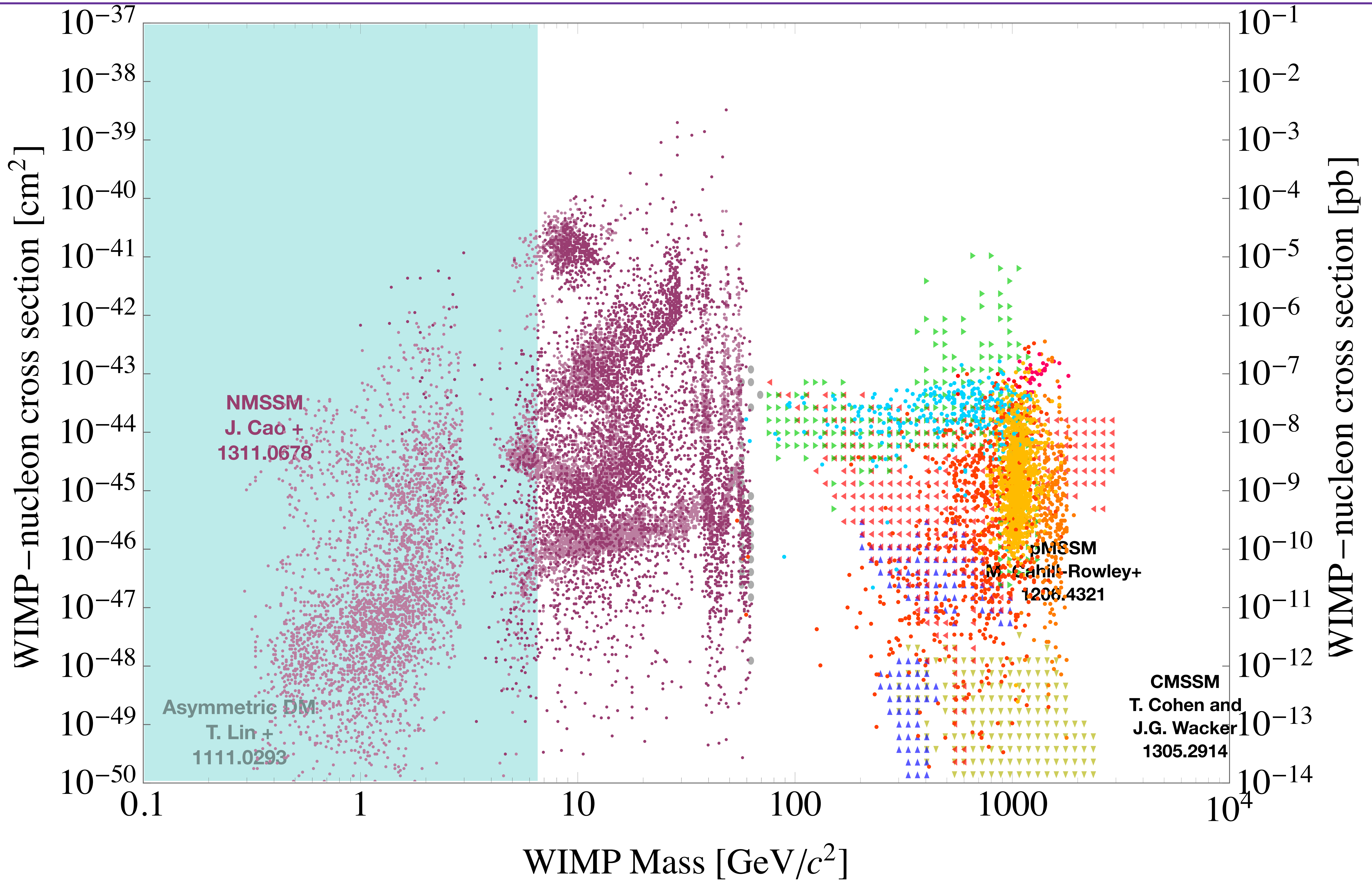




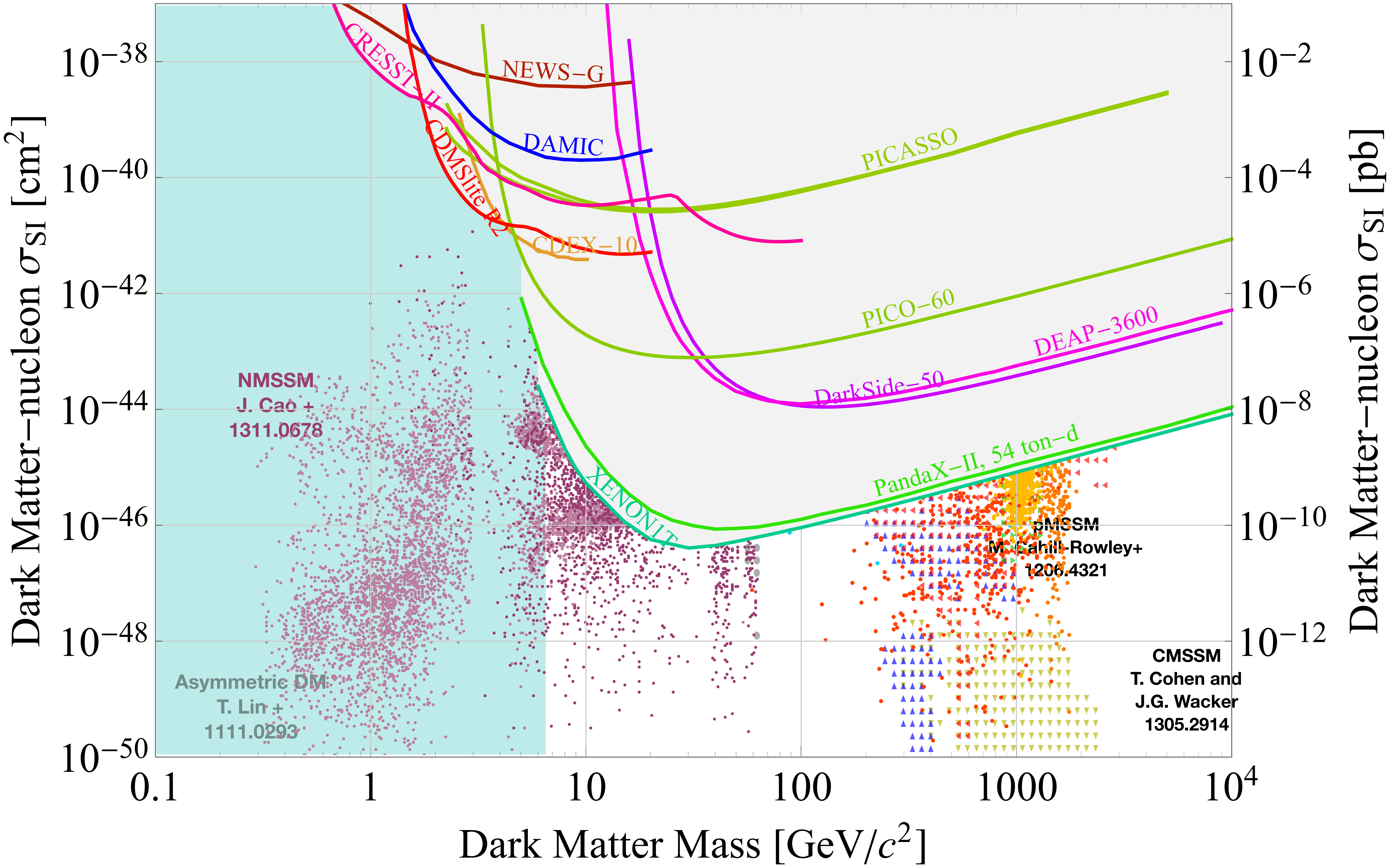
DAMA/LIBRA: Dark Matter or Not?

This question will be answered in a year or two!

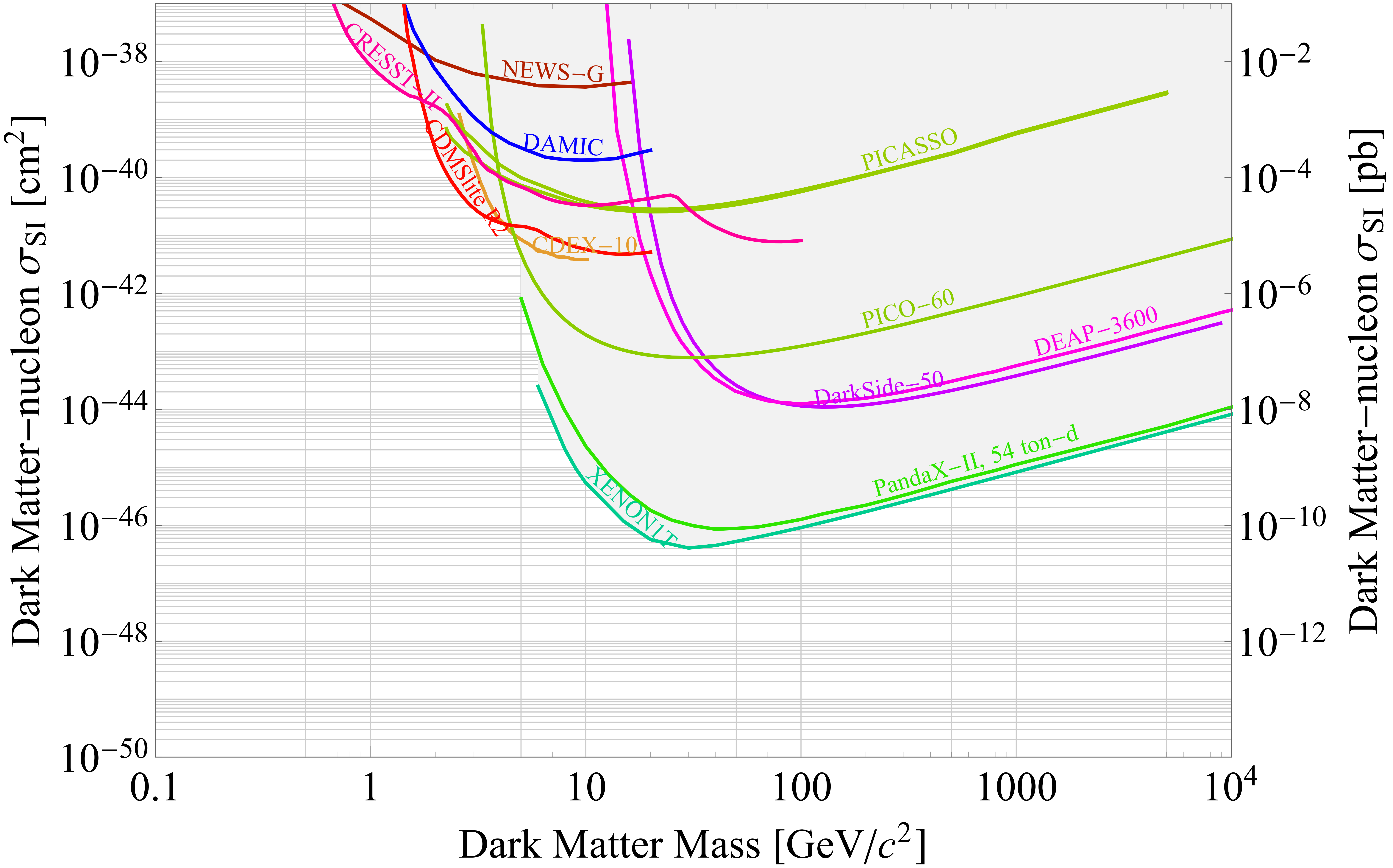
The Model-Dependent Playing Field



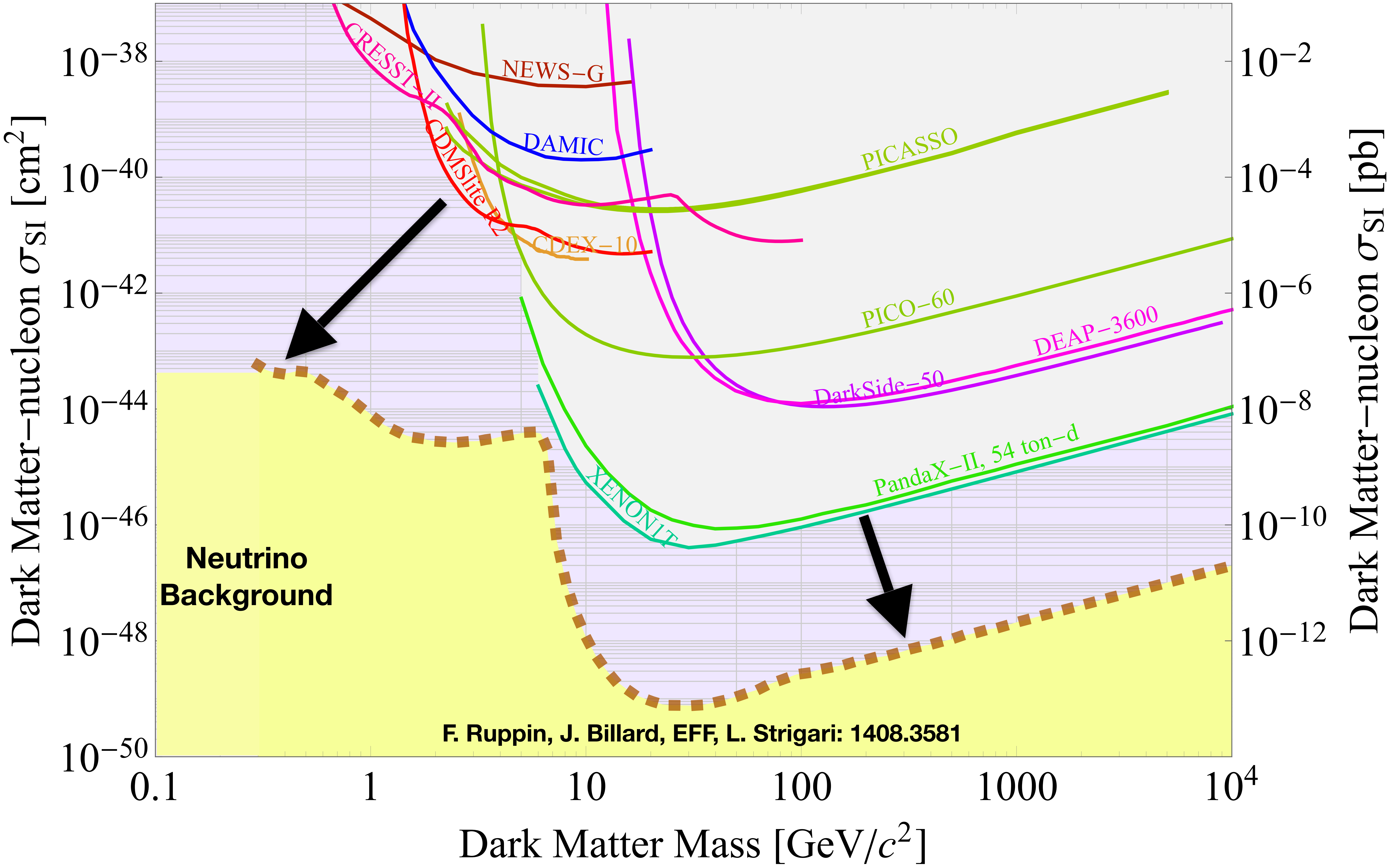
Current Limits



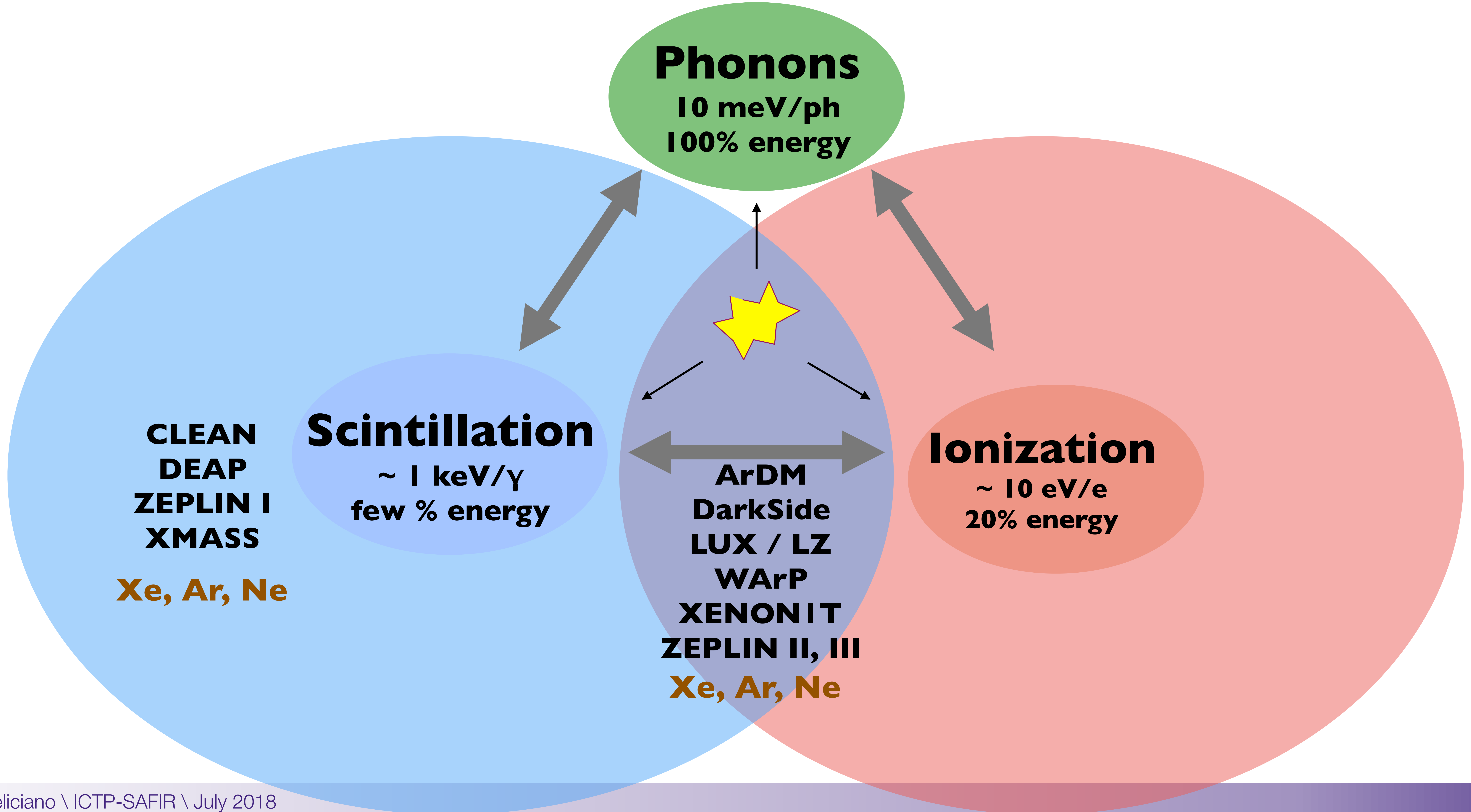
How Far Can We Push?



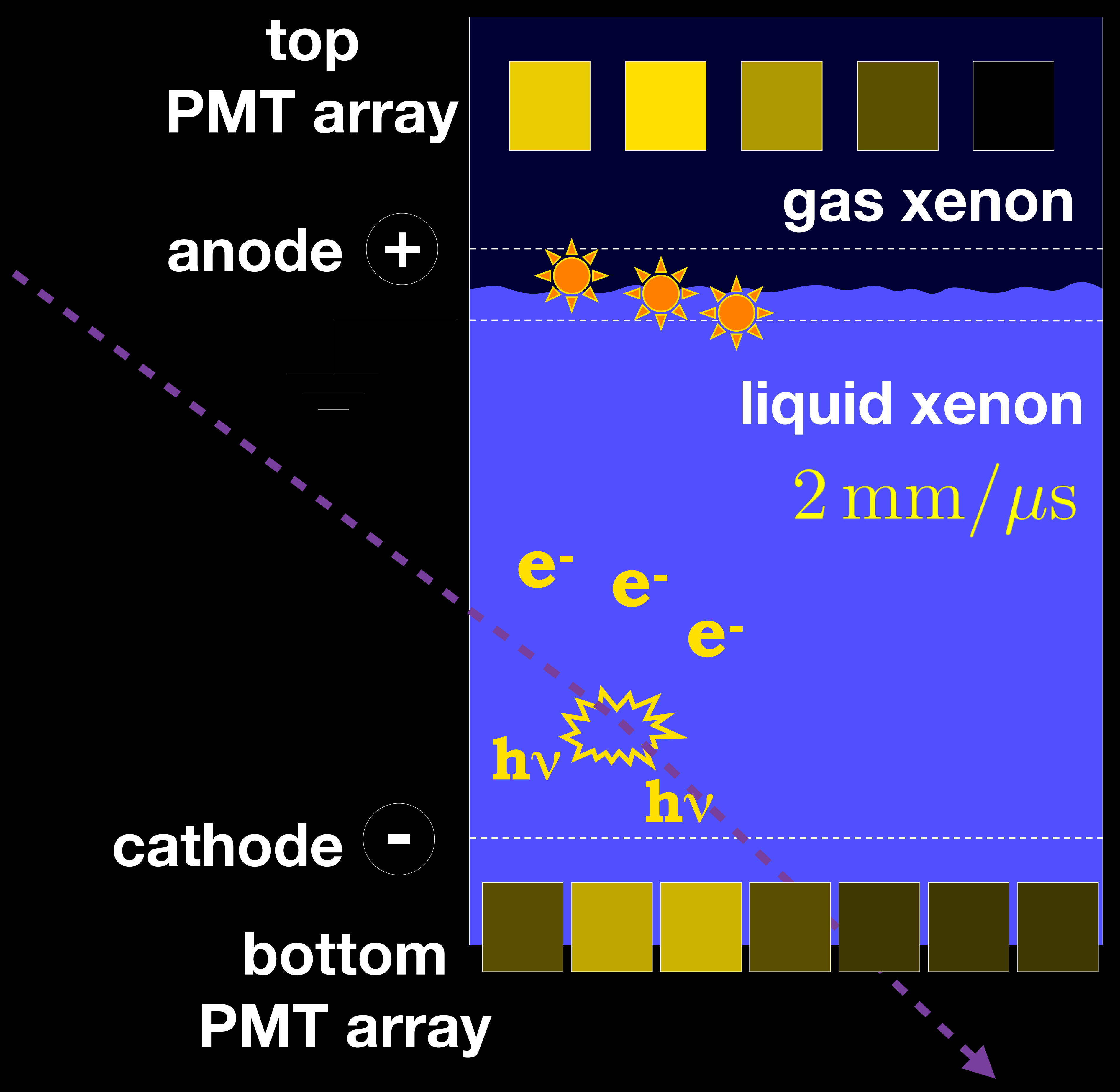
To Neutrinos, and Beyond!



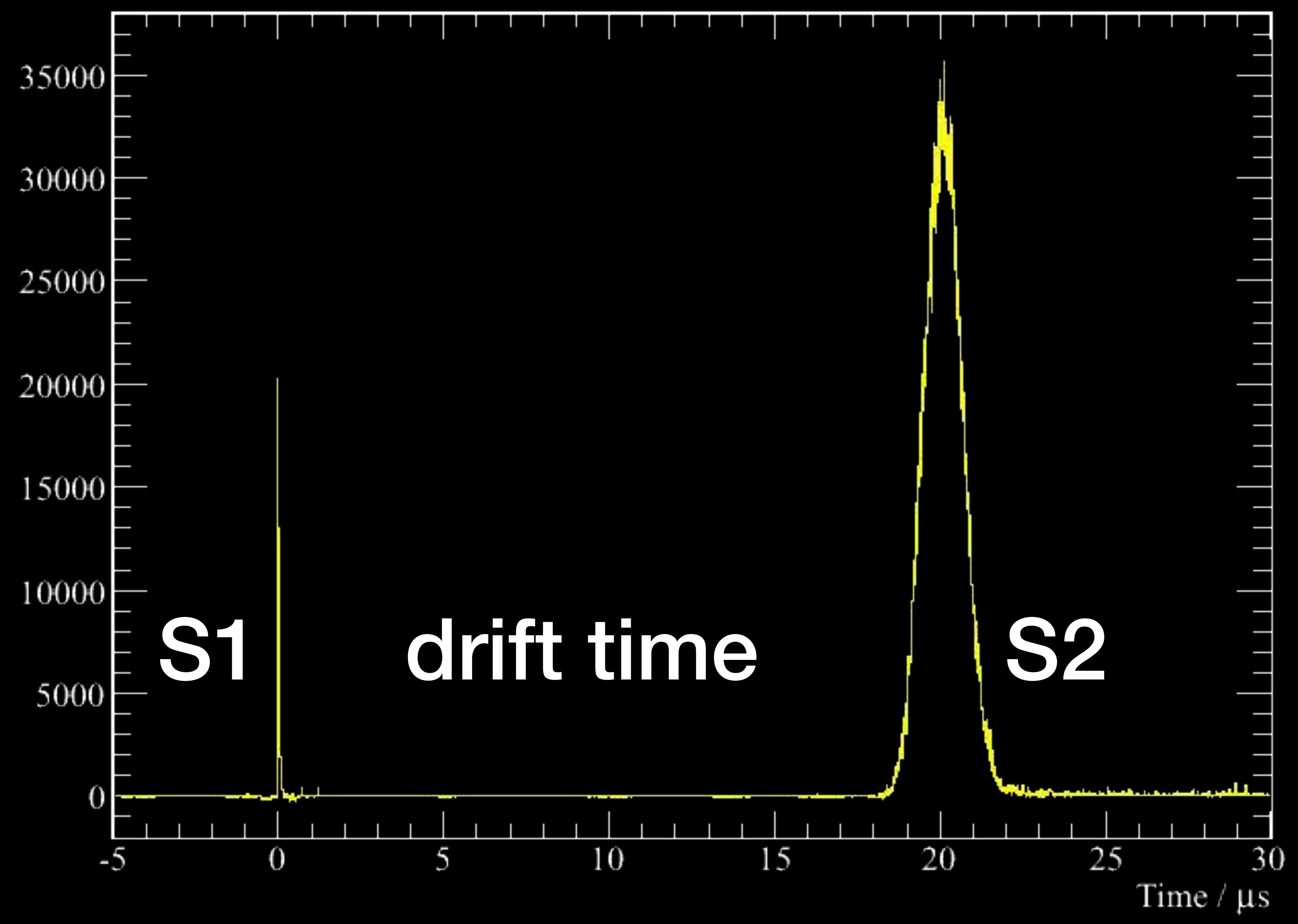
Noble Liquid Detectors



Noble Liquid Time Projection Chambers

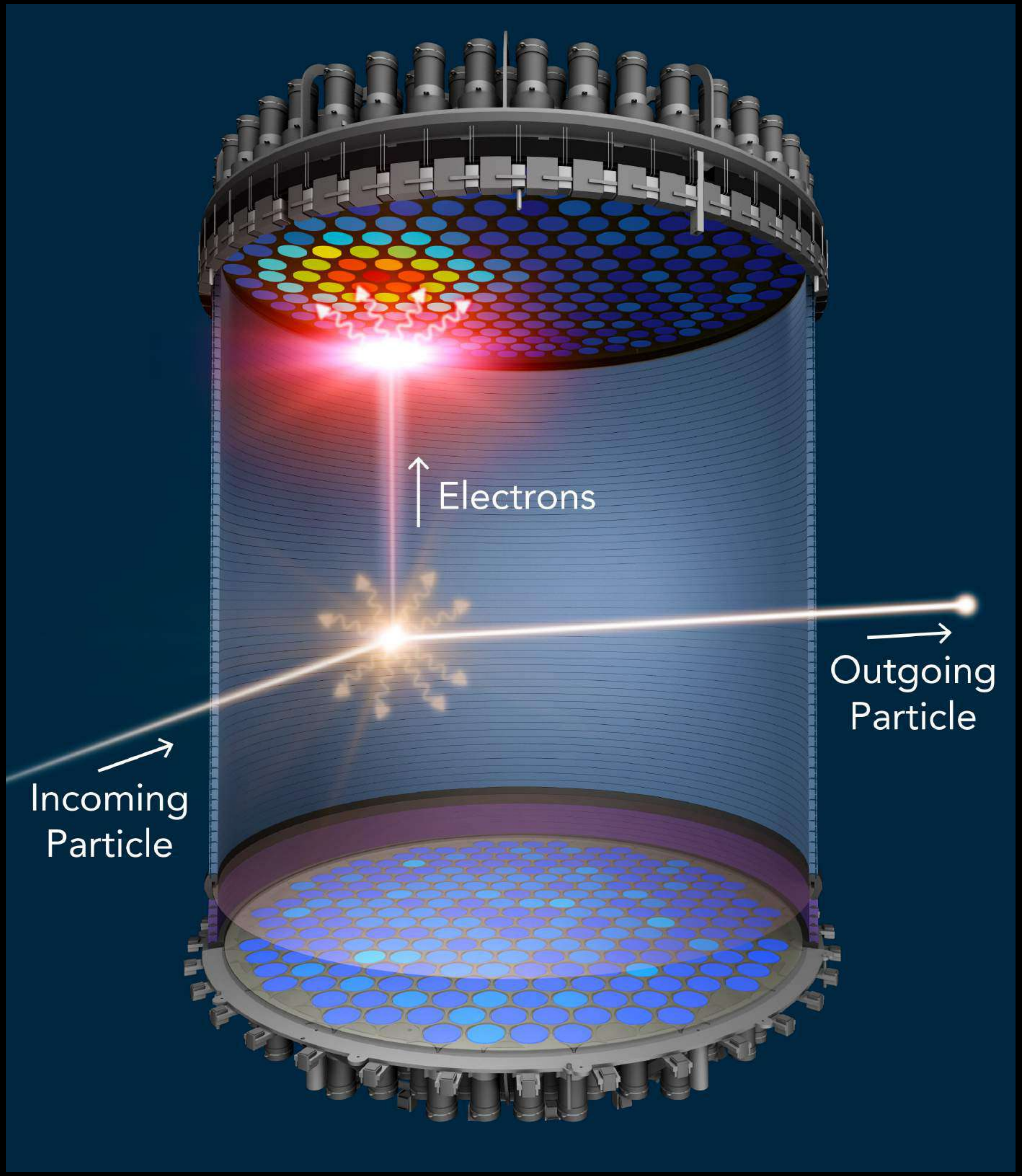


- Obtain vertex position from S2 hit pattern and drift time
- Ratio of S2/S1 provides nuclear/electron recoil discrimination



Slide curtsey of Rafael Lang

Noble Liquid Time Projection Chambers



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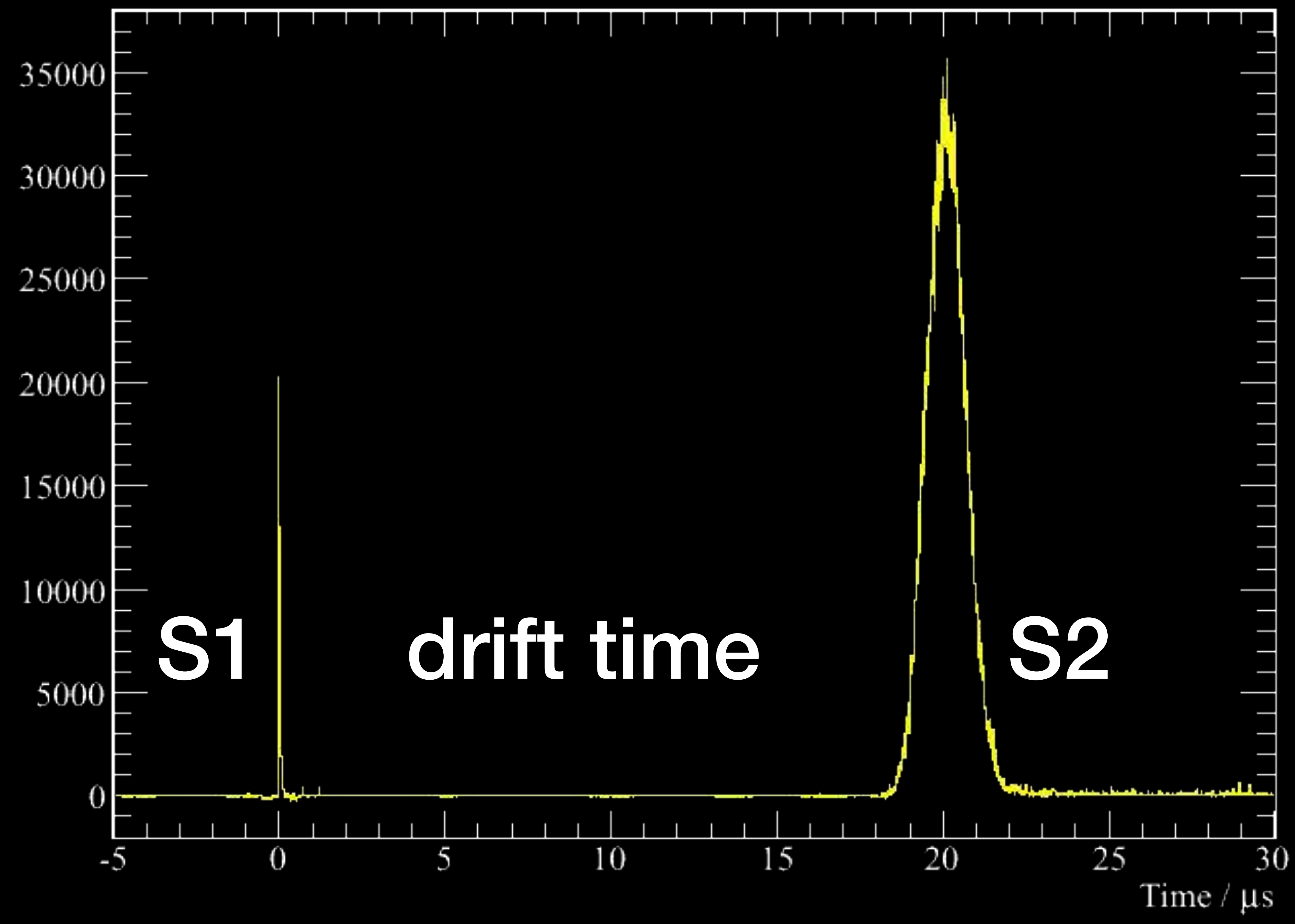
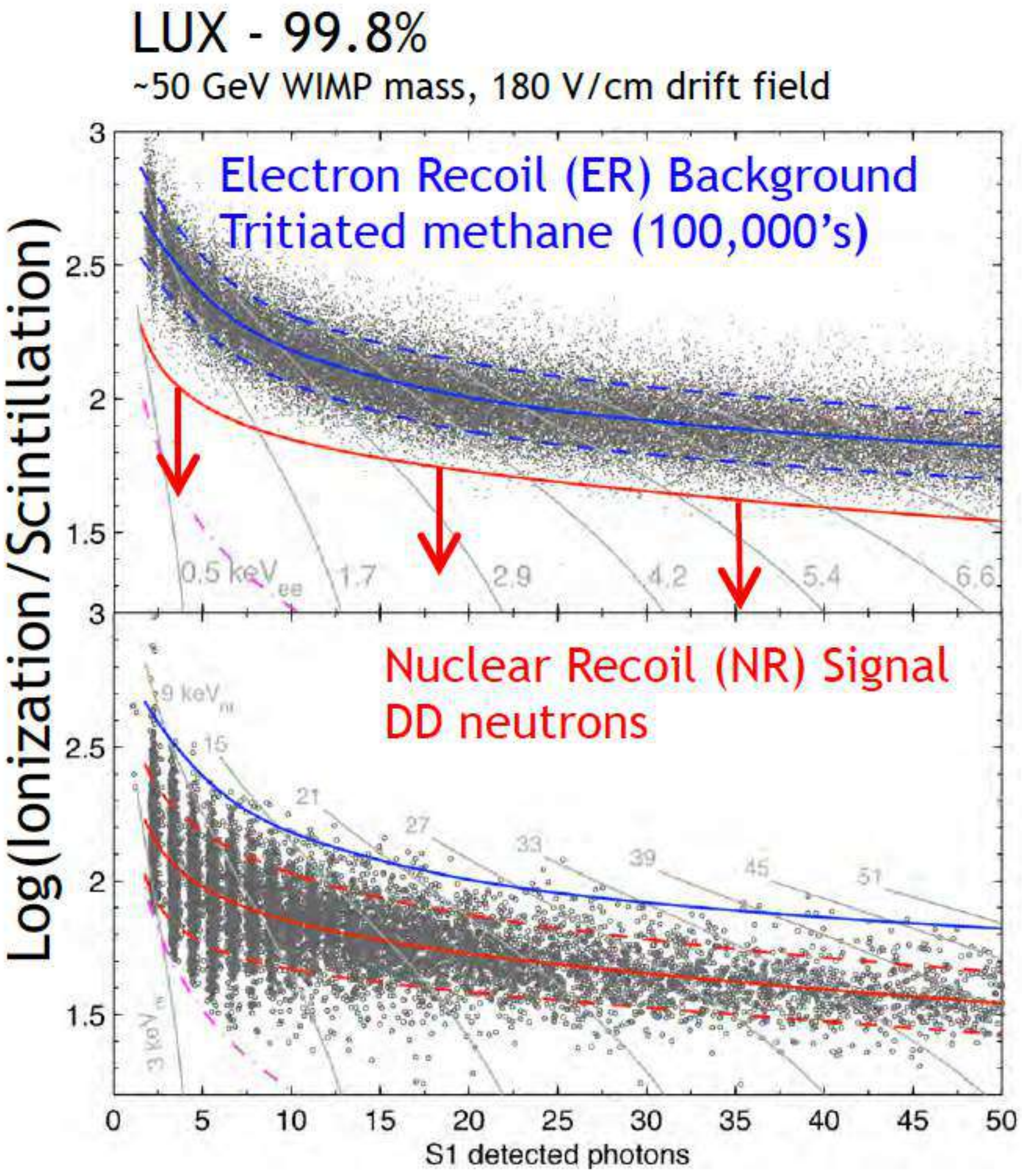


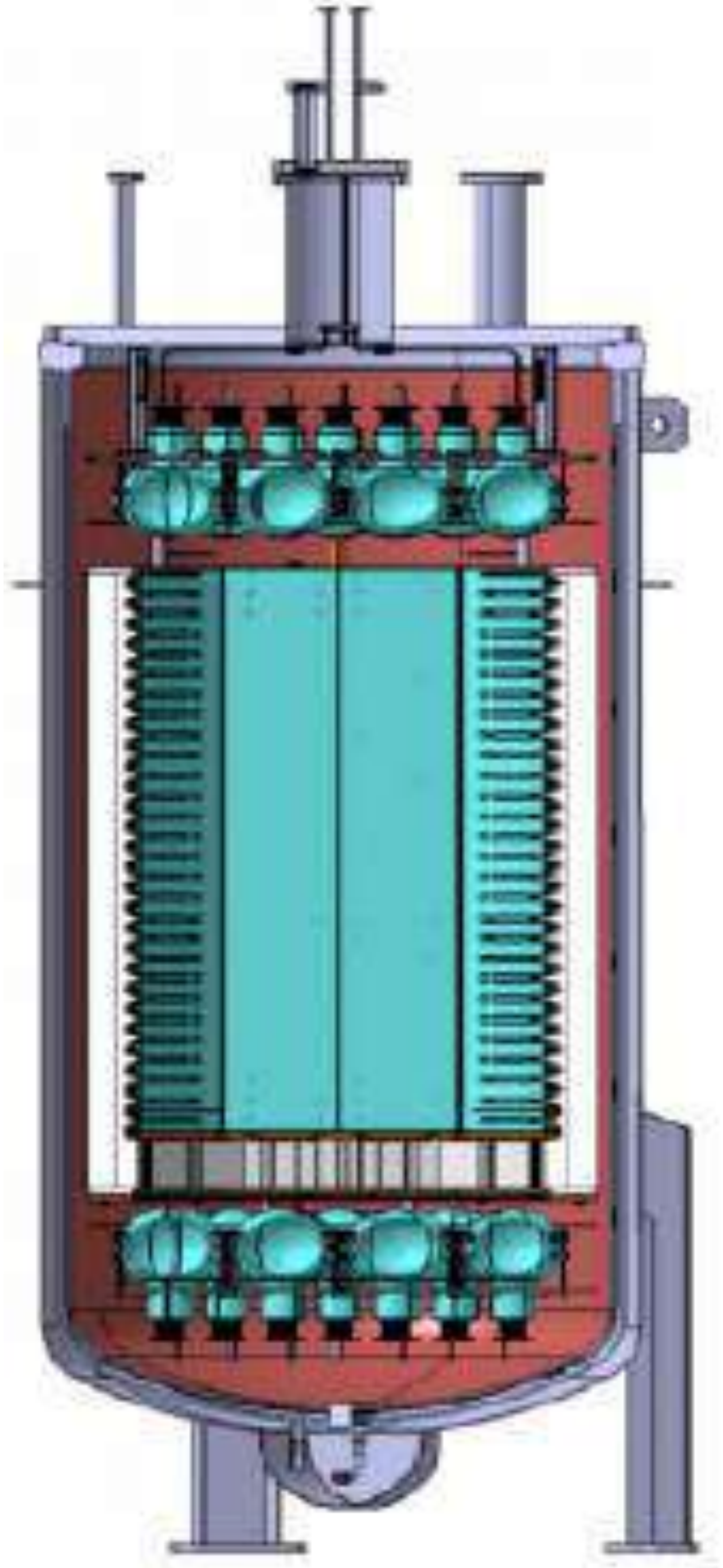
Signal Production in Noble Liquids

- Electron Recoils and Nuclear Recoils are Separated in Log(S2/S1) vs S1 plane
- Look for WIMPs below the mean of the nuclear recoil distribution (the red line in the plot)

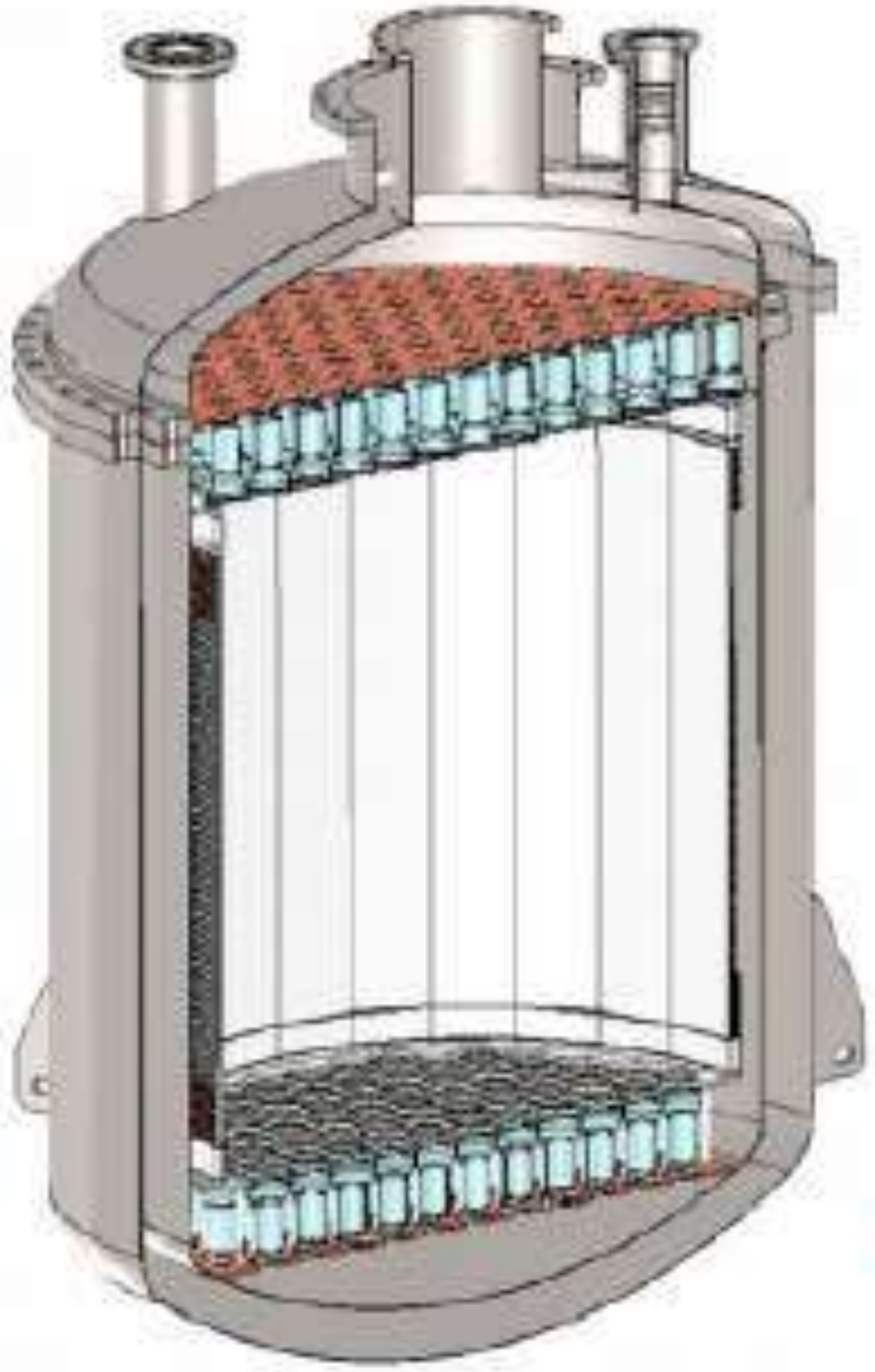


Noble Liquid Time Projection Chambers

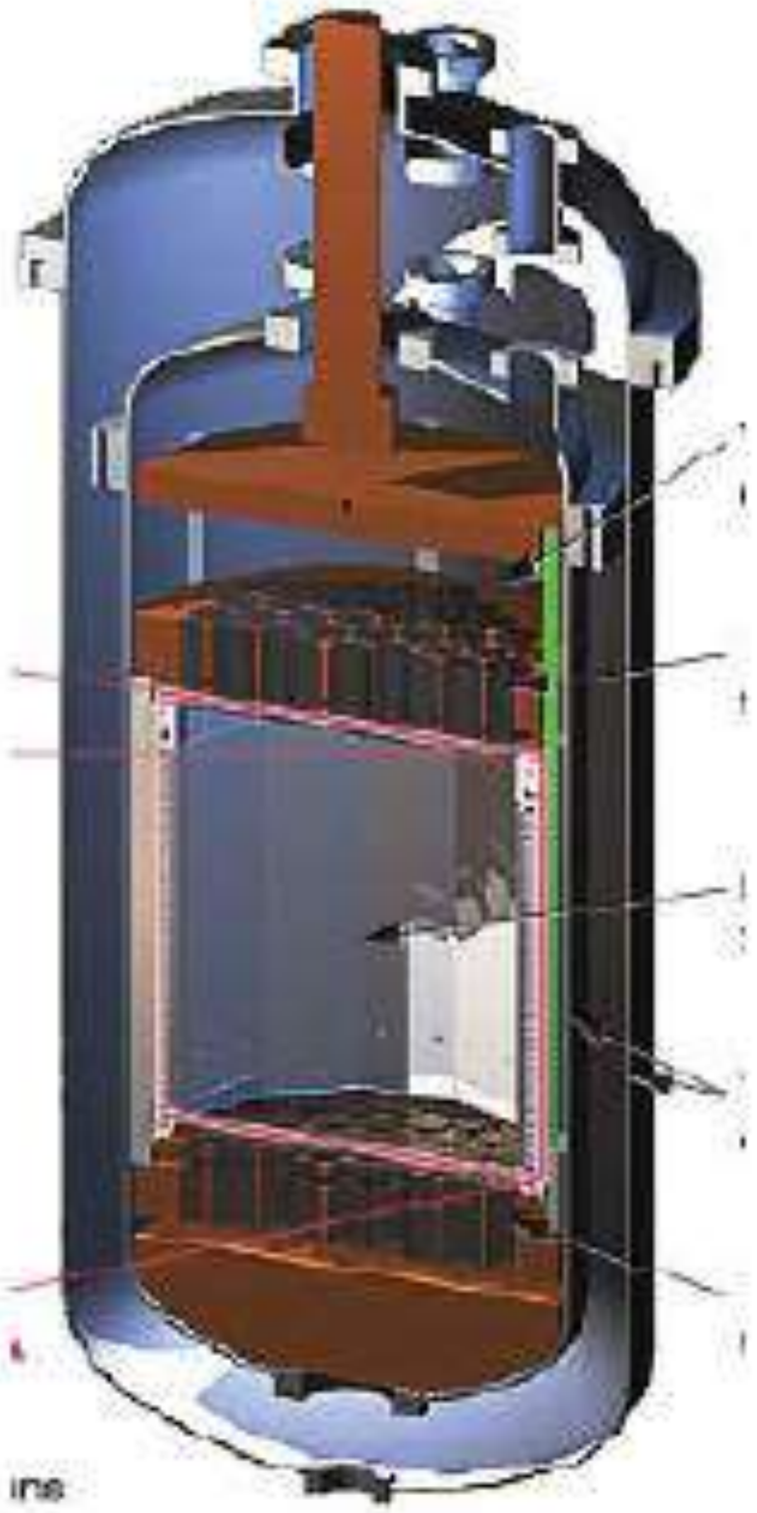
ArDM



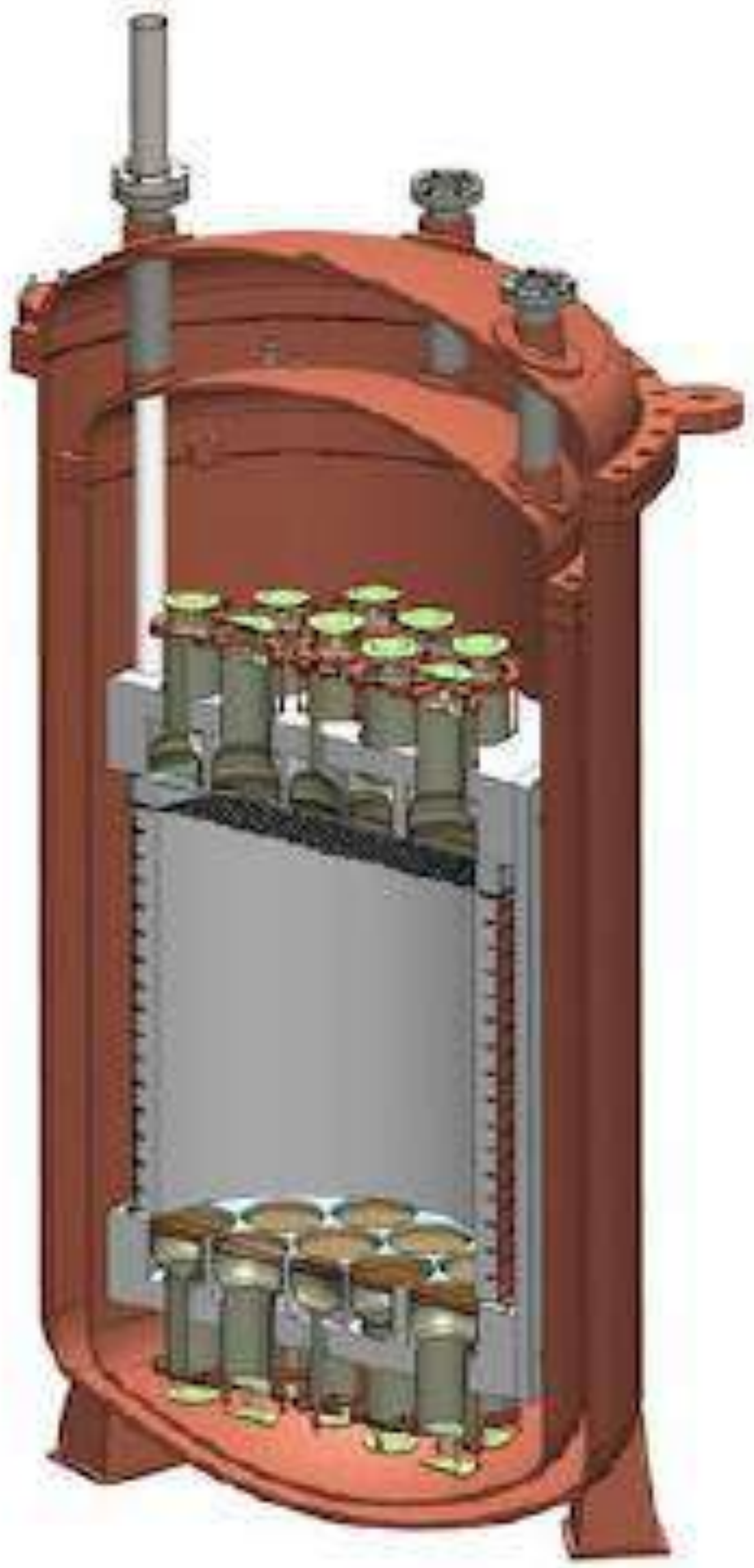
XENON1T



LUX



DarkSide-50



NOT TO SCALE!

XENON1T: Current World-leading Limit > 6 GeV

Laboratori Nazionali del Gran Sasso

XENON1T: Current World-leading Limit > 6 GeV

LARGEST
2-PHASE LXE TPC

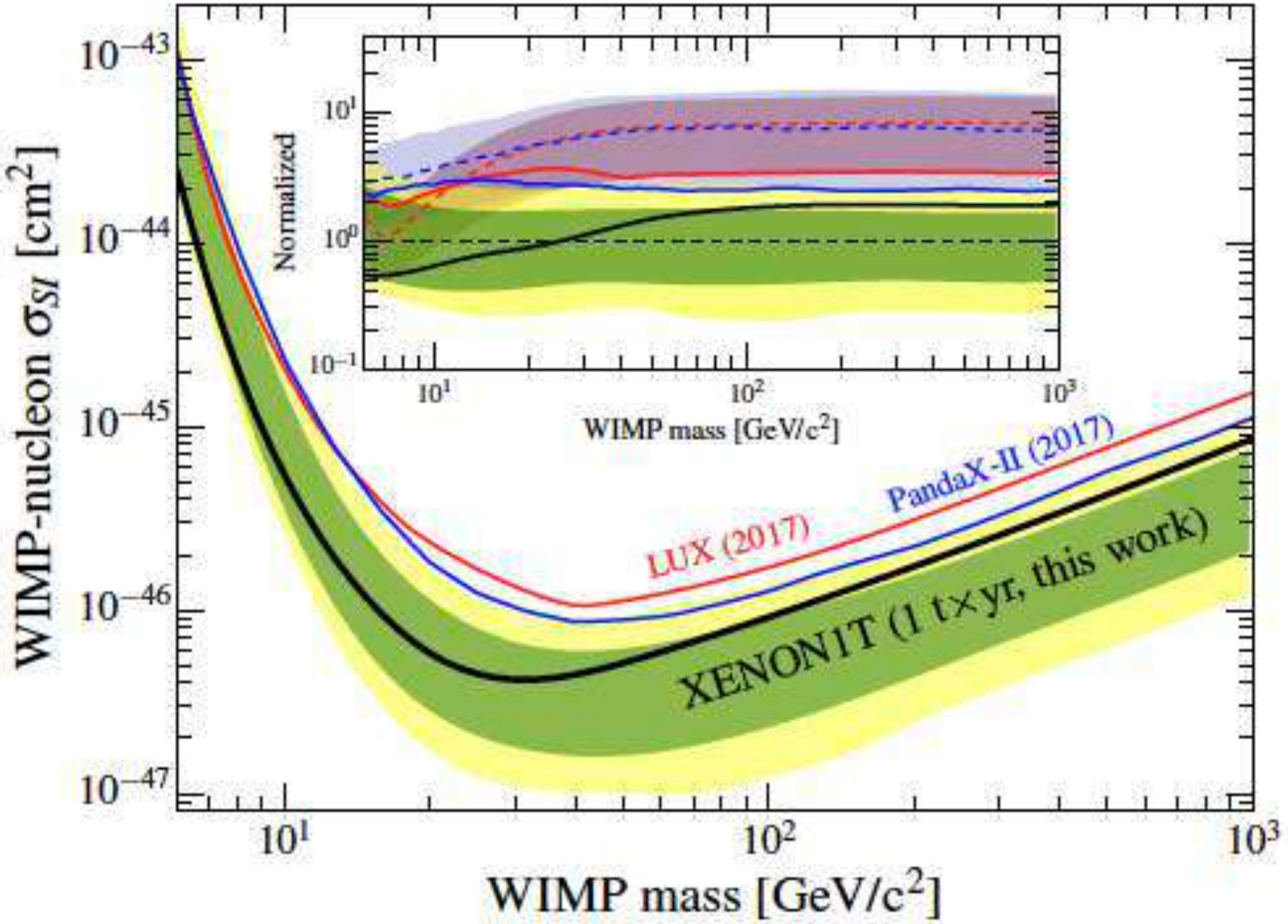
TPC

2-tonne Active Volume
(3.2 t total)

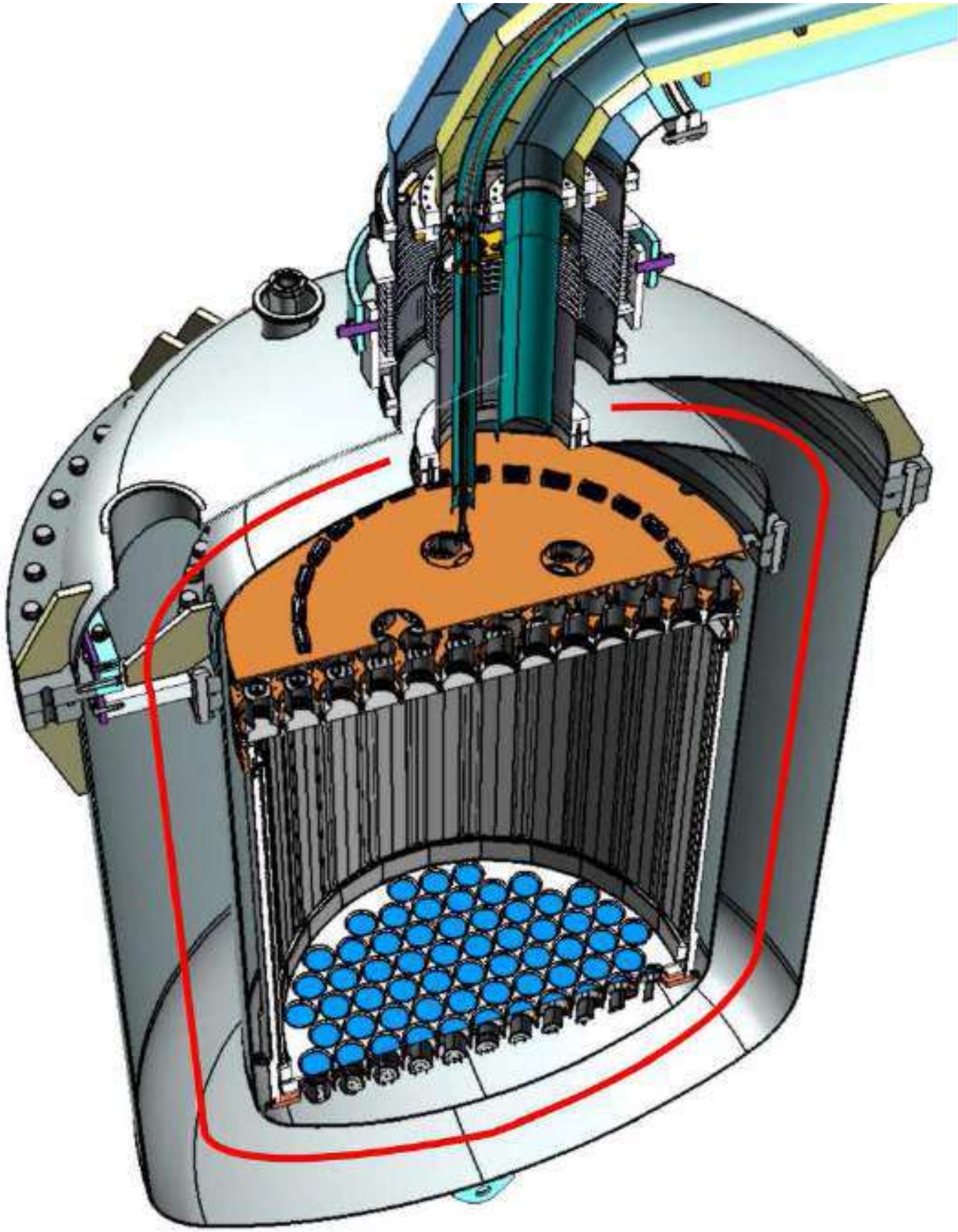
121+127 low-background Hamamatsu 3" PMTs

1m-long Drift Region

Drift Field ~100 V/cm

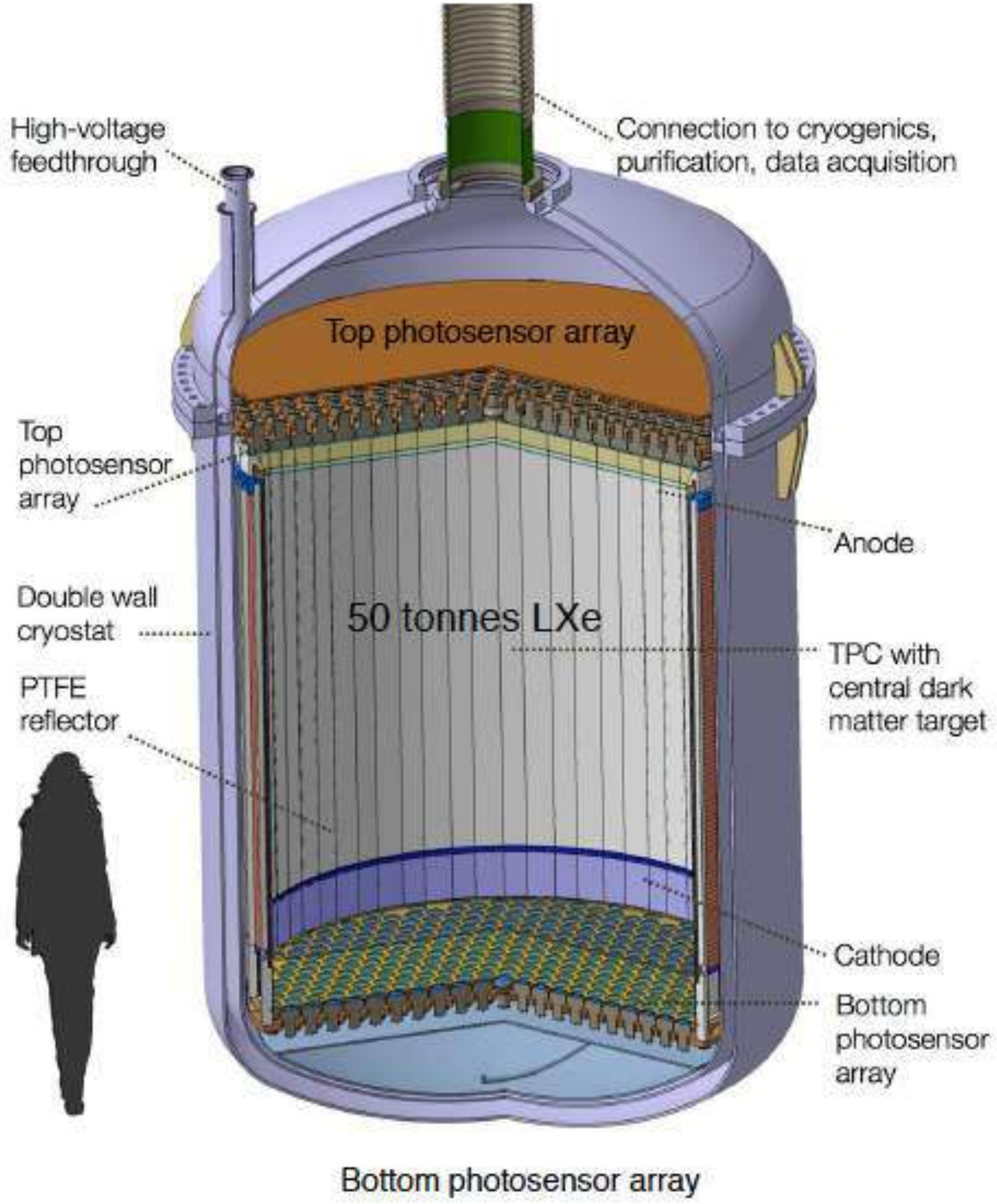


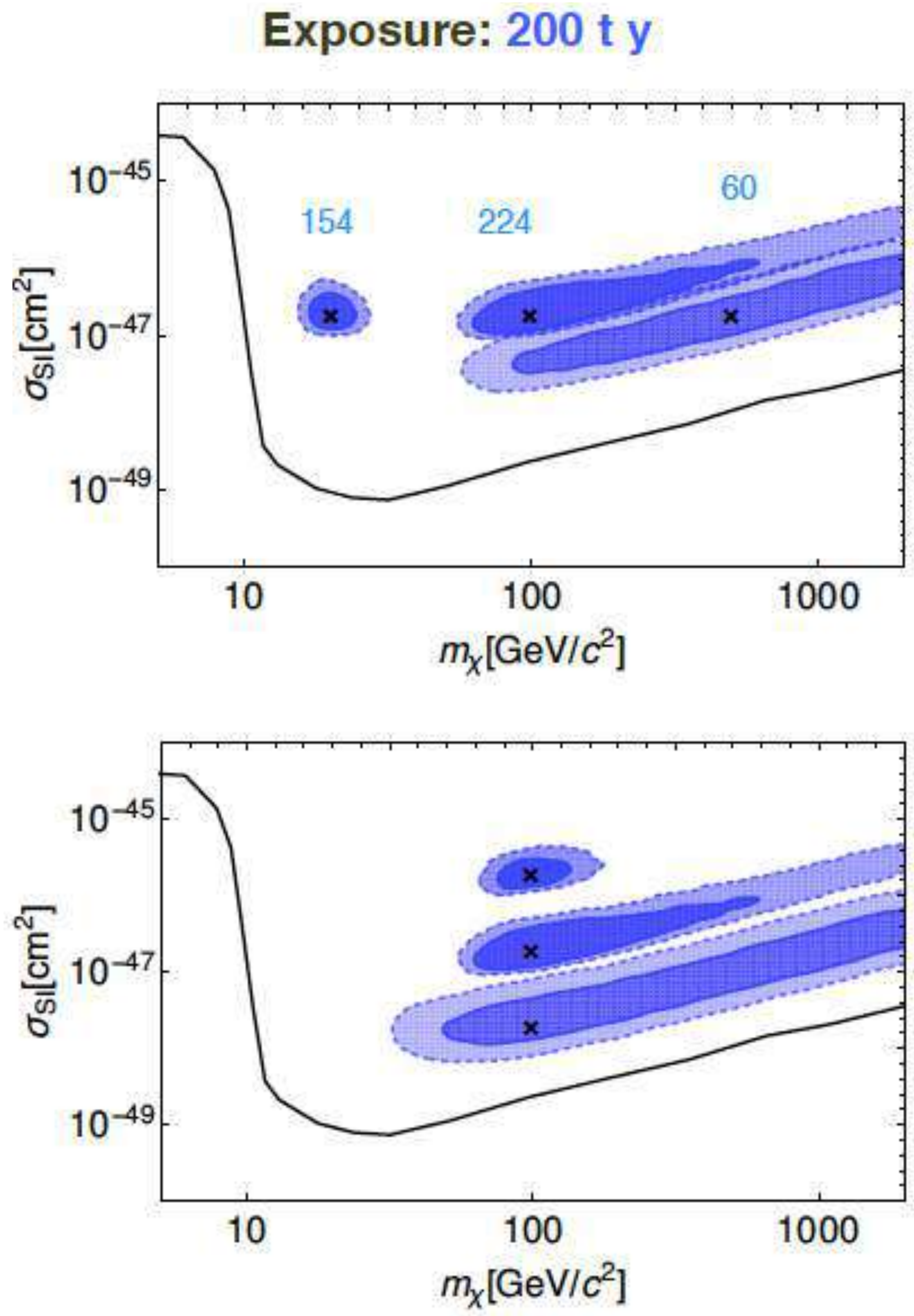
XENONnT



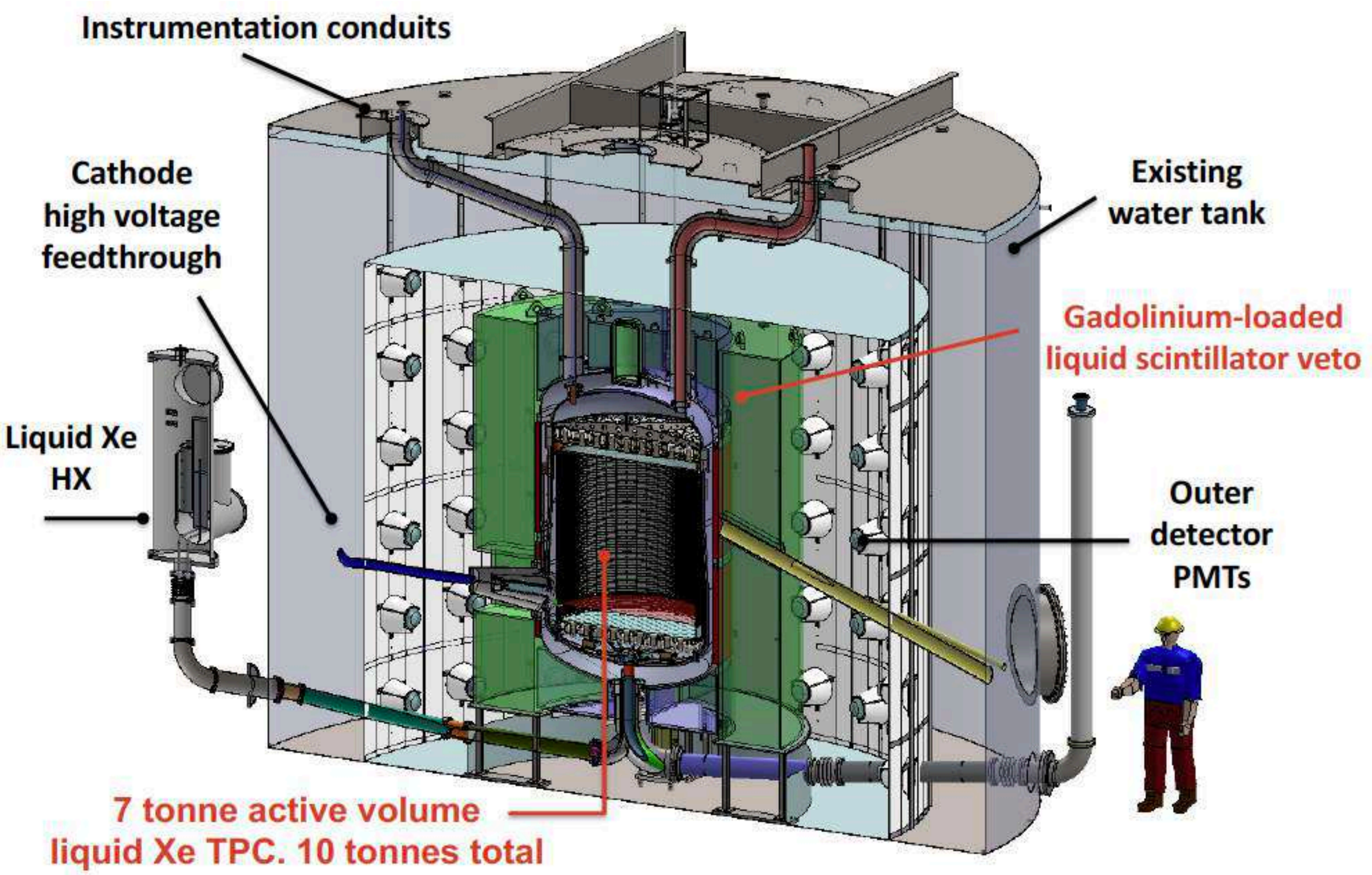
- Upgrades required for XENONnT
  - Larger cryostat inner vessel
  - New TPC
  - Additional ~200 PMTs, PMTs with lower radioactivity currently under development
  - Additional DAQ electronics
  - LXe
- Target mass of ~6 tons, sensitivity to spin-independent WIMP-nucleon elastic scattering cross sections of $1.6 \times 10^{-48}\ \mathrm{cm}^2$

Darwin Large Xe Experiment Concept





LUX-ZEPLIN (LZ)



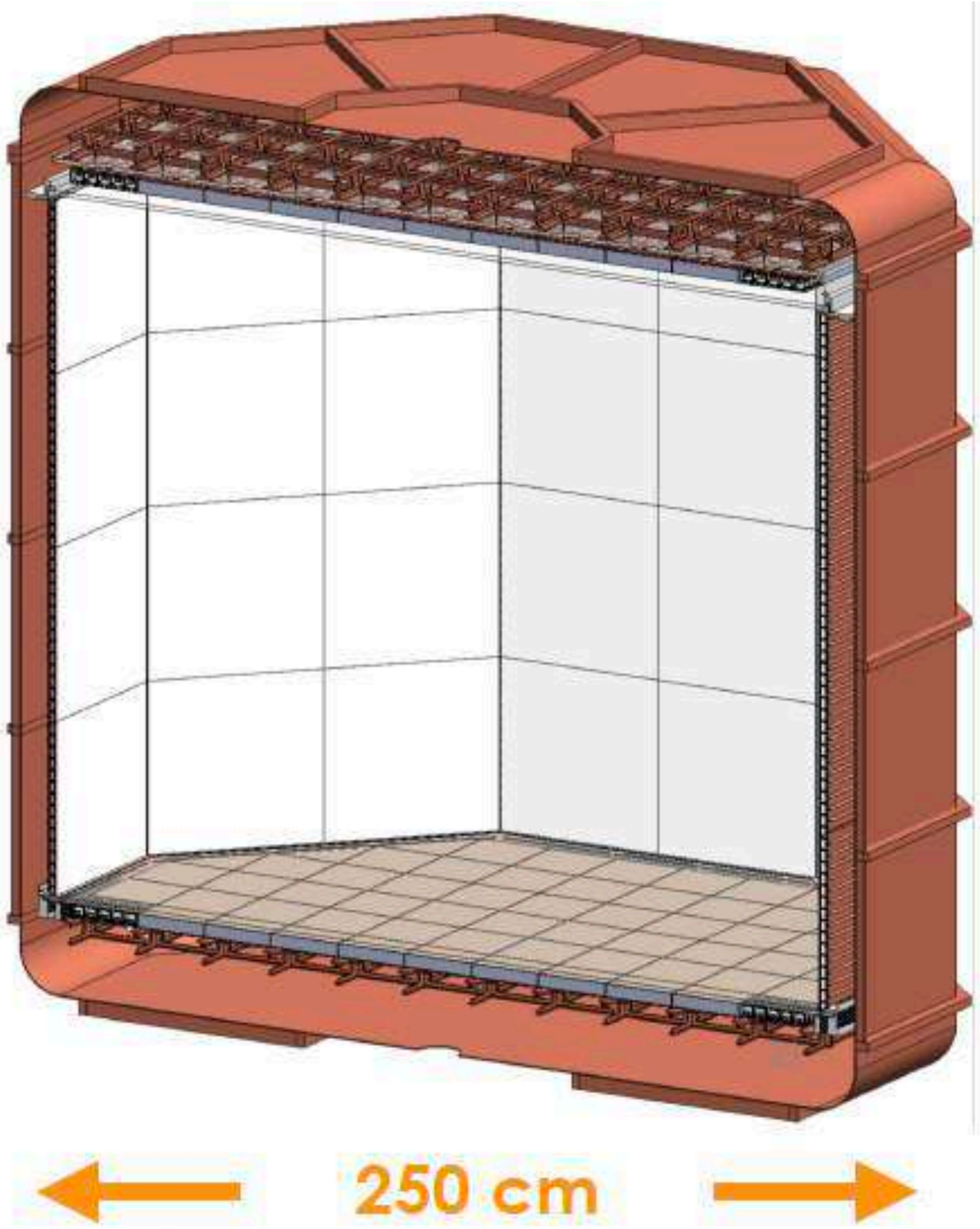
- LZ: Funded G2 Experiment
- 50 x LUX fiducial volume
- 10 Ton Xenon, 7 Ton Active, 5.6 Ton fiducial
- Begin taking data in 2019

The DarkSide Program: Liquid Argon TPC

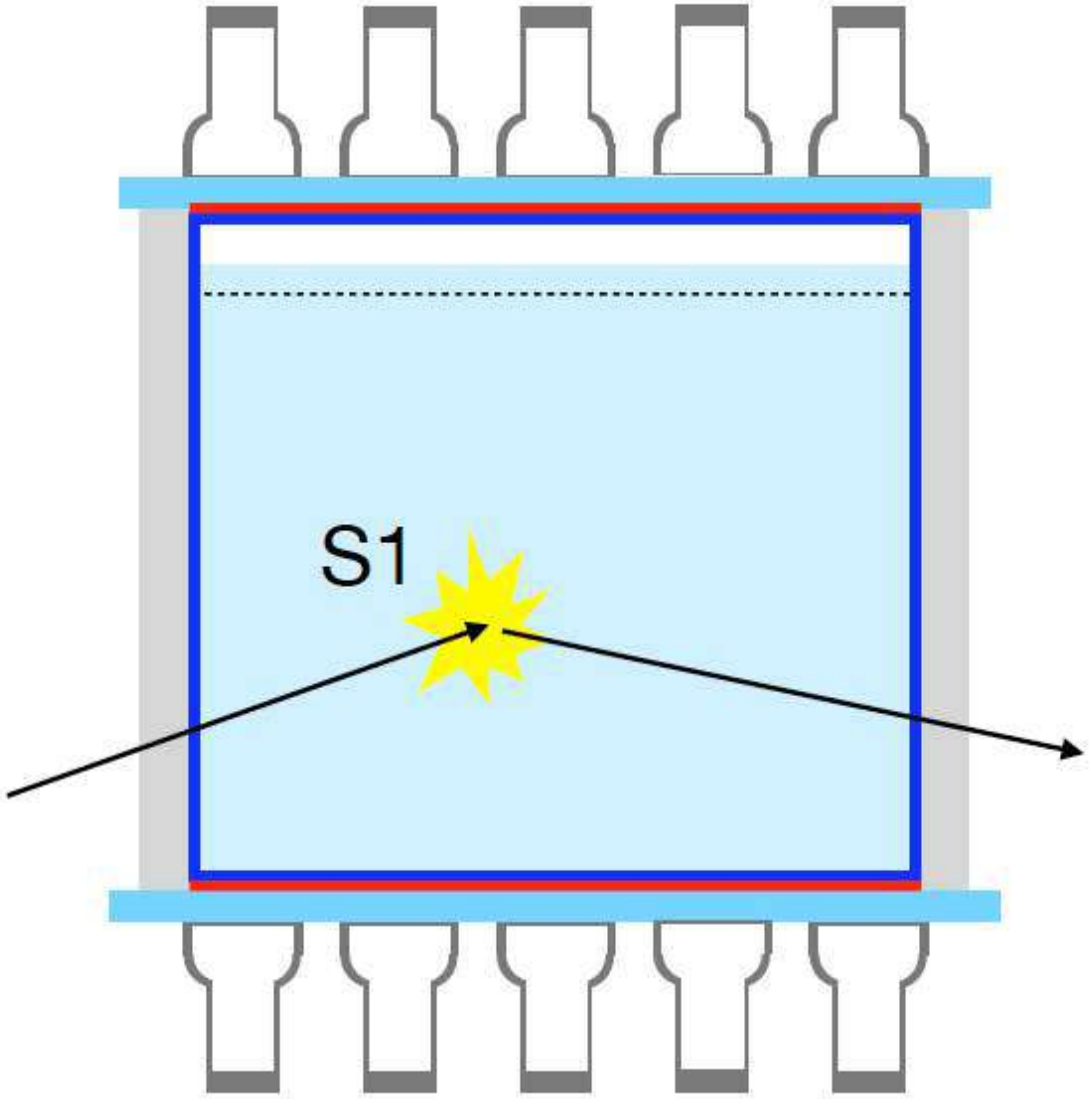
DarkSide-50

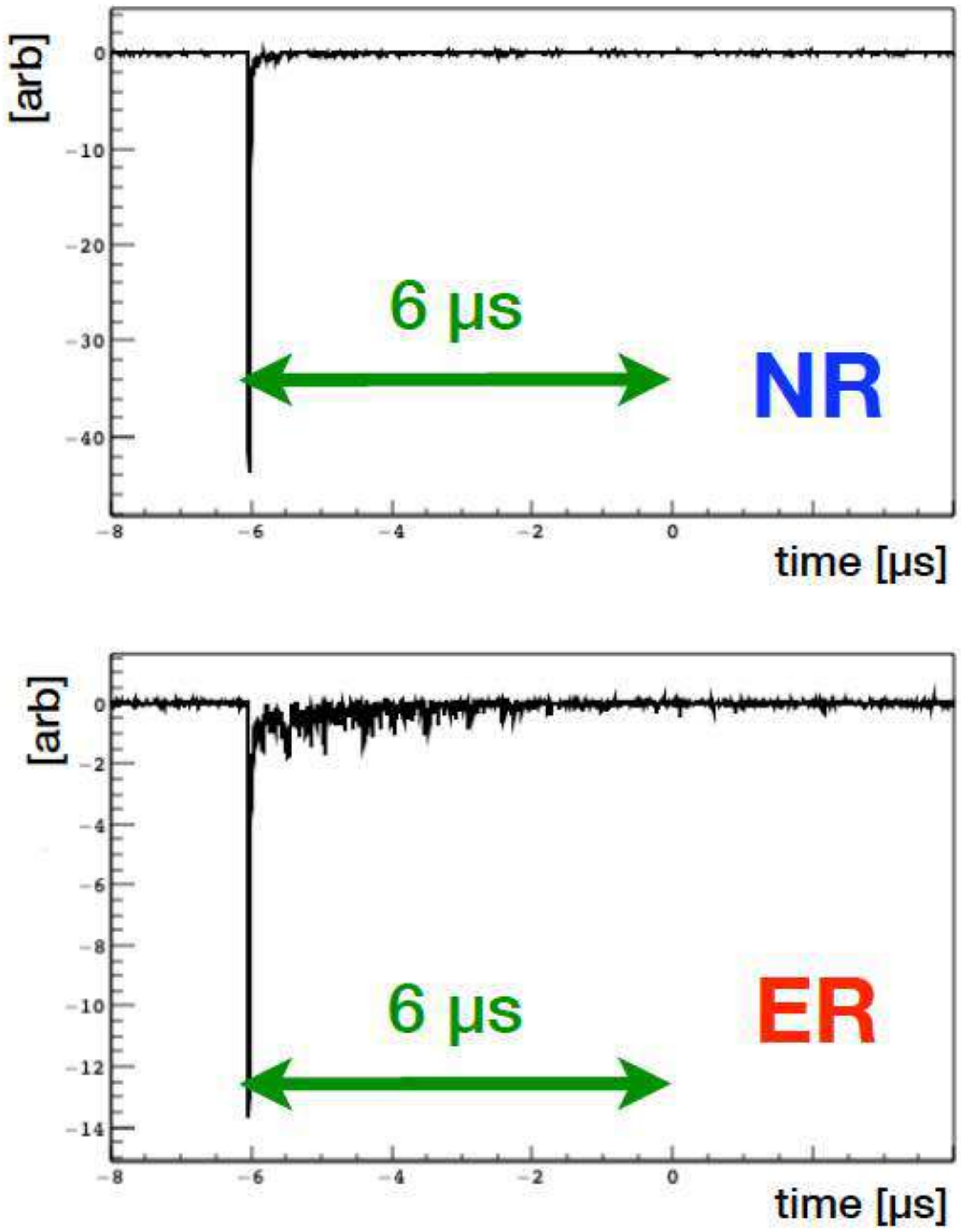
Global Argon Dark Matter Collaboration

- GADMC incorporates members from all existing argon experiments
- DarkSide-20k is a 50 tonne dual-phase argon TPC, 30 tonne fiducial
- >20 m^2 SiPM detectors
- goal of 0.1 "instrumental" background events in 100 tonne-years



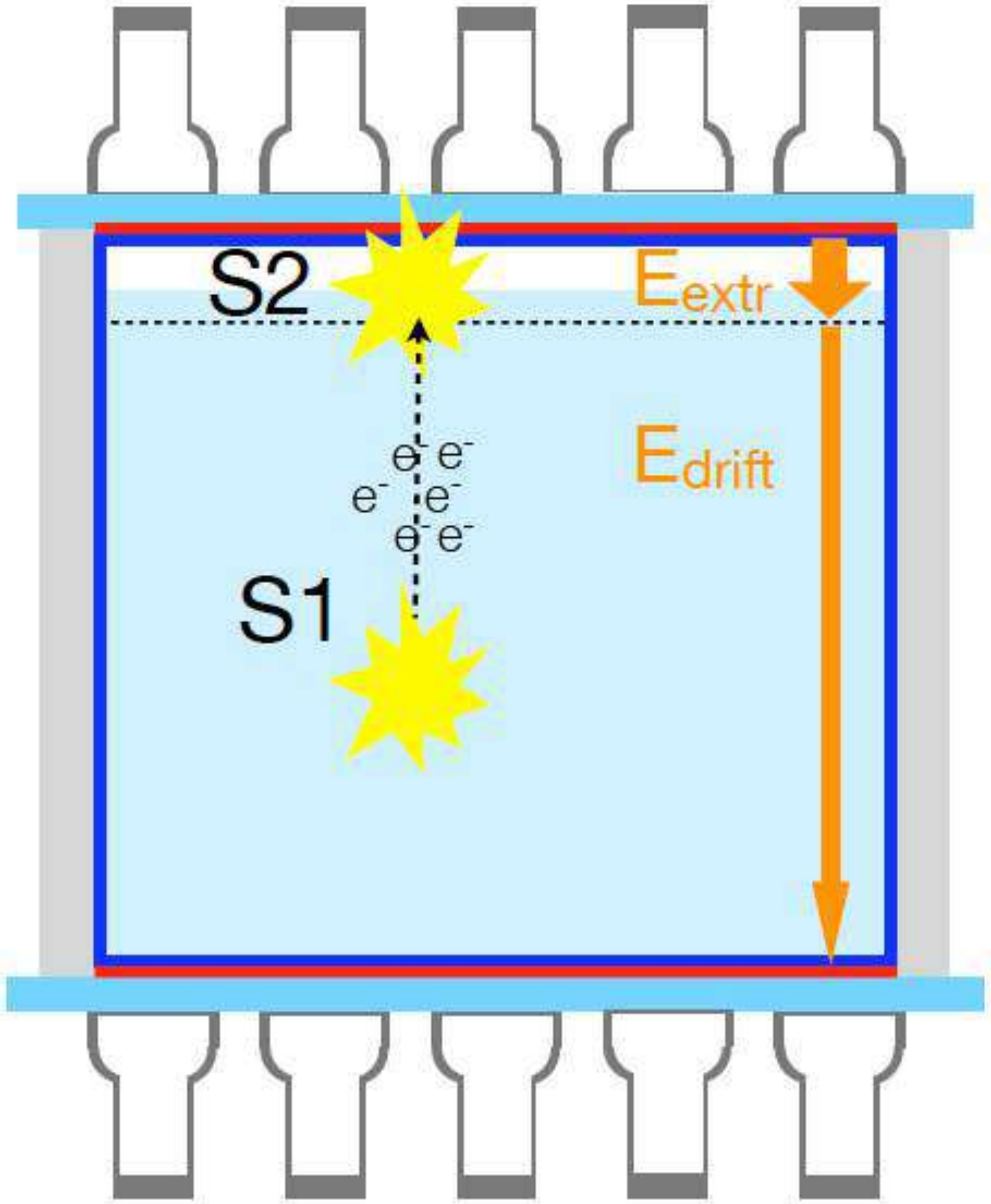
Dual Phase Liquid Argon TPC

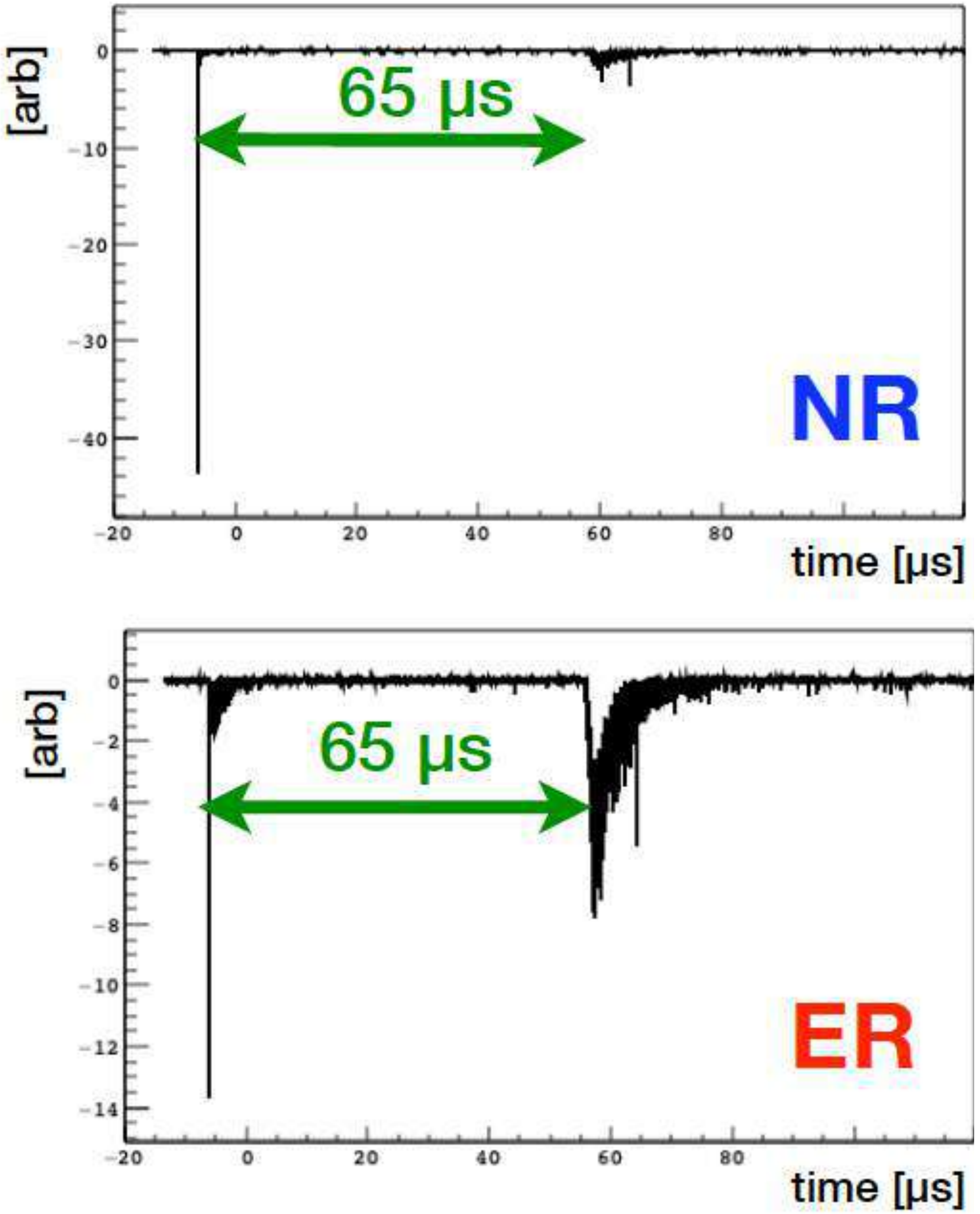




PSD parameter: **F90** = fraction of light in first 90 ns

Dual Phase Liquid Argon TPC

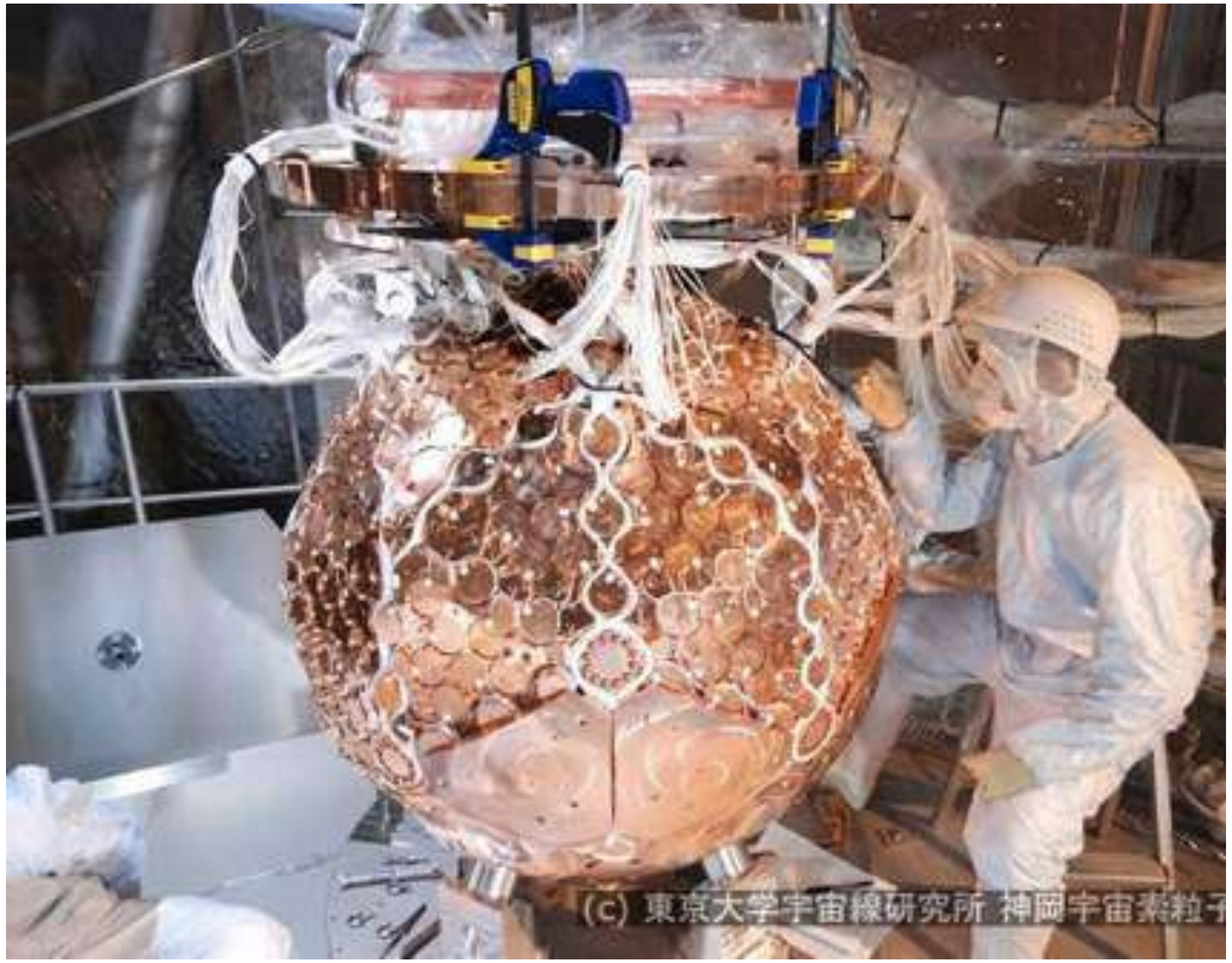




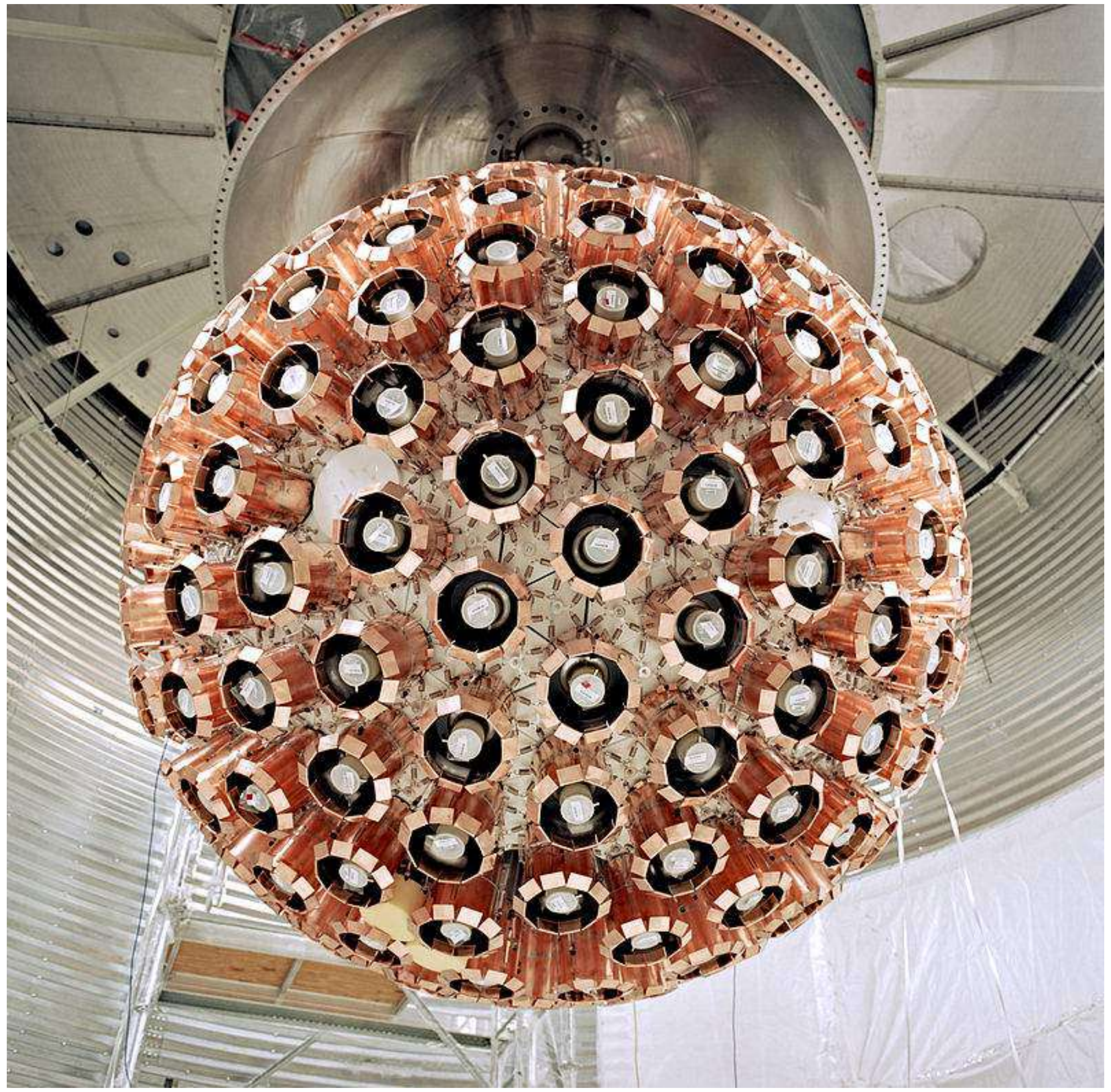
S2 allows for **3D position reconstruction** and additional discrimination power

Single-phase Noble Liquid Detectors

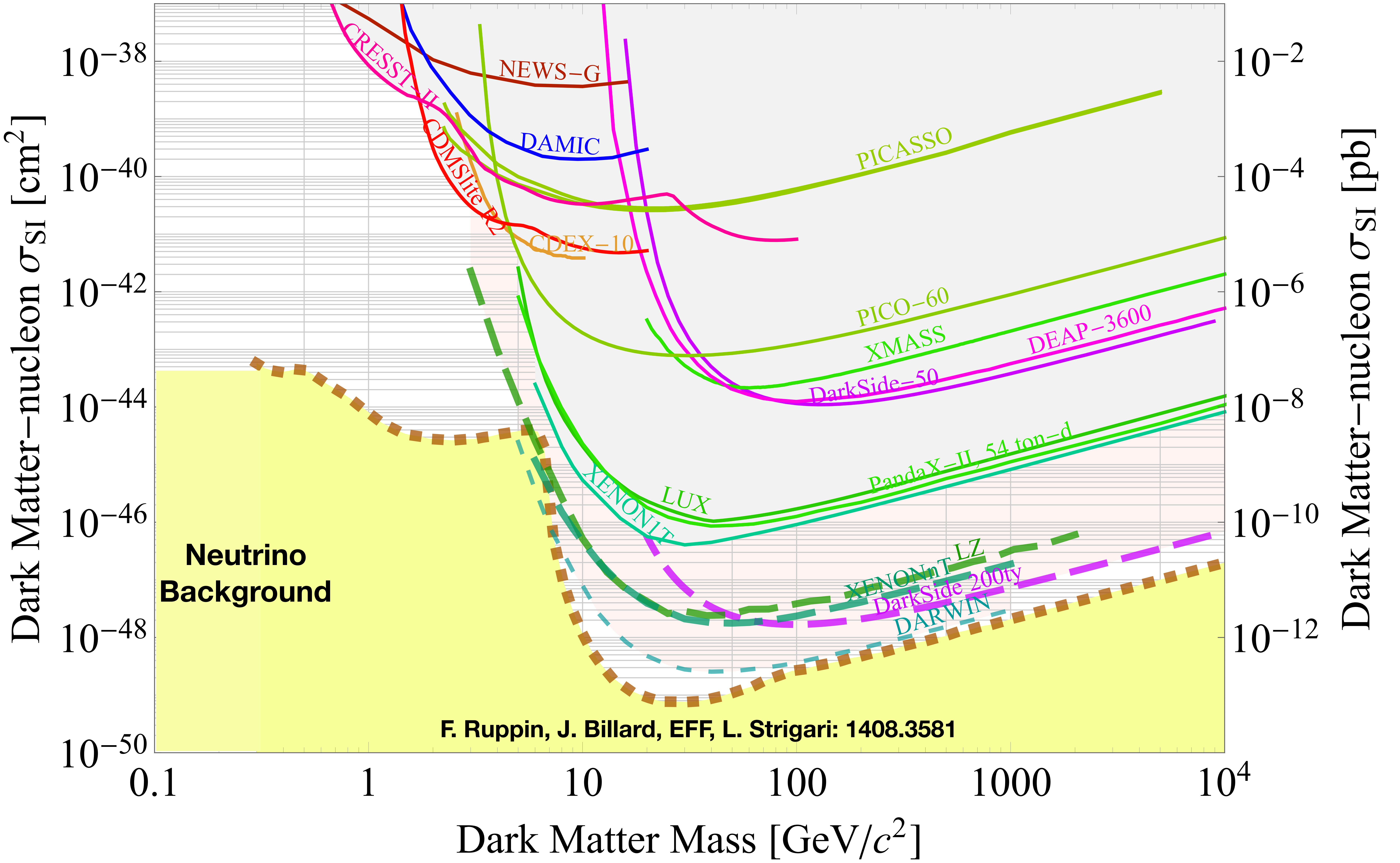
XMASS



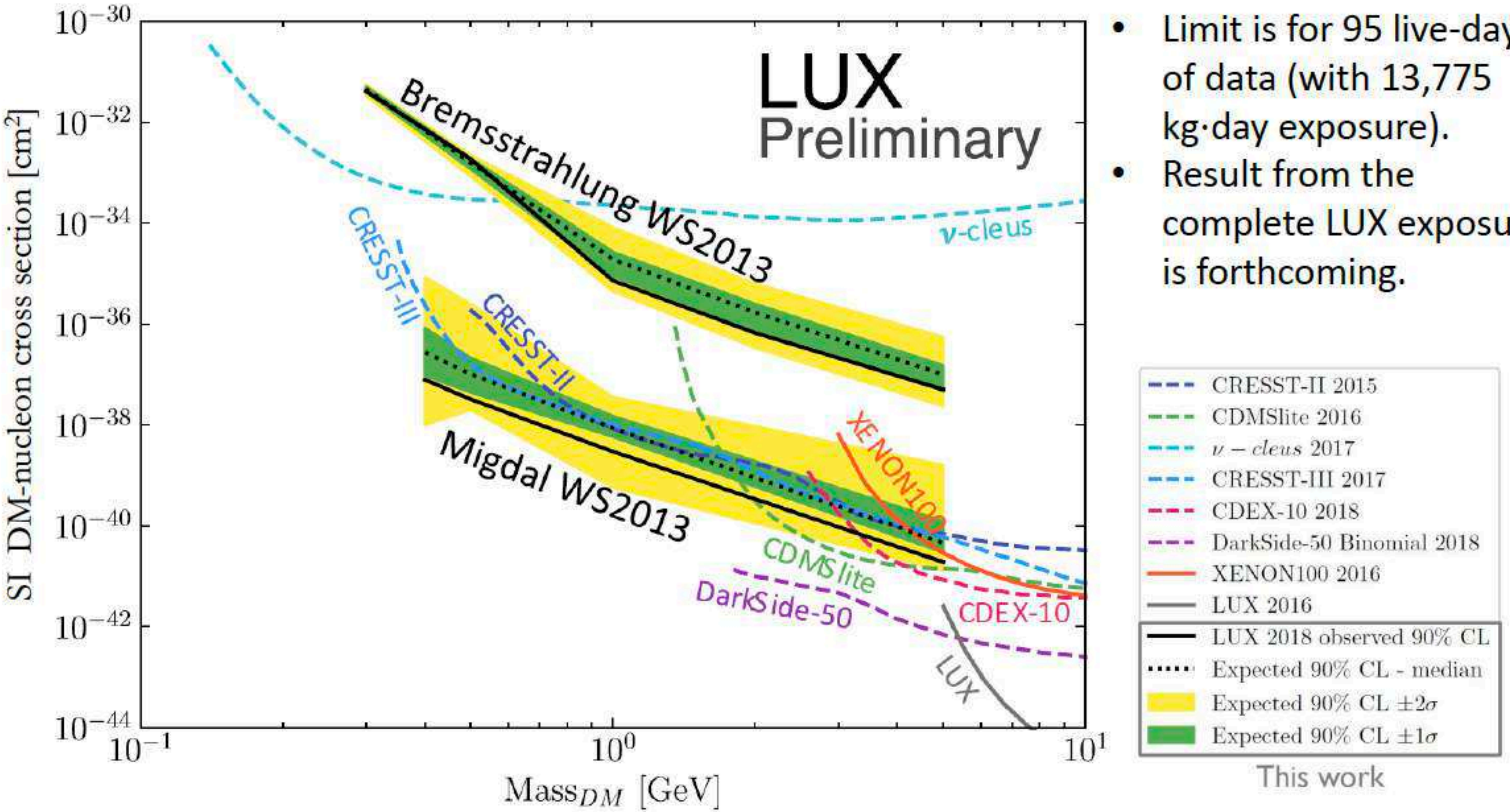
DEAP3600



Noble Liquids Will Cover the High Mass Region!

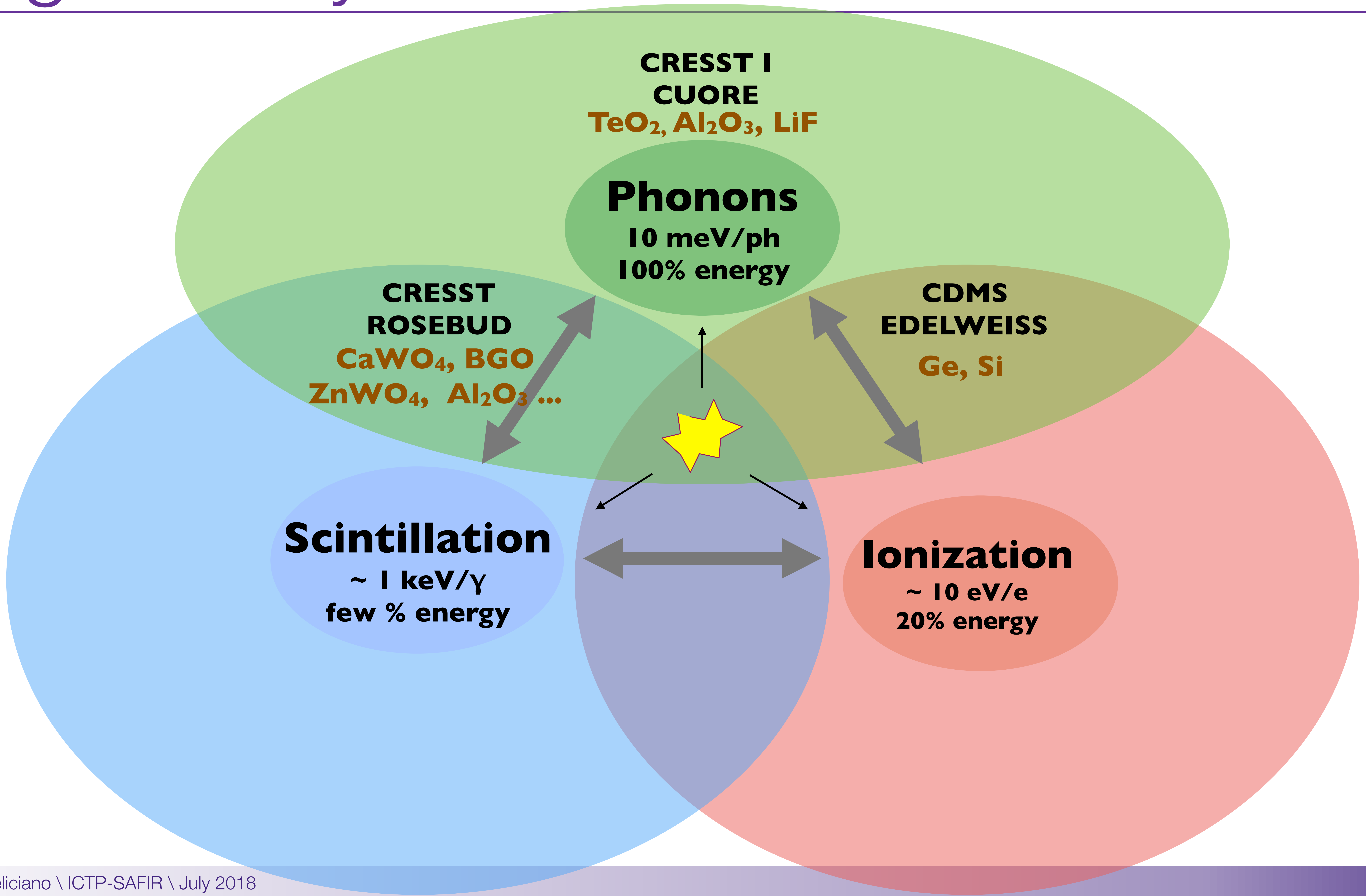


And are also looking for light DM as well!



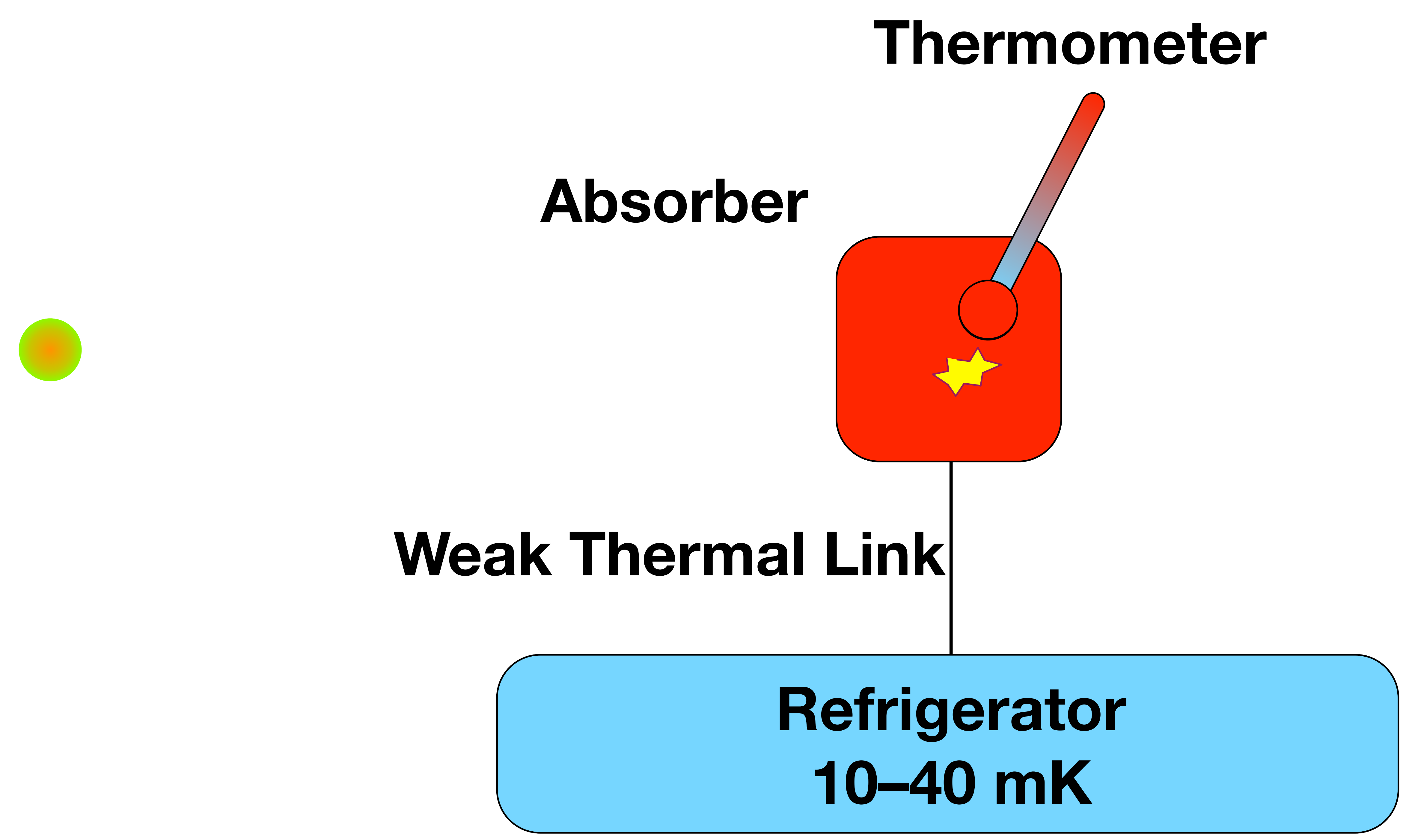
- Limit is for 95 live-days of data (with 13,775 kg·day exposure).
- Result from the complete LUX exposure is forthcoming.

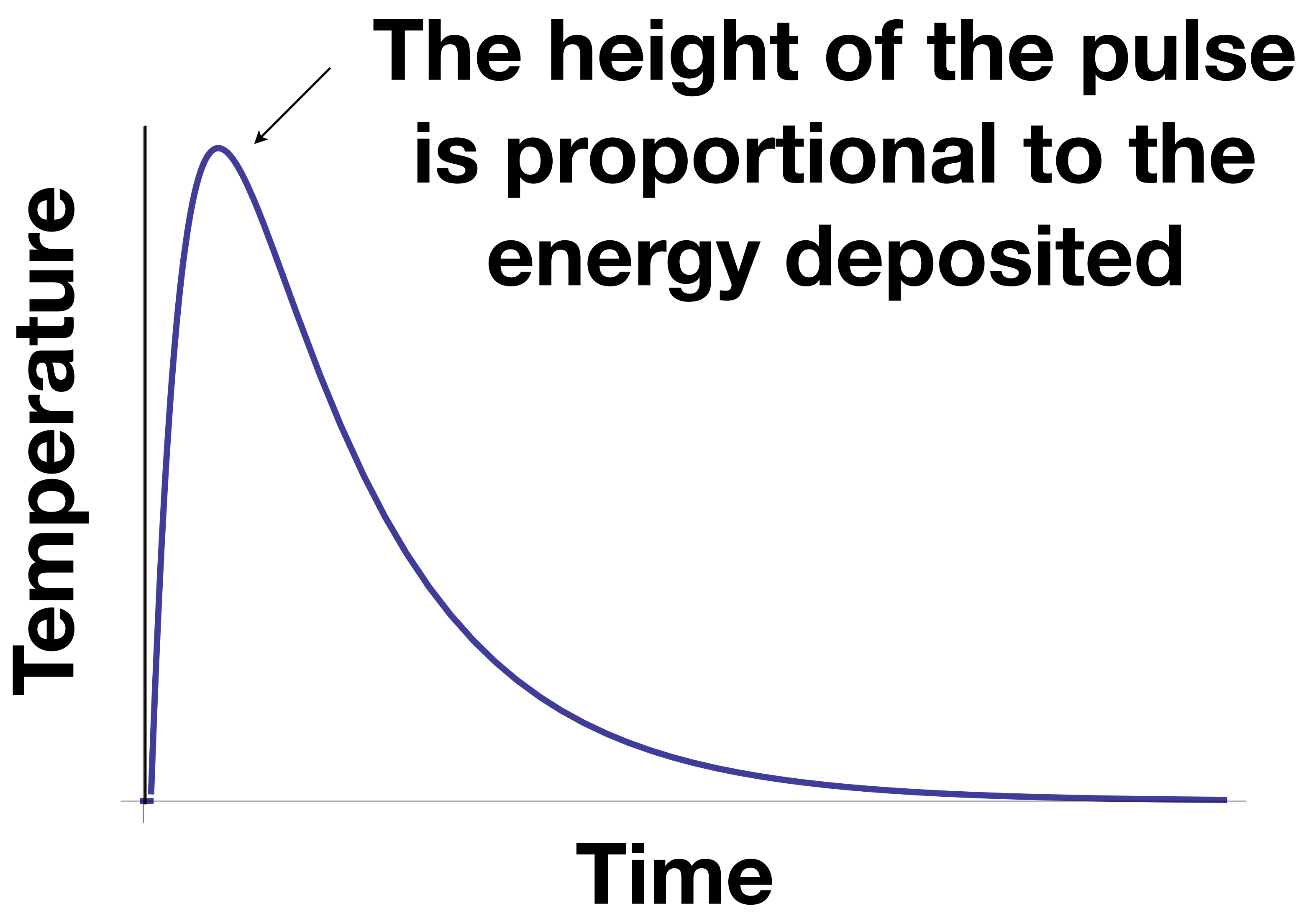
Cryogenic Crystal Detectors: Low Mass DM



Cryogenic Crystal Detectors

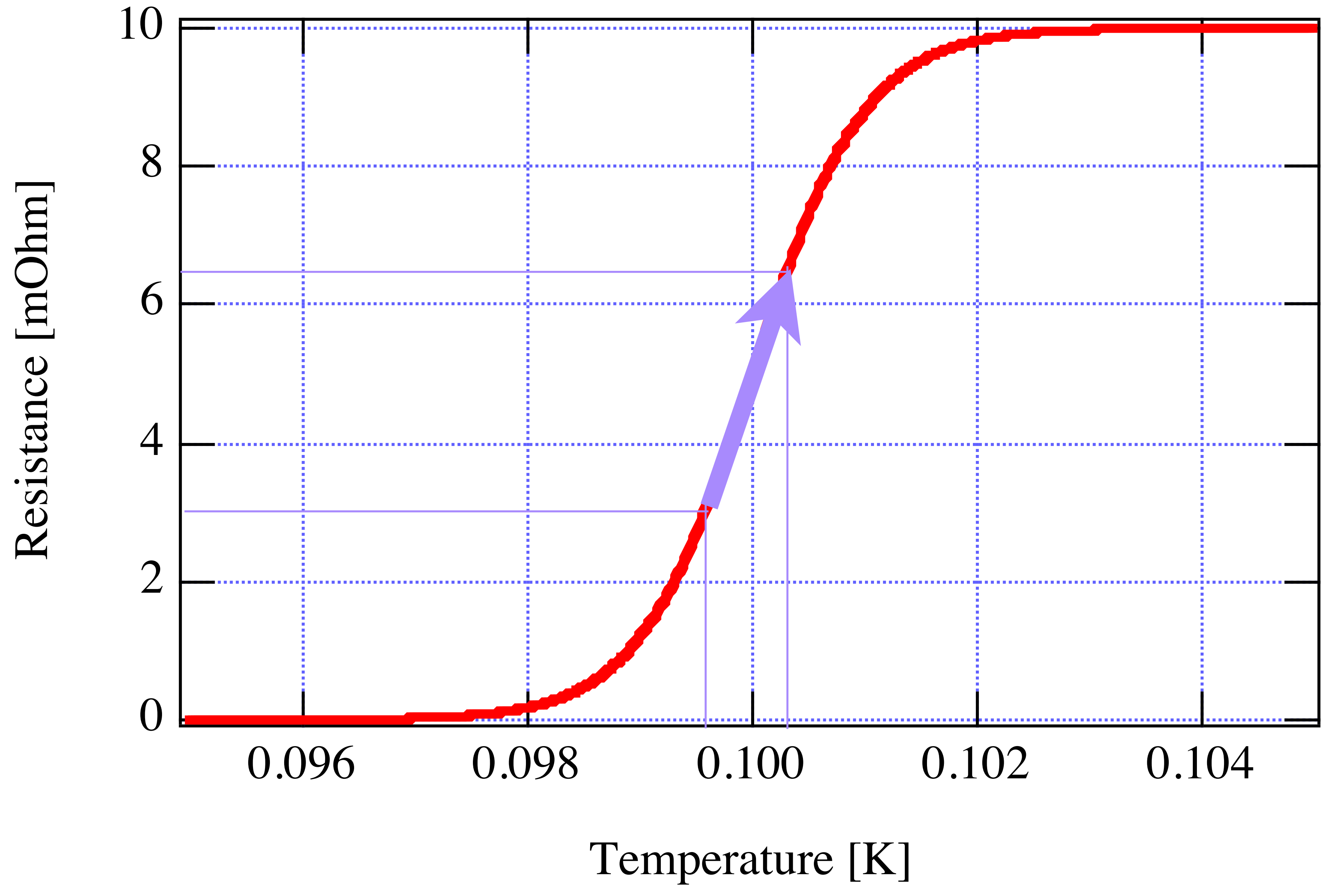
The Phonon Channel





Microcalorimeters 102: Transition-Edge Sensros

- Refrigerator temperature has to be close to absolute zero
- Thermometer is a Superconducting Transition-Edge Sensor (TES)
- Readout is done with Superconducting Quantum Interference Devices (SQUIDs)

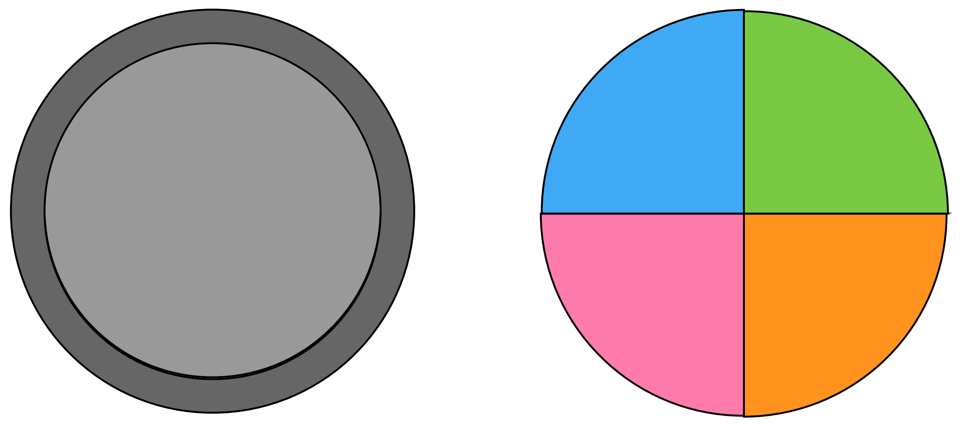


SuperCDMS SNOLAB

CDMS II

4.6 kg Ge (19 x 240 g)
1.2 kg Si (11 x 106g)
3” Diameter
1 cm Thick

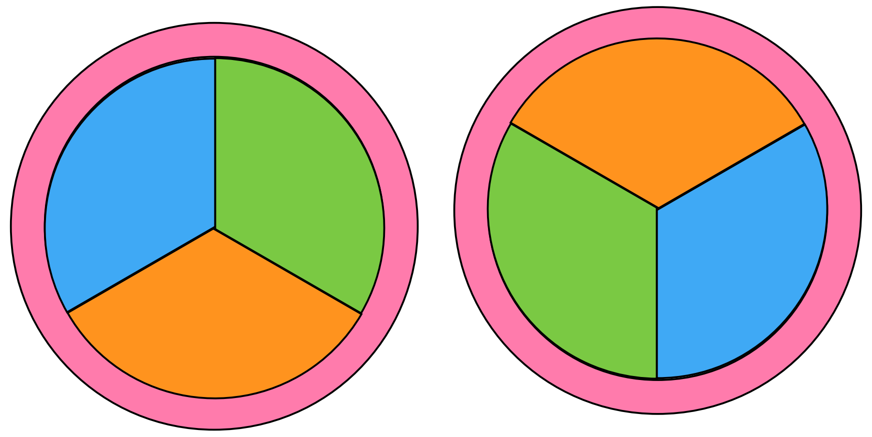
2 charge + 4 phonon

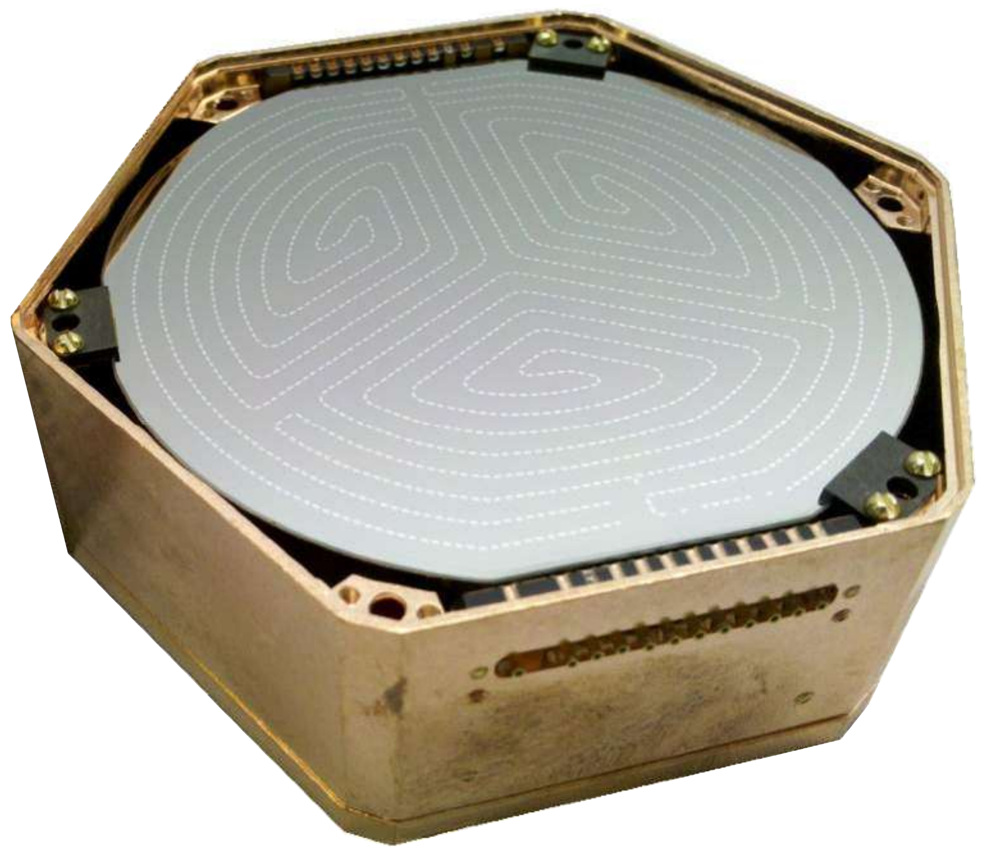


SuperCDMS Soudan

9.0 kg Ge (15 x 600g)
3” Diameter
2.5 cm Thick

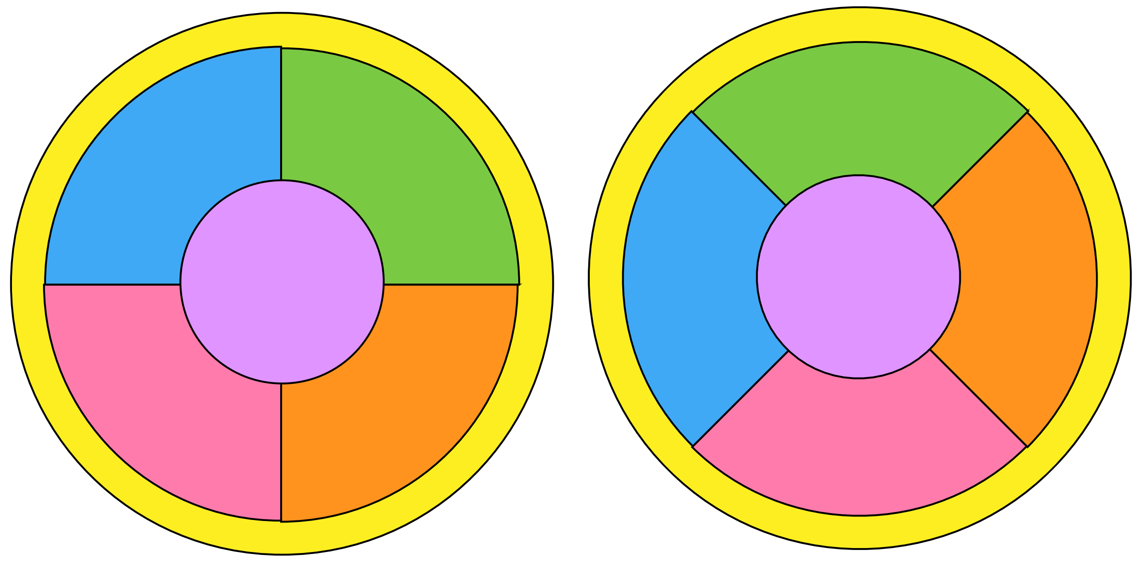
2 charge + 2 charge
4 phonon + 4 phonon





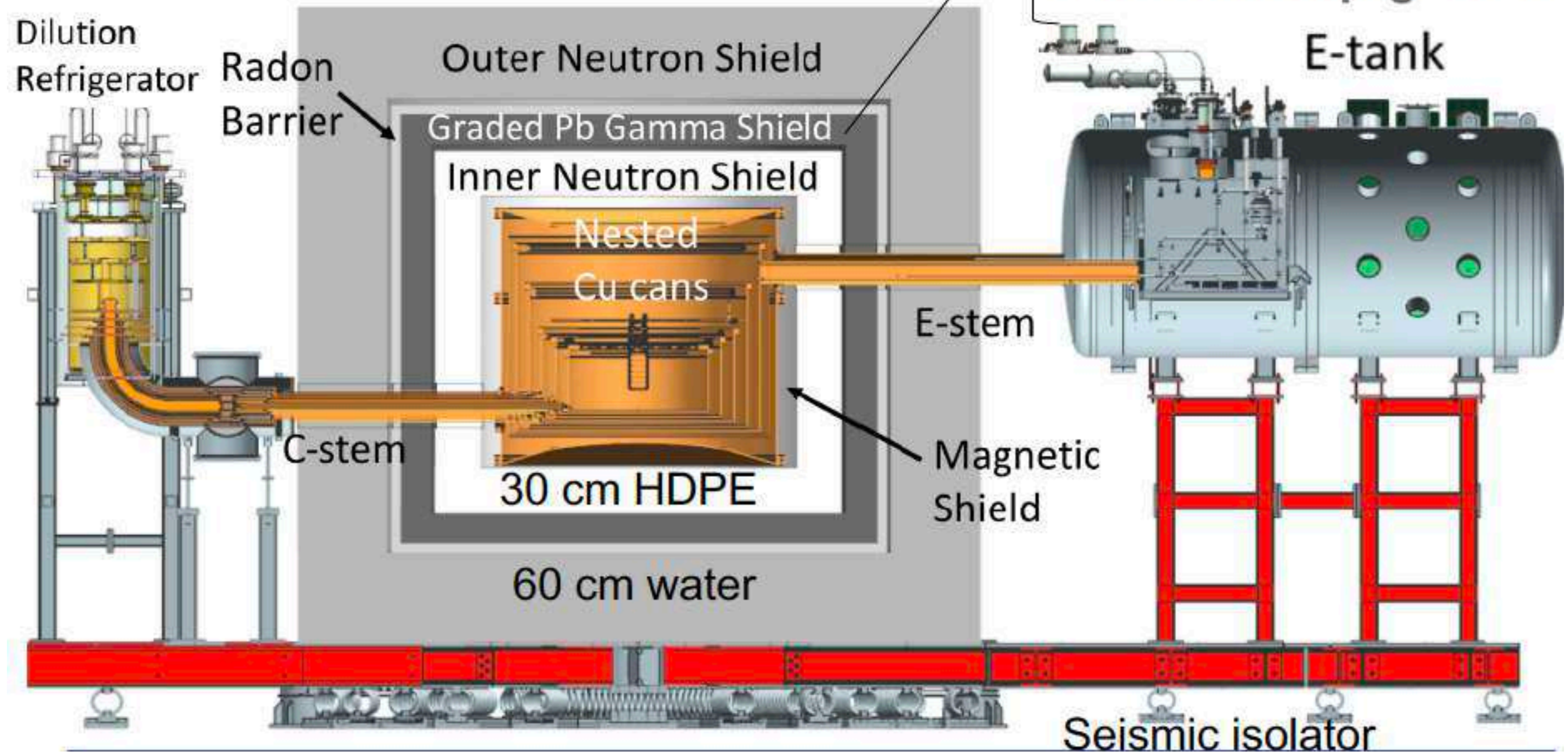
SuperCDMS SNOLAB

Funded G2 Experiment
Data Taking in 2020
25 kg Ge (18 x 1.4 kg)
3.6 kg Si (6 x 0.6 kg)
4” Diameter
3.3 cm Thick
2 charge + 2 charge
6 phonon + 6 phonon



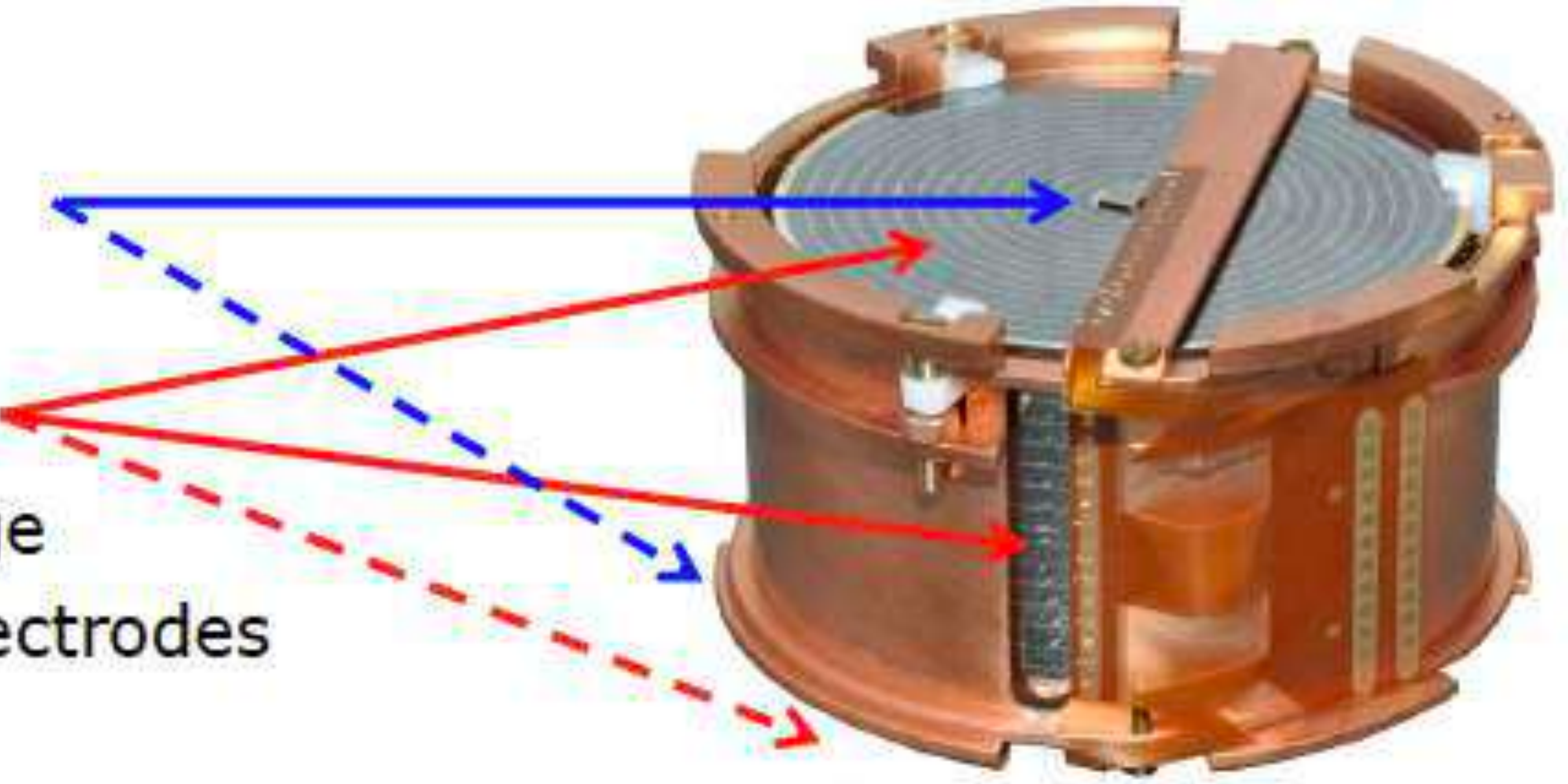
SuperCDMS SNOLAB @ the Ladder Lab

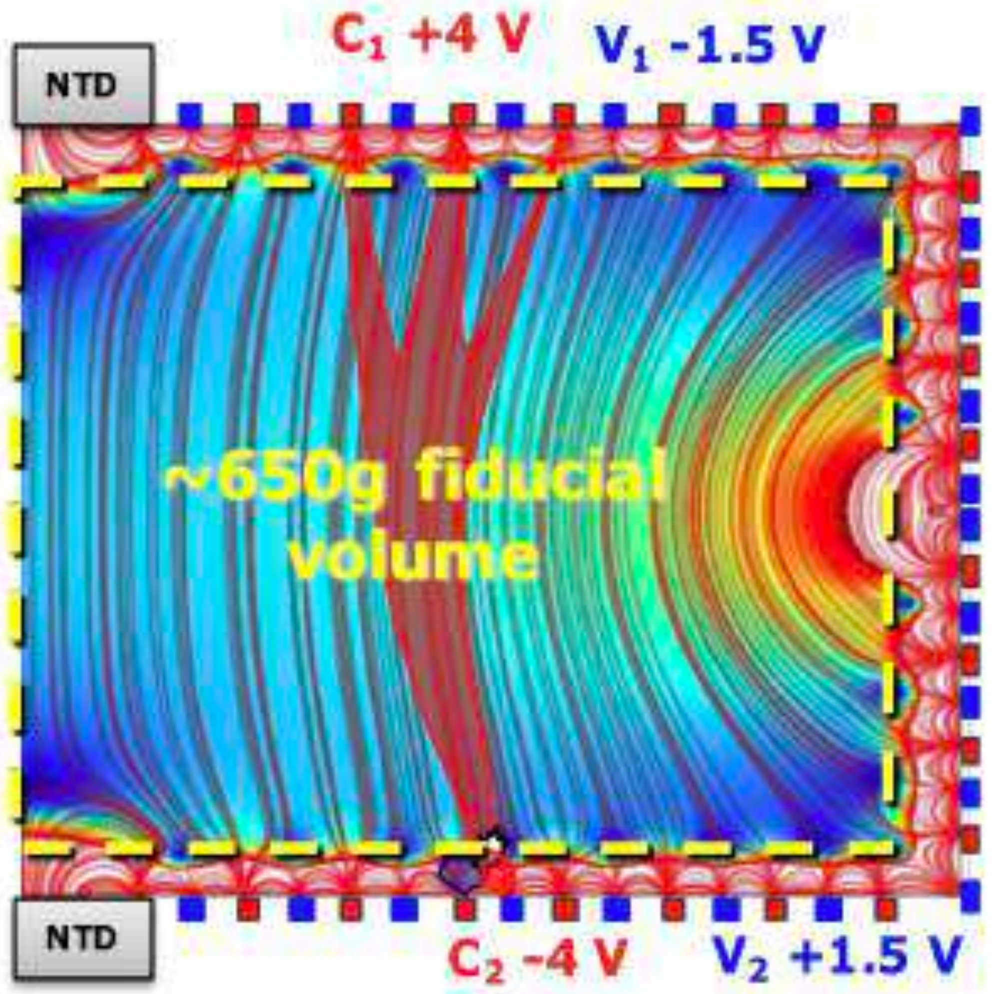
Graded shield reduces environmental γ by 10^6.
Sufficiently clean materials used so that internal contamination of detectors (^3H, ^{32}Si) dominates.



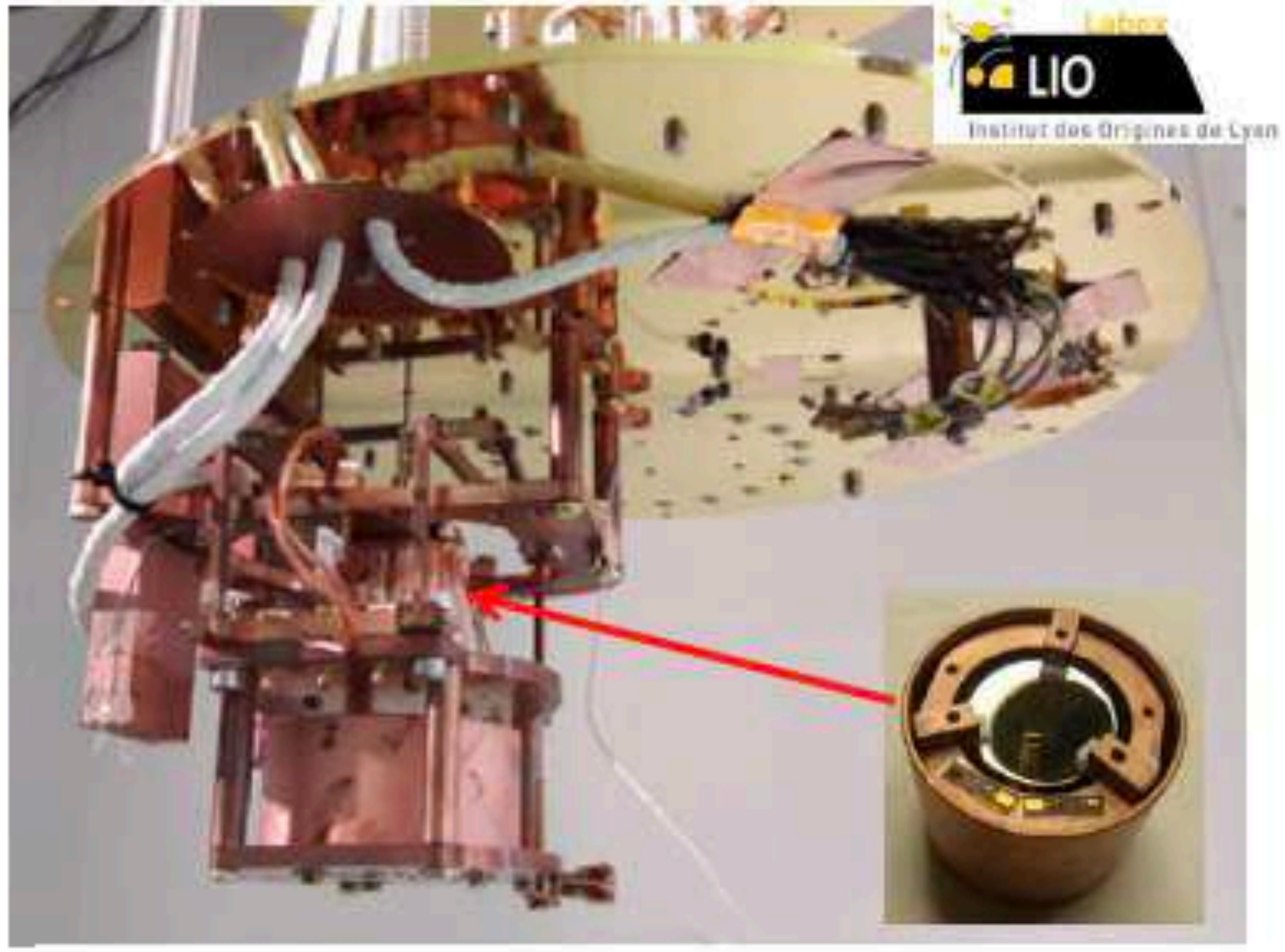
EDELWEISS

- ~870g detectors (ϕ=70 h=40 mm)
- 2 GeNTDs heat sensor per detector
- Electrodes: concentric Al rings (2 mm spacing) covering all faces
- XeF_2 surface treatment → low leakage current (<1 fA) between adjacent electrodes
  J Low Temp Phys (2014) 176: 182-187



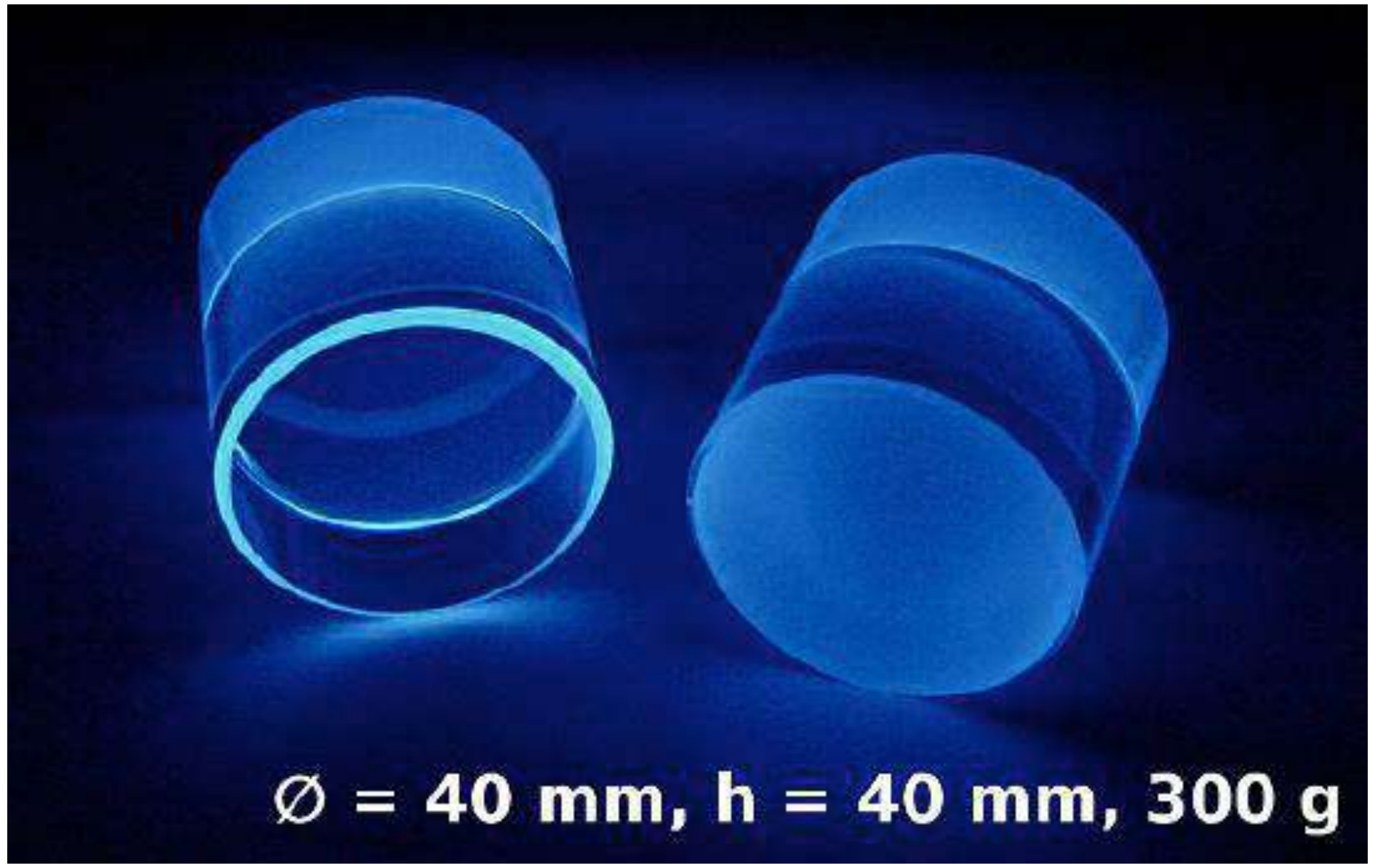


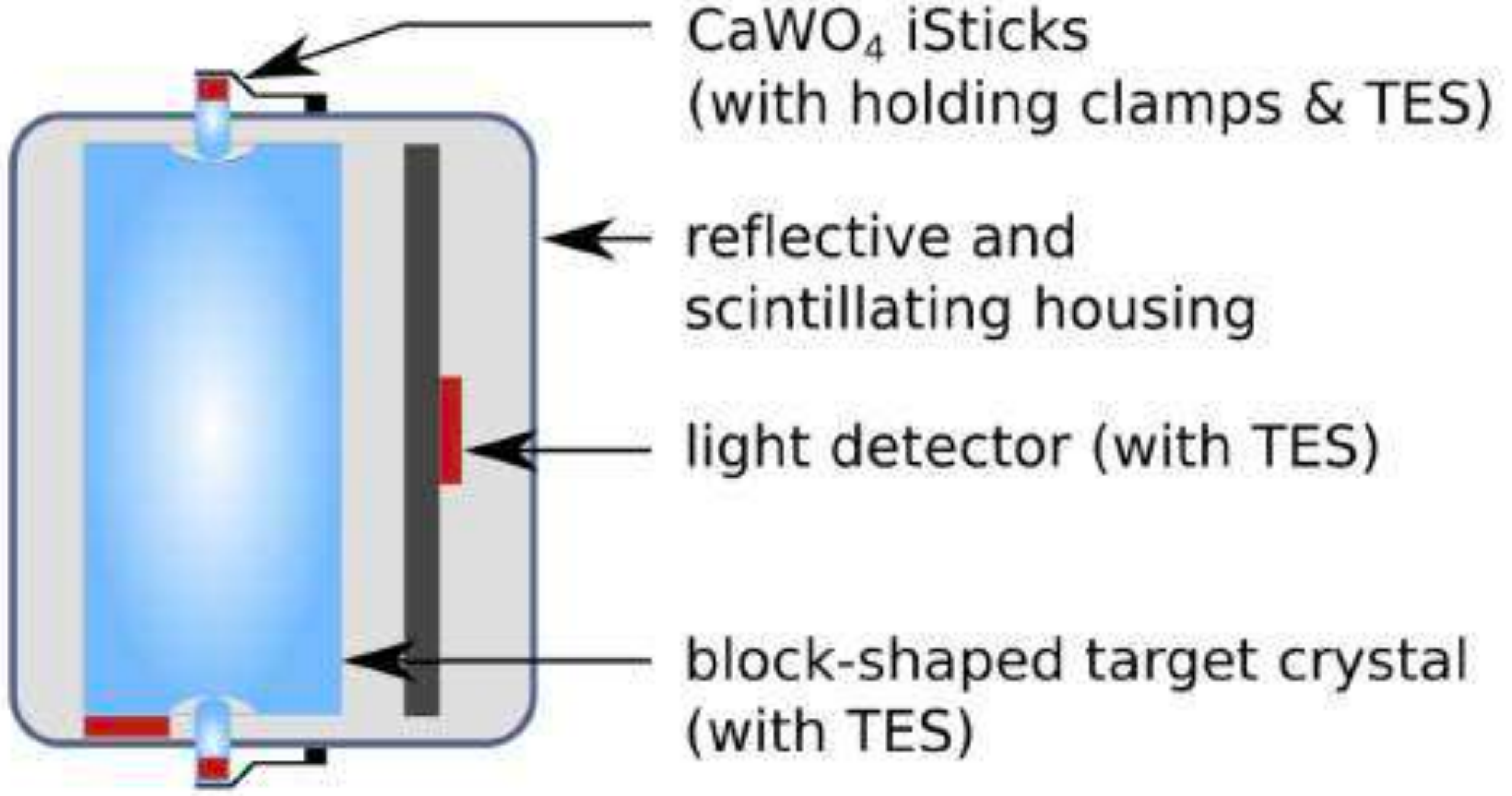
- R&D with 32 g combined with the objective of testing the above-ground sensitivity to sub-GeV WIMPs
- *Optimized* NTD heat sensor on a 32g crystal, no electrodes (i.e. 1 keV = 1 keV_{NR})
- Kept at 17 mK in IPNL low-vibration dilution fridge [ArXiv:1803.03463]
- Stable σ = 18 eV baseline resolution
- One day blinded for WIMP search in [0-2] keV region

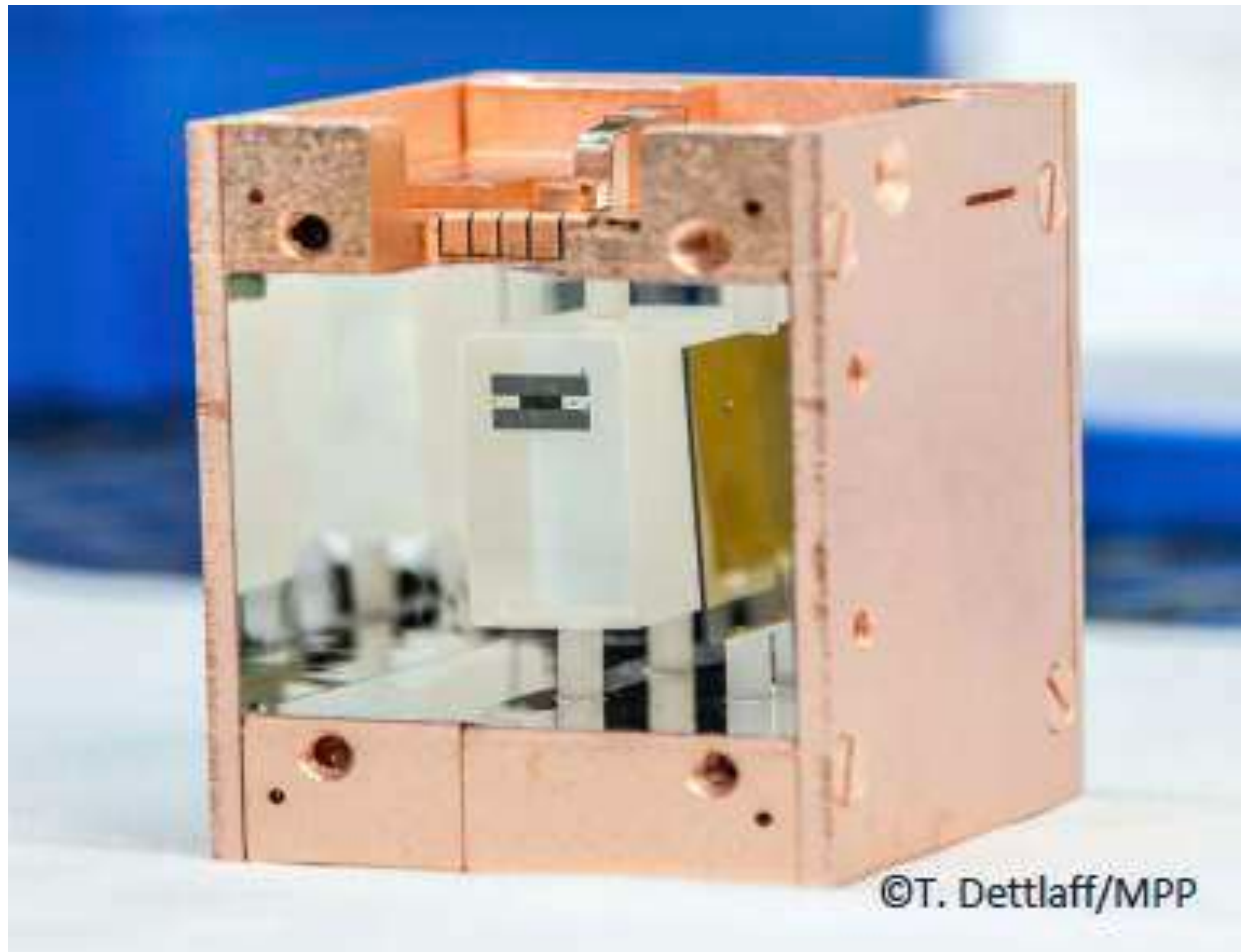


CRESST

- CRESST: phonon + light
- Scintillating $CaWO_4$ crystals as target
- Separate cryogenic light detector to detect scintillation light signal
- New small 24g detectors optimized for light DM
- 4.5 eV sigma Baseline Resolution





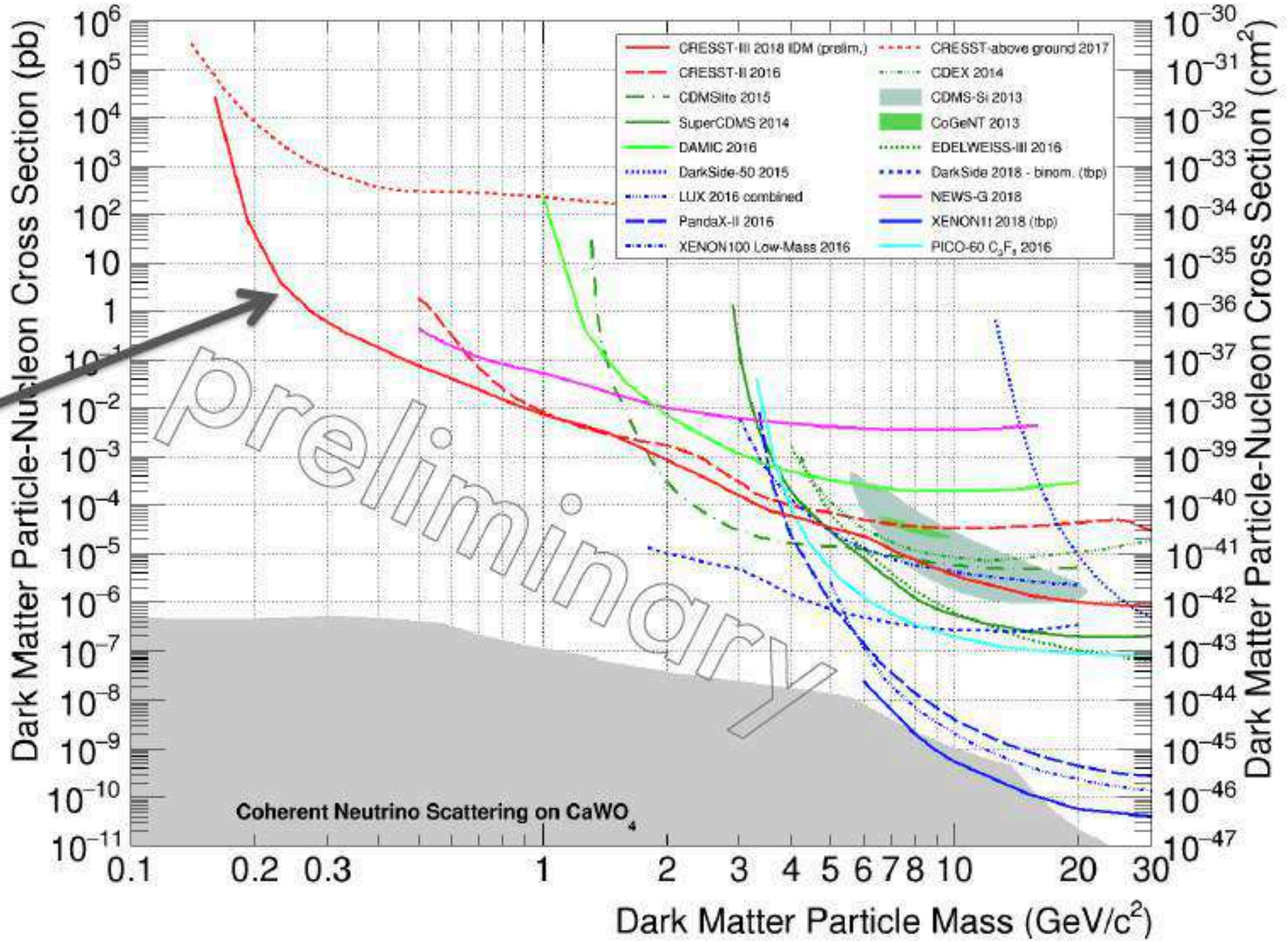


CRESST New Results

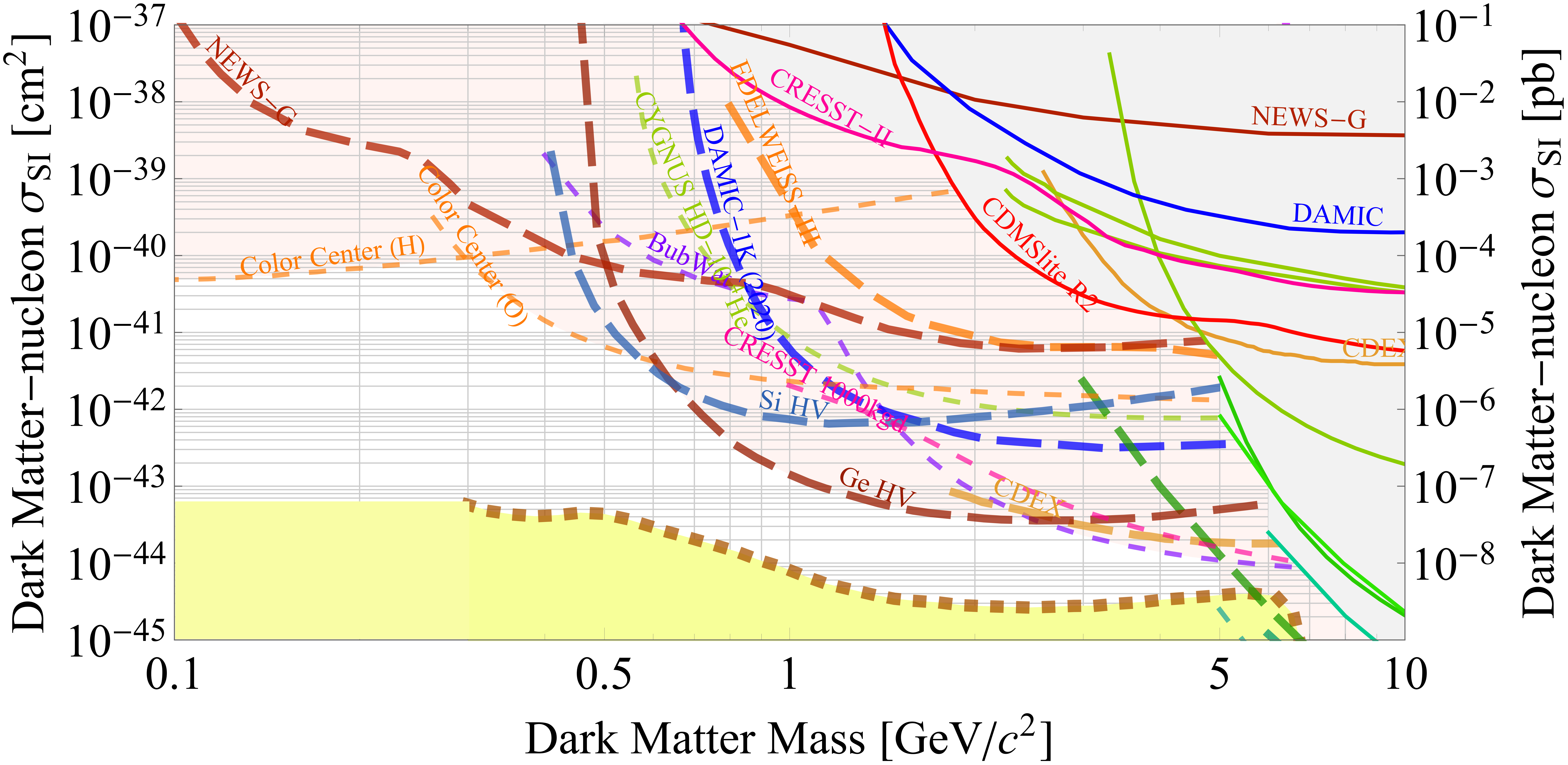
Energy spectrum of accepted events

Yellin 1D optimum interval method

Energy spectrum expected for DM



The Low Mass Region Is an Exciting Place To Look for DM!



End of Lecture 2