KNUT DUNDAS MORÅ | knut.dundas.moraa@columbia.edu

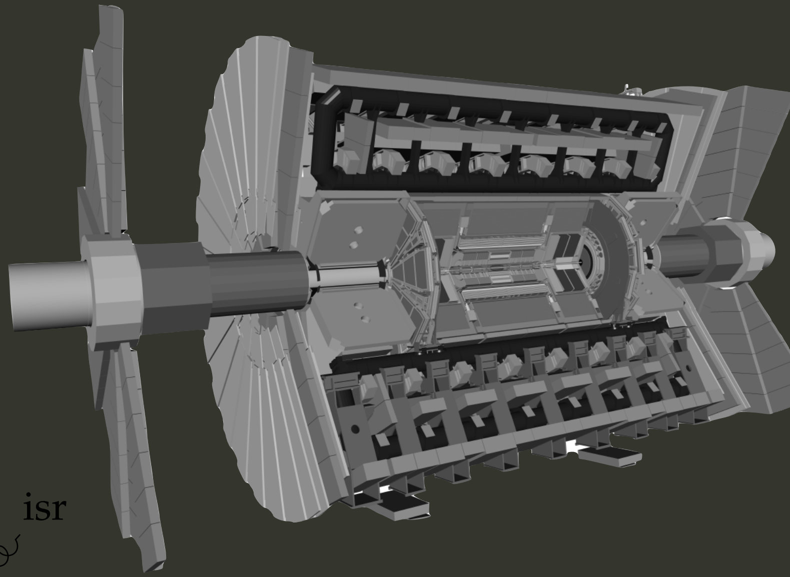
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

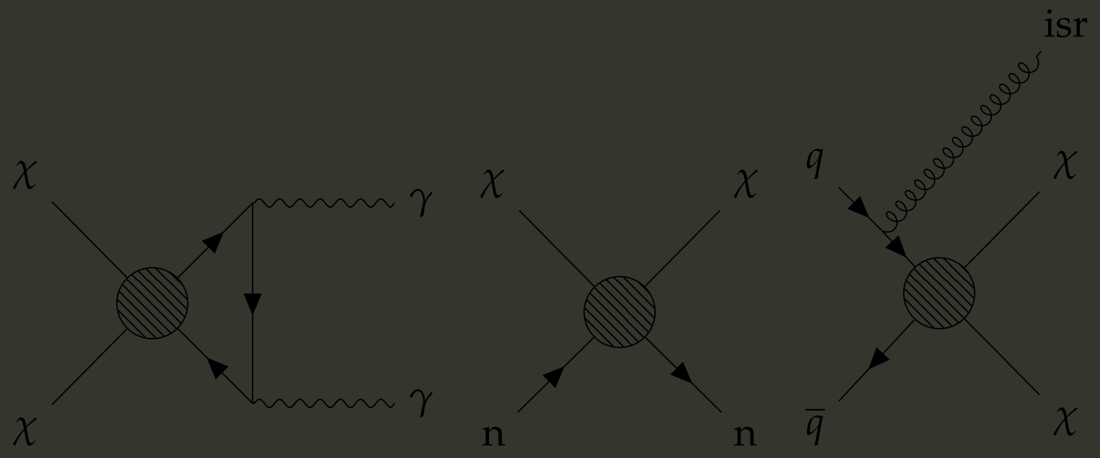
DIRECT DETECTION OF DARK MATTER

Skeikampen 2023

INDIRECT

COLLIDER





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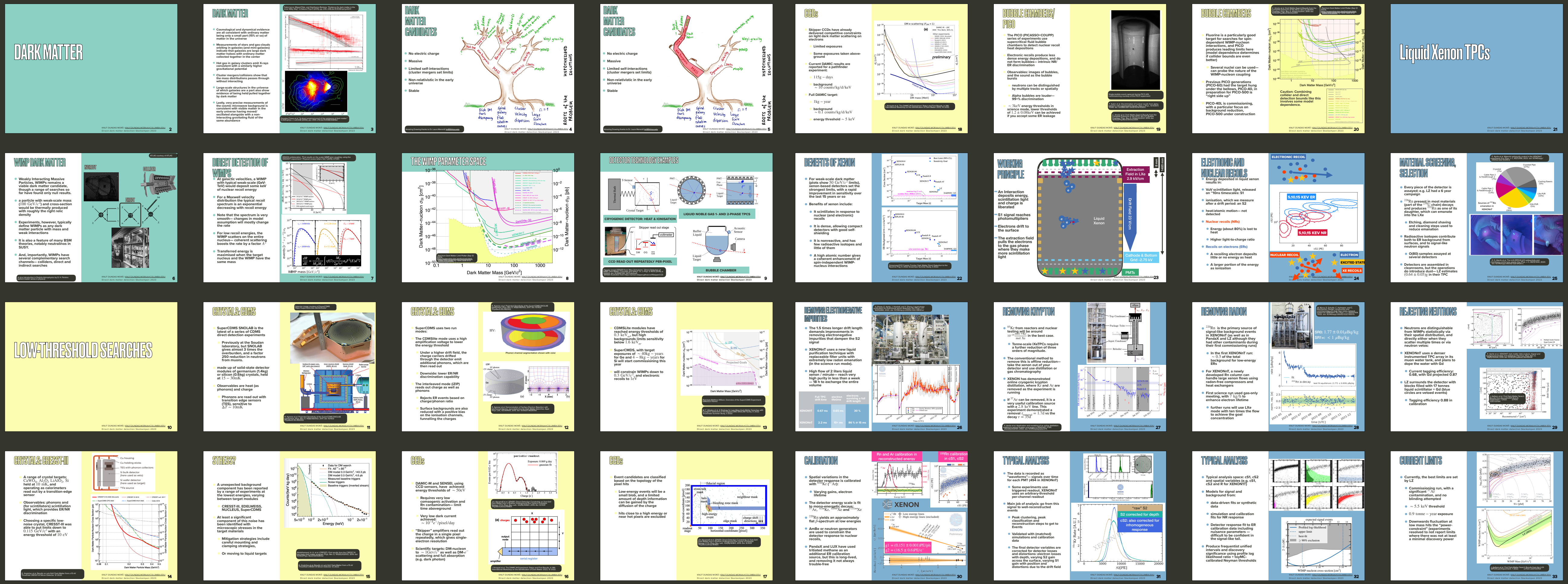
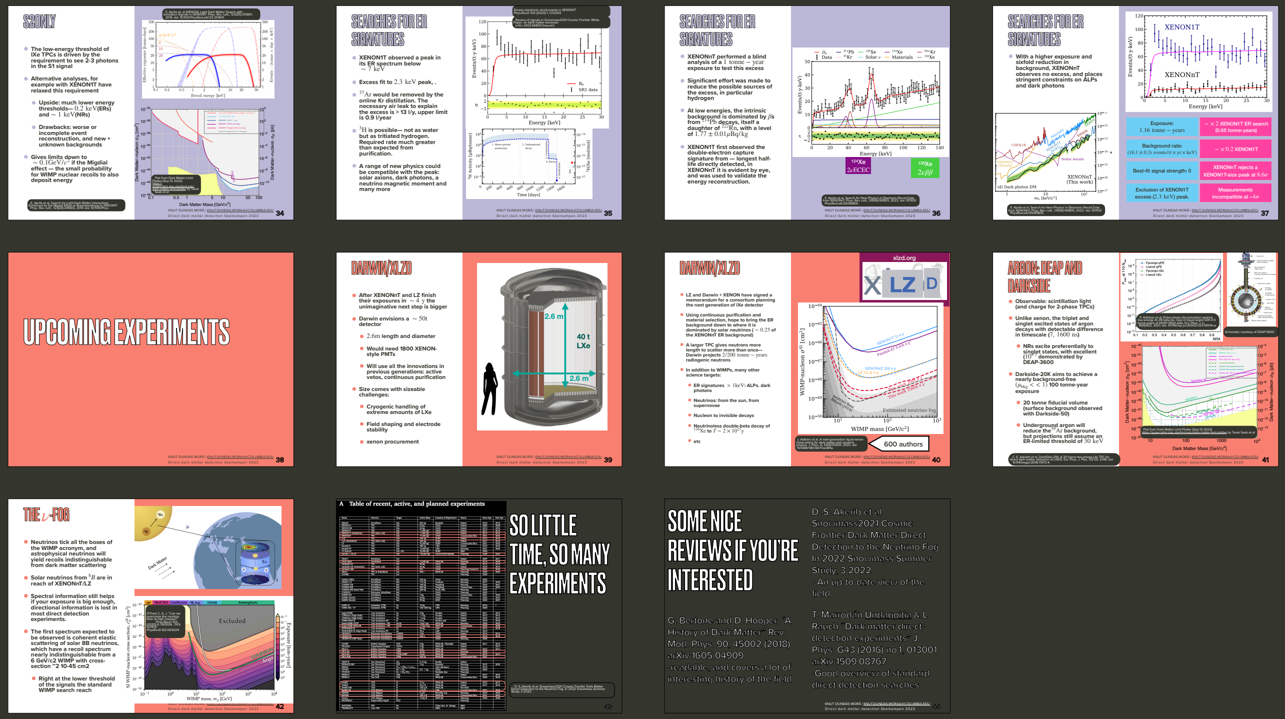
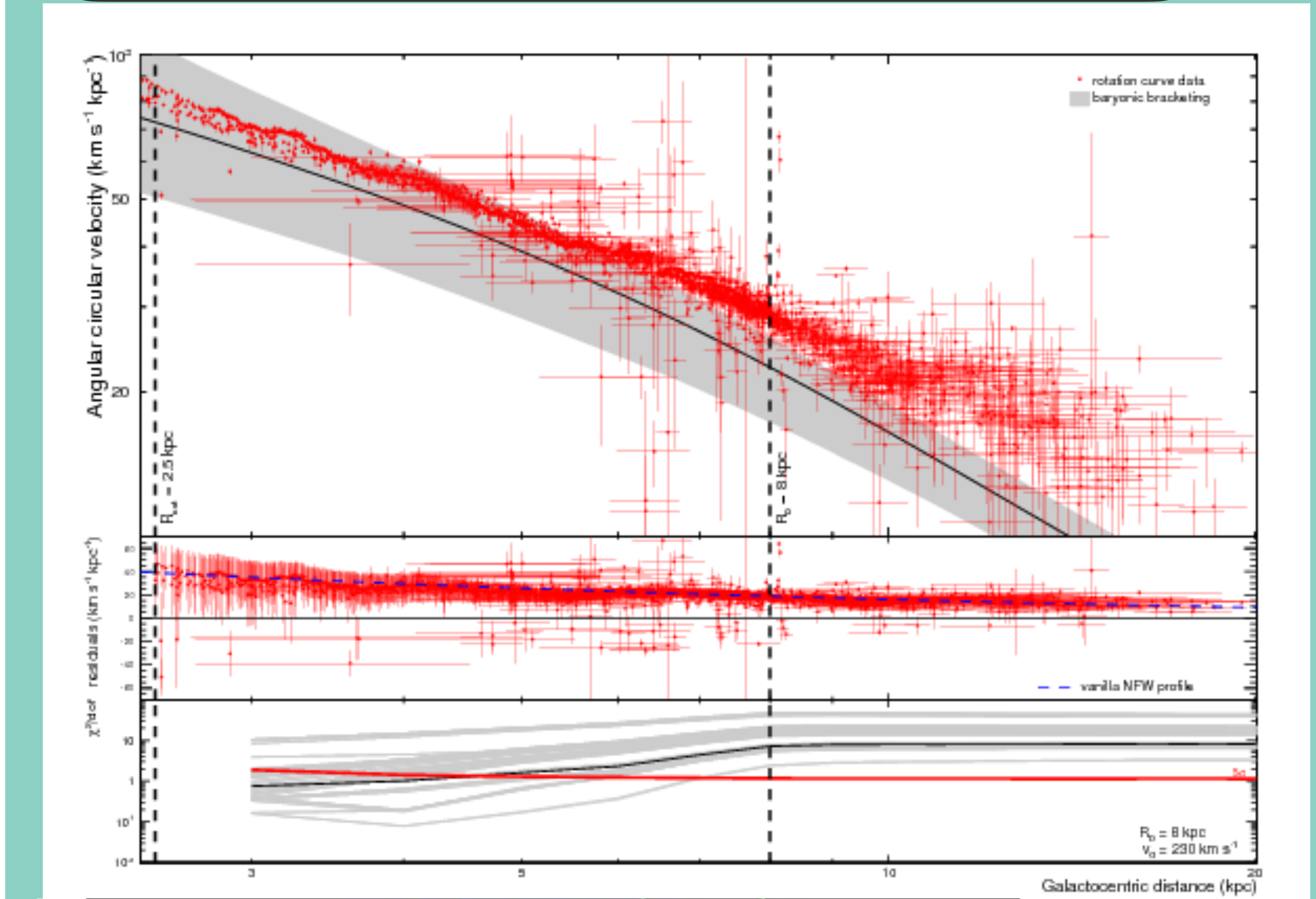



- Dark Matter and general direct detection
- Low-threshold experiments
- LXe detectors
- Non-WIMP LXe searches
- Future detectors

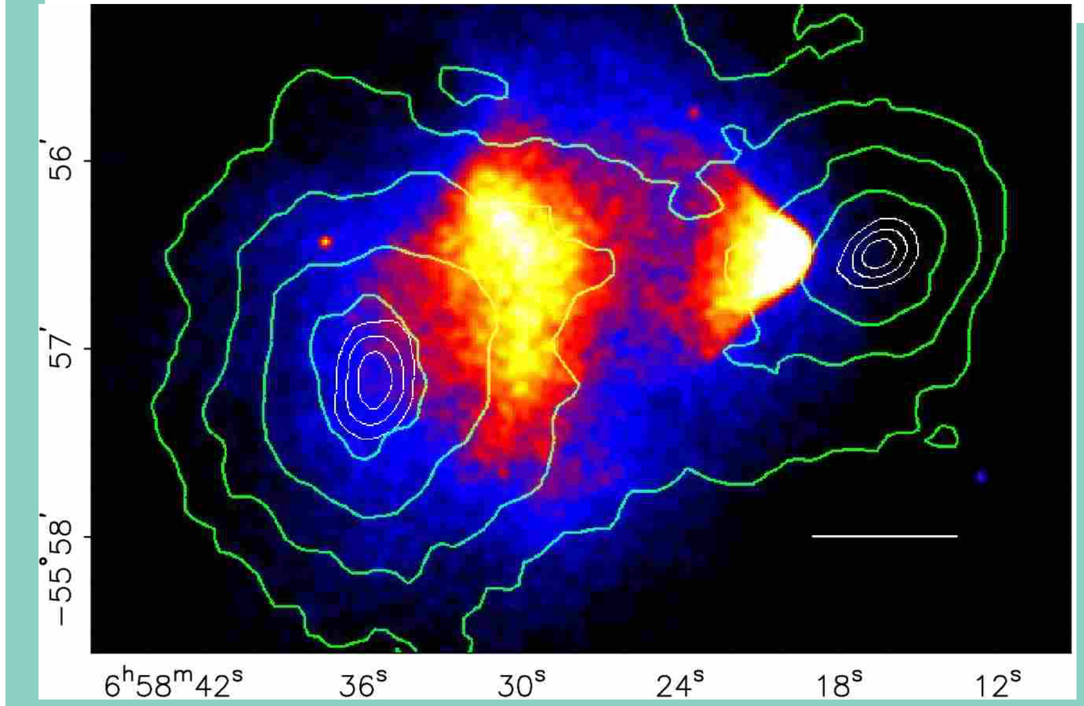
DARK MATTER

DARK MATTER

- **Cosmological and dynamical evidence are all consistent with ordinary matter being only a small part (15% or so) of matter in the universe**
- **Measurements of stars and gas-clouds orbiting in galaxies (and mini-galaxies) indicate that galaxies are large dark matter haloes with ordinary matter collected together in the center**
- **Hot gas in galaxy clusters emit X-rays consistent with a similarly higher gravitational potential**
- **Cluster mergers/collisions show that the mass distributions passes through without interacting**
- **Large-scale structures in the universe of which galaxies are a part also show evidence of being held/pulled together by dark matter**
- **Lastly, very precise measurements of the cosmic microwave background is consistent with visible matter in the early universe having moved/oscillated alongside with a non-interacting gravitating fluid of the same abundance**



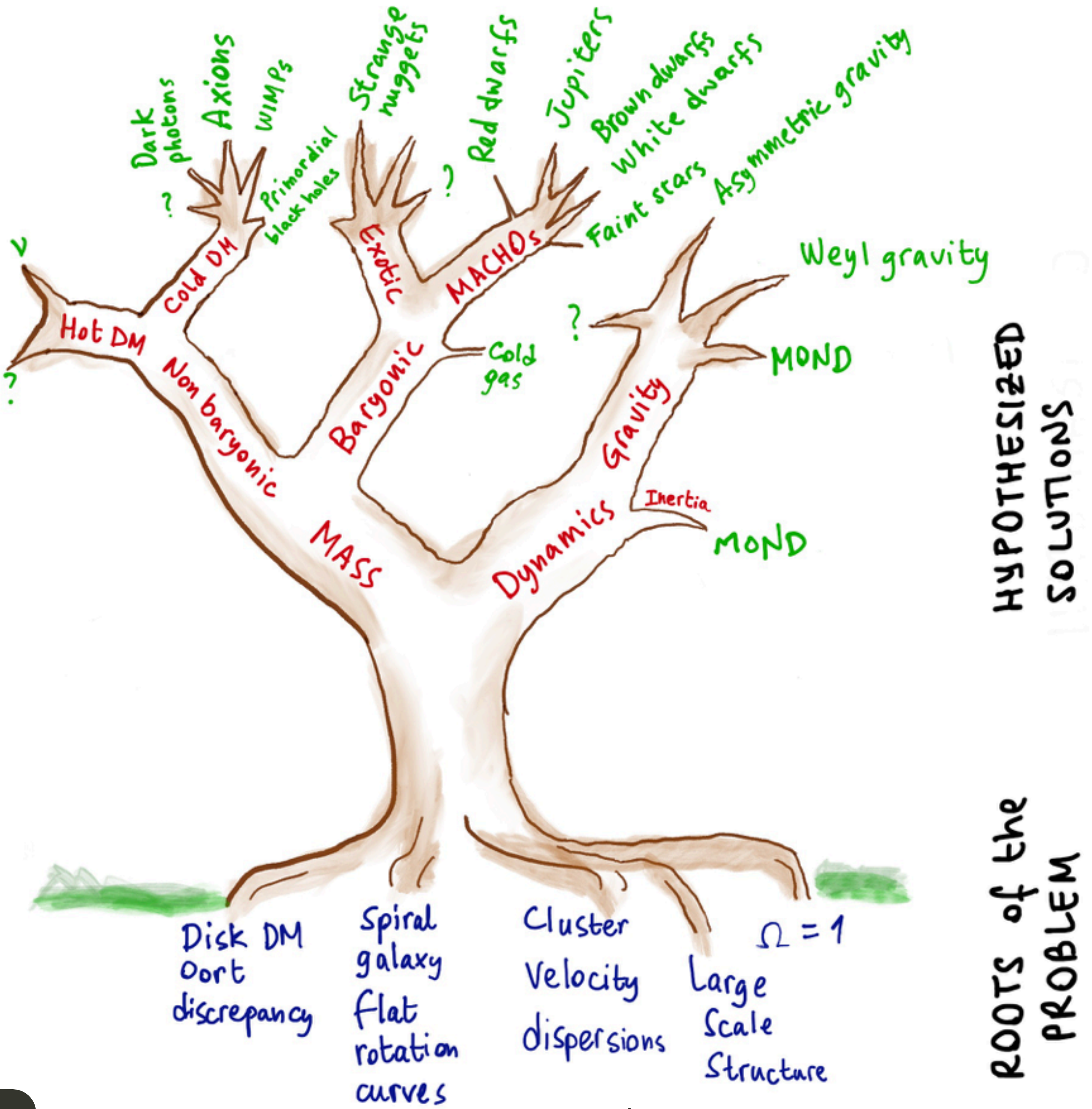
Fabio Iocco, Miguel Pato, and Gianfranco Bertone. “Evidence for dark matter in the inner Milky Way”. In:Nature Phys.11 (2015), pp. 245–248.doi:10.1038/nphys3237.



Douglas Clowe et al. “A direct empirical proof of the existence of dark matter”. In:Astrophys. J. Lett.648 (2006), pp. L109–L113.doi:10.1086/508162.

DARK MATTER CANDIDATES

- **No electric charge**
- **Massive**
- **Limited self-interactions (cluster mergers set limits)**
- **Non-relativistic in the early universe**
- **Stable**



Amazing Drawing thanks to Dr. Laura Manenti! lm189@nyu.edu

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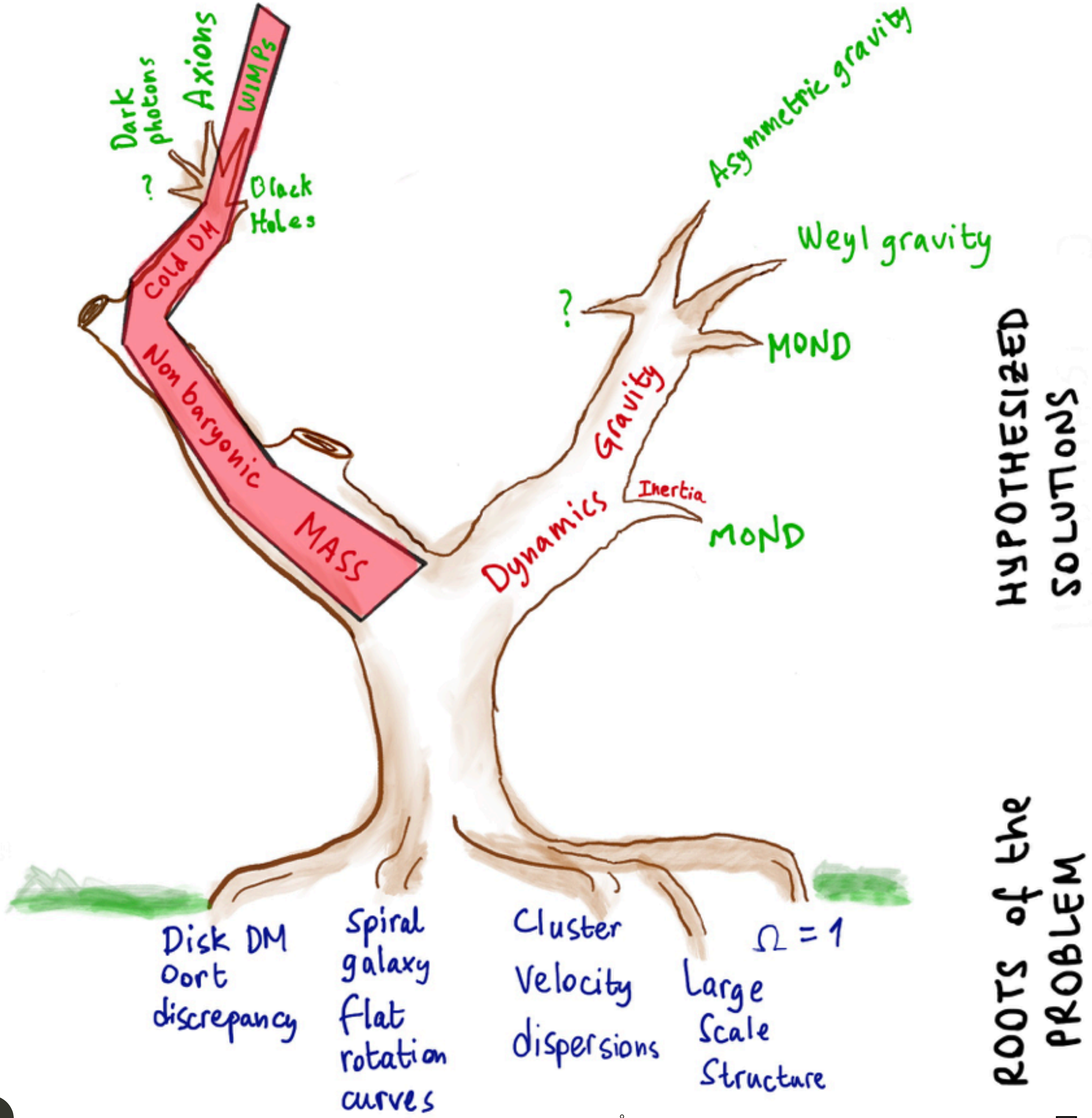

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WIMP DARK MATTER

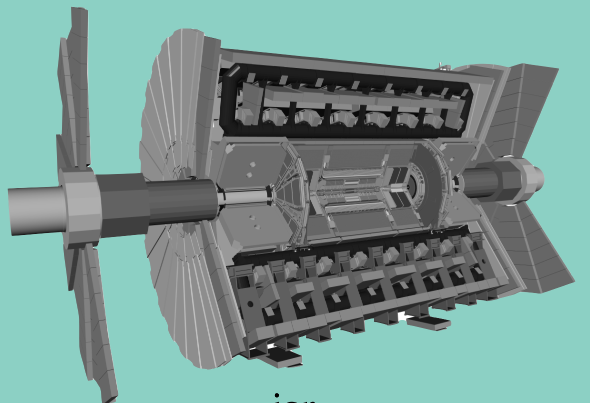
- **Weakly Interacting Massive Particles, WIMPs remains a viable dark matter candidate, though a range of searches so far have found only null results.**
- **a particle with weak-scale mass ($100\ \mathrm{GeV}/c^2$) and cross-section would be thermally produced with roughly the right relic density**
- **Experiments, however, typically define WIMPs as any dark matter particle with mass and weak interactions**
- **It is also a feature of many BSM theories, notably neutralinos in SUSY.**
- **And, importantly, WIMPs have several complementary search channels— colliders, direct and indirect searches**

A nice introduction in Particle Astrophysics by D. H. Perkins (oxford master series in physics)

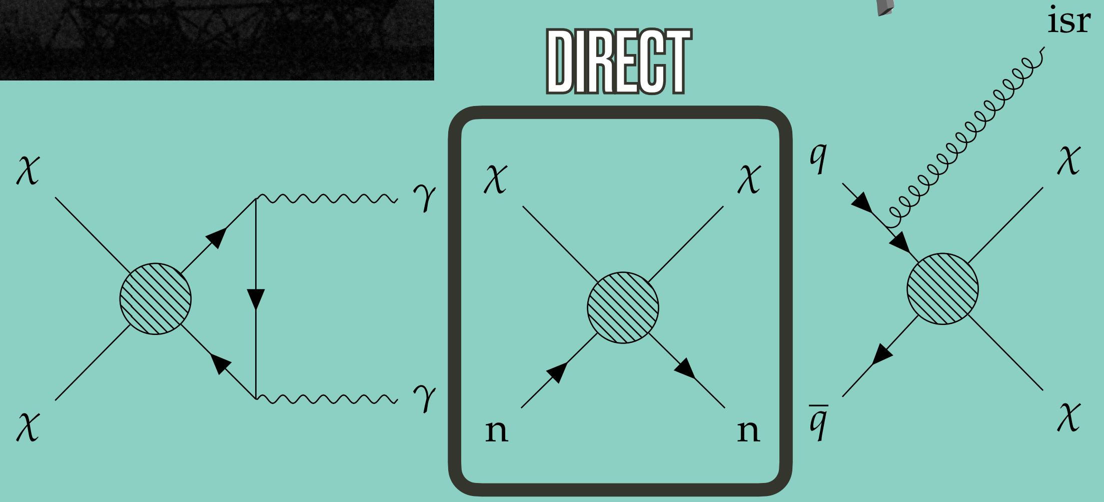
ATLAS courtesy of ATLAS

INDIRECT

COLLIDER



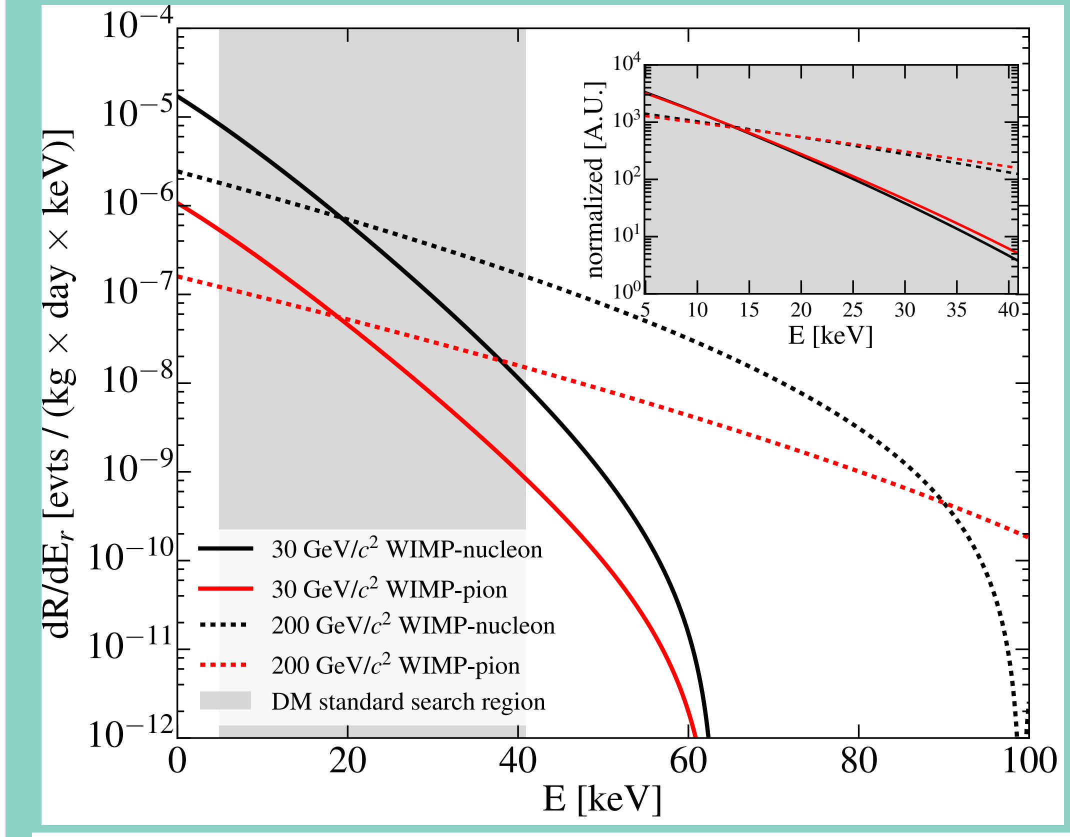
DIRECT

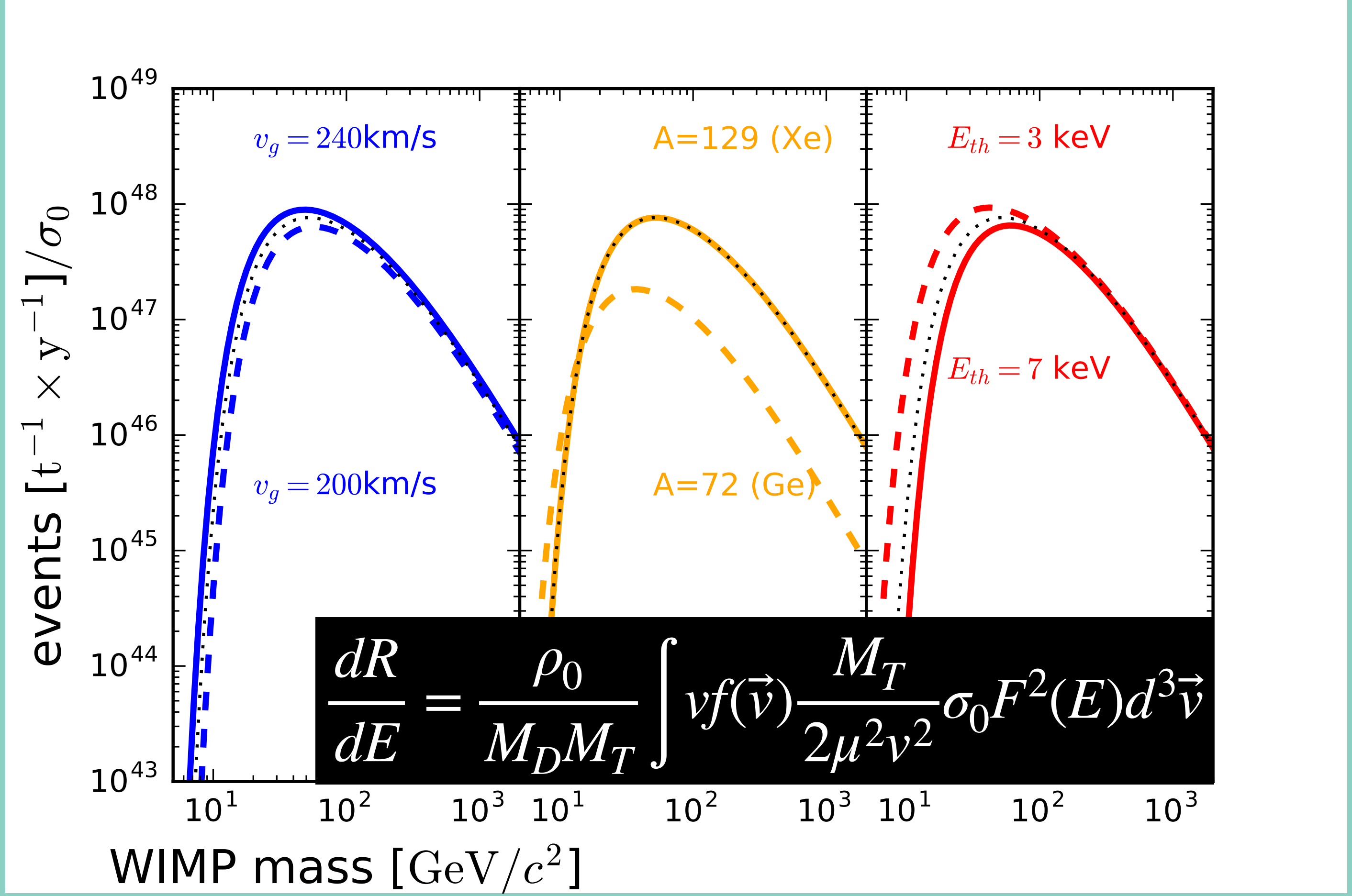


DIRECT DETECTION OF WIMPS

- At galactic velocities, a WIMP with typical weak-scale (GeV-TeV) would deposit some keV of nuclear recoil energy
- For a Maxwell velocity distribution the typical recoil spectrum is an exponential decreasing with recoil energy
- Note that the spectrum is very smooth— changes in model assumption will mostly change the rate
- For low recoil energies, the WIMP scatters on the entire nucleus— coherent scattering boosts the rate by a factor A^2
- Transferred energy is maximised when the target nucleus and the WIMP have the same mass

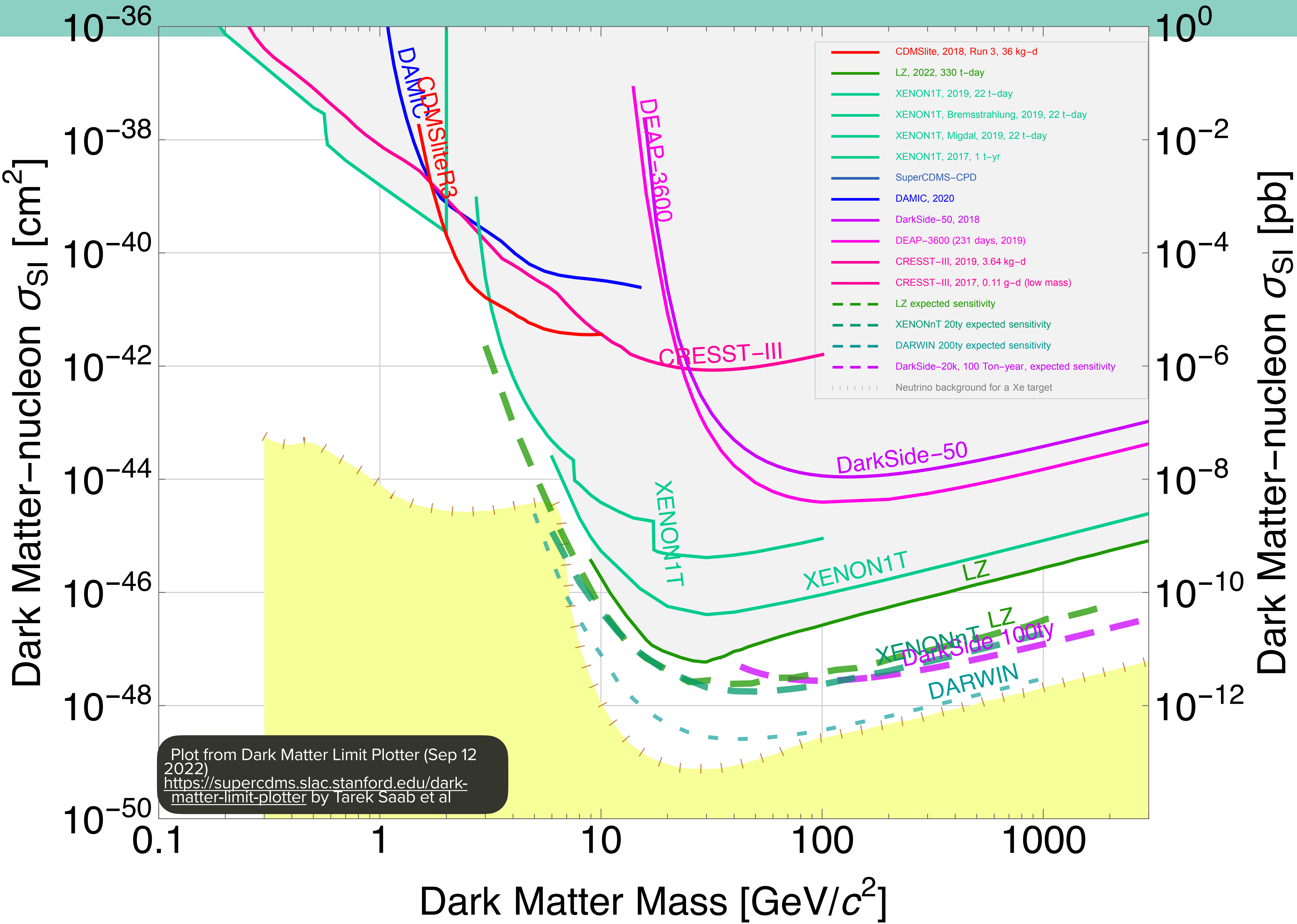
XENON collaboration. "First results on the scalar WIMP-pion coupling, using the XENON1T experiment." Physical review letters 122.7 (2019): 071301.





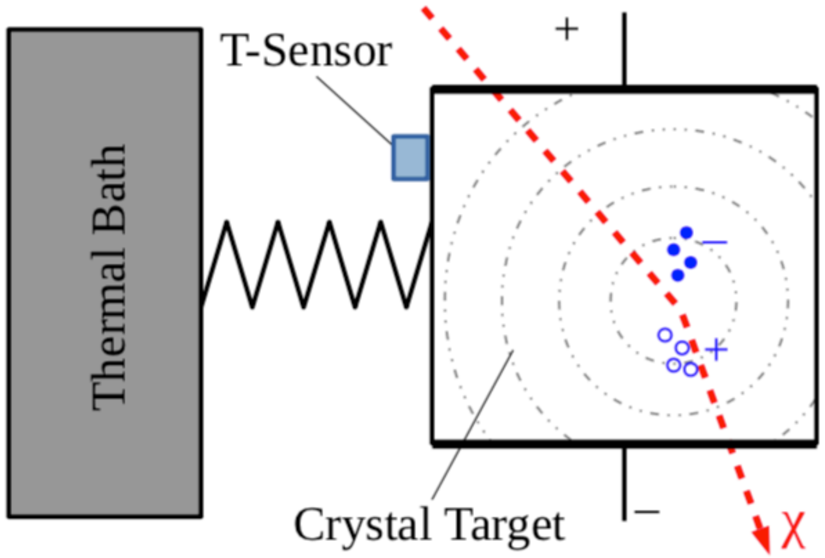
$$\frac{dR}{dE} = \frac{\rho_0}{M_D M_T} \int v f(\vec{v}) \frac{M_T}{2\mu^2 v^2} \sigma_0 F^2(E) d^3\vec{v}$$

THE WIMP PARAMETER SPACE

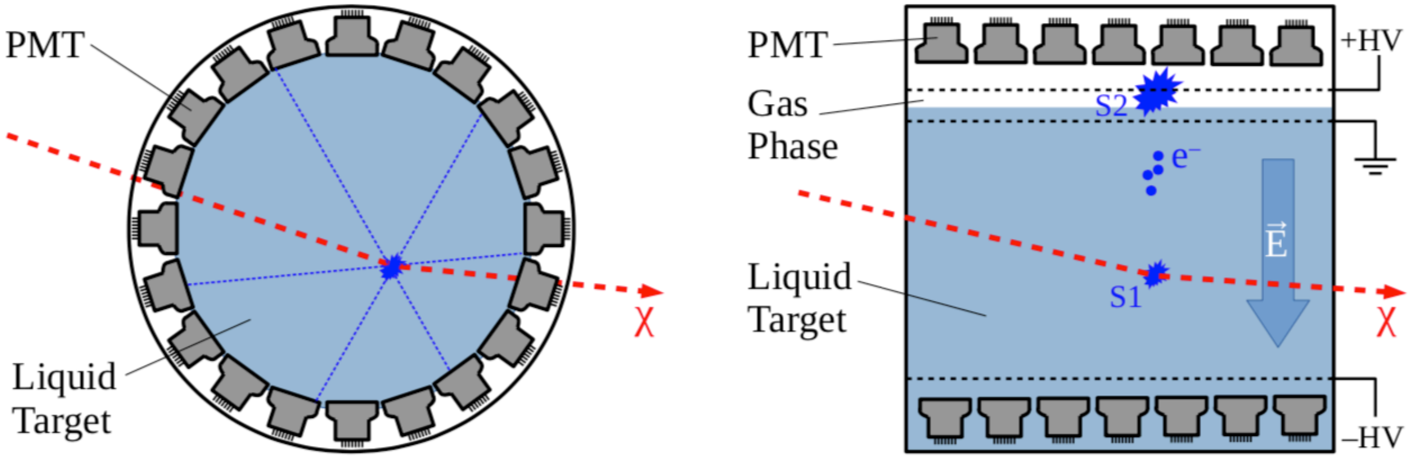


Plot from Dark Matter Limit Plotter (Sep 12 2022) https://supercdms.slac.stanford.edu/dark-matter-limit-plotter by Tarek Saab et al

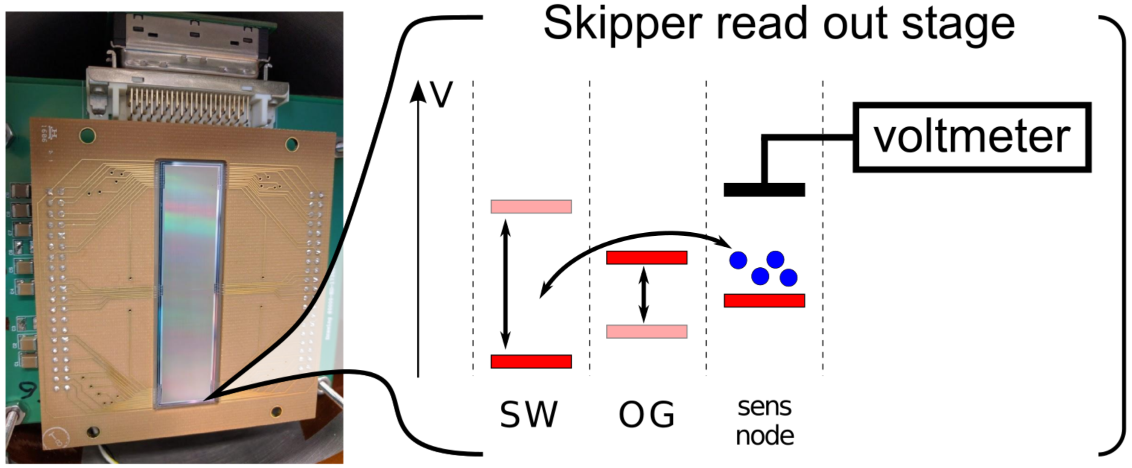
DETECTOR TECHNOLOGY EXAMPLES



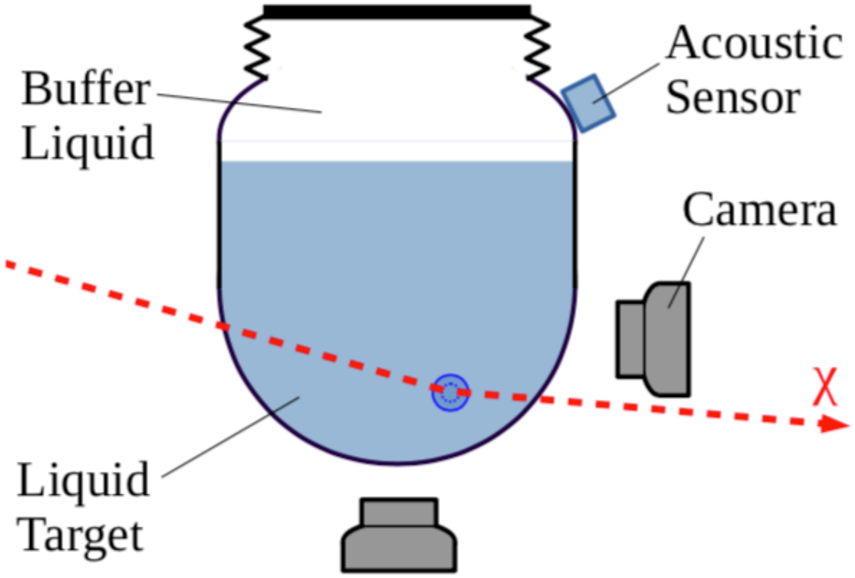
CRYOGENIC DETECTOR: HEAT & IONISATION



LIQUID NOBLE GAS 1- AND 2-PHASE TPCS



CCD READ OUT REPEATEDLY PER-PIXEL



BUBBLE CHAMBER

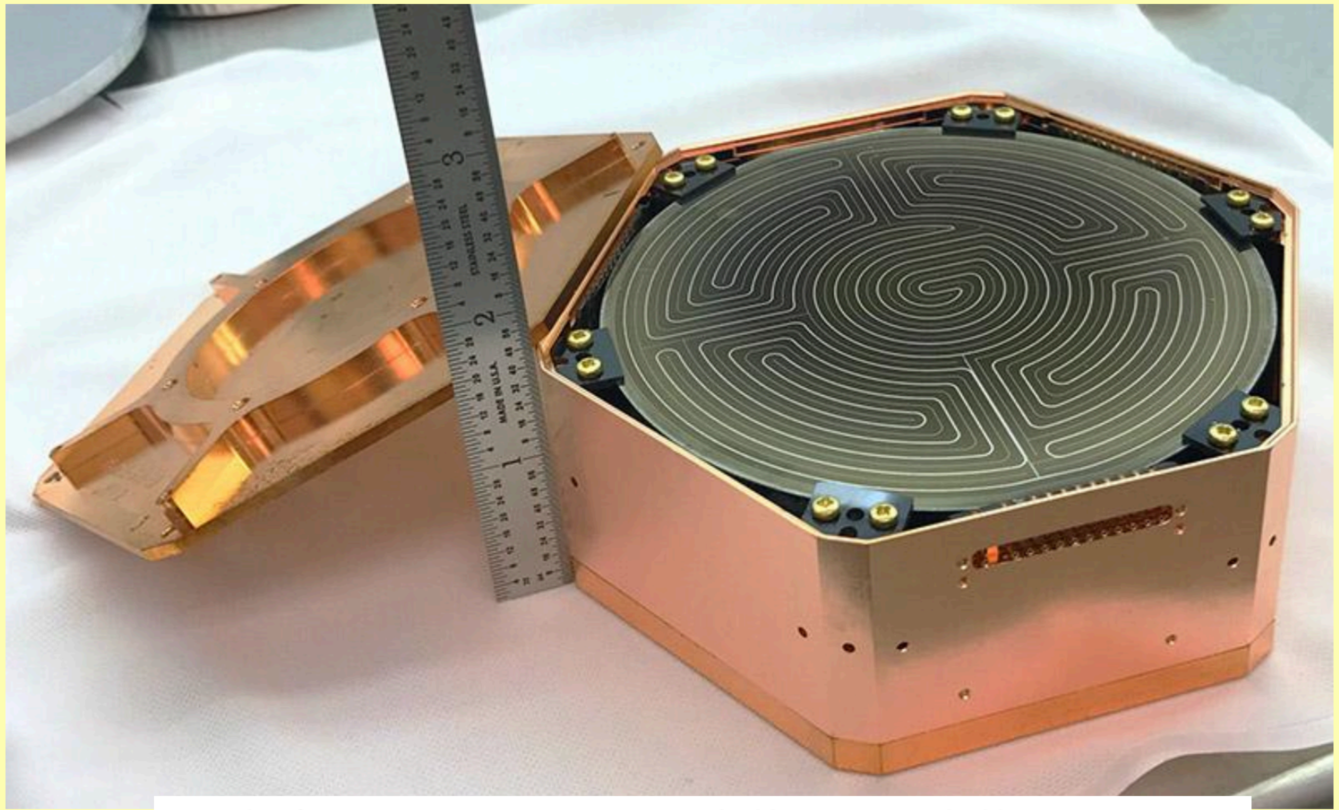
Figures except SENSEI from: Marc Schumann. “Direct Detection of WIMP Dark Matter: Concepts and Status”. In: J. Phys. G 46.10 (2019), p. 103003. doi: 10.1088/1361- 6471/ab2ea5.
SENSEI illustration from https://sensei-skipper.github.io/#SkipperCCD

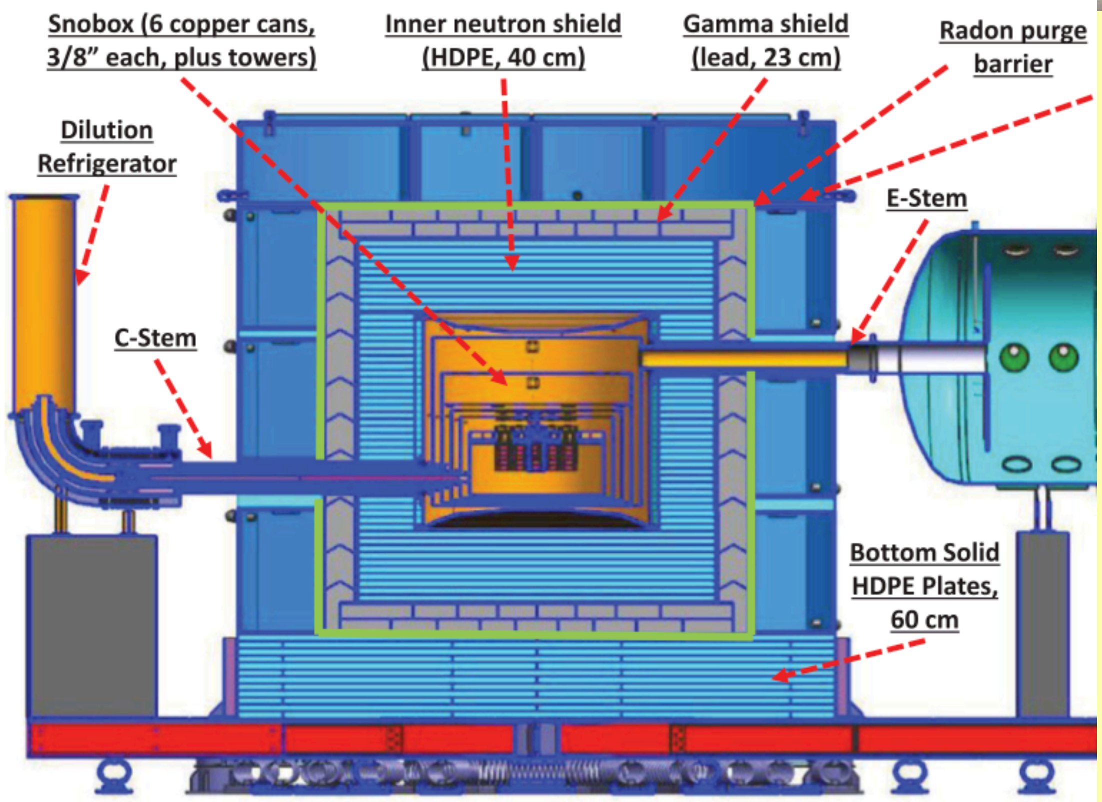
LOW-THRESHOLD SEARCHES

CRYSTALS: CDMS

- SuperCDMS SNOLAB is the latest of a series of CDMS direct detection experiments
  - Previously at the Soudan laboratory, but SNOLAB gives almost 3 times the overburden, and a factor 250 reduction in neutrons from muons.
- made up of solid-state detector modules of germanium (1.4kg) or silicon (0.6kg) crystals, held at $15 - 30\text{mK}$
- Observables are heat (as phonons) and charge
  - Phonons are read out with transition edge sensors (TES), sensitive to $\Delta T \sim 10\text{mK}$

Detector image courtesy of SuperCDMS https://supercdms.slac.stanford.edu/



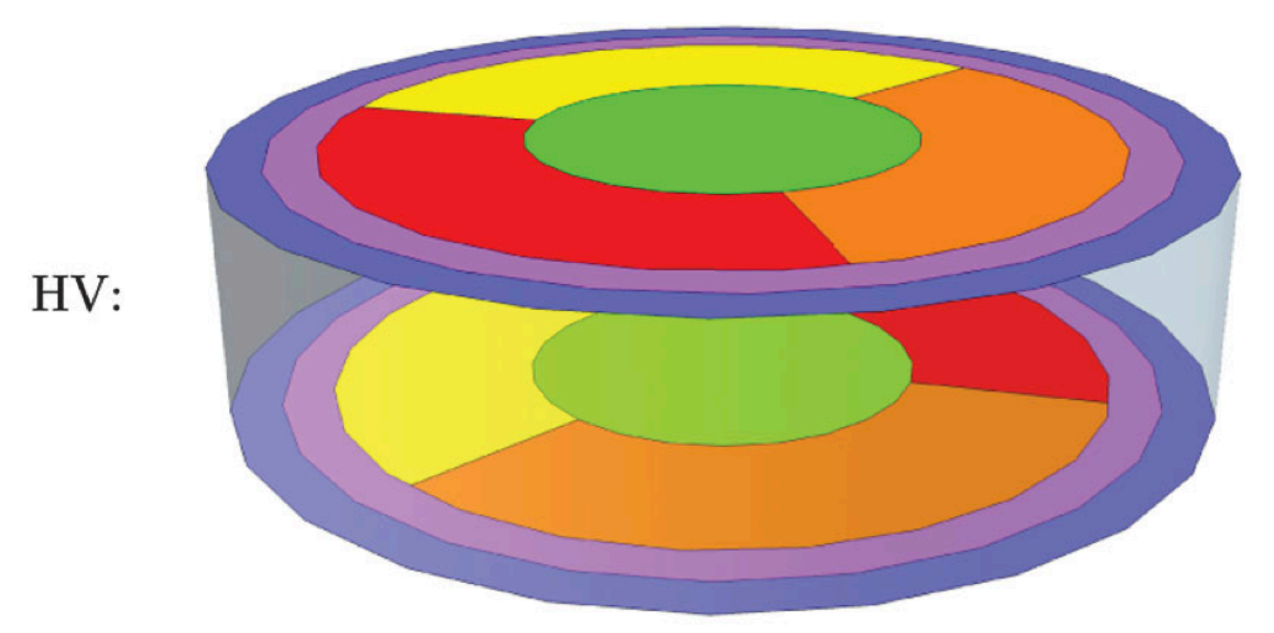


R. Agnese et al. Projected Sensitivity of the SuperCDMS SNOLAB experiment. Phys. Rev. D, 95(8):082002, 2017. doi: 10.1103/PhysRevD.95.082002.

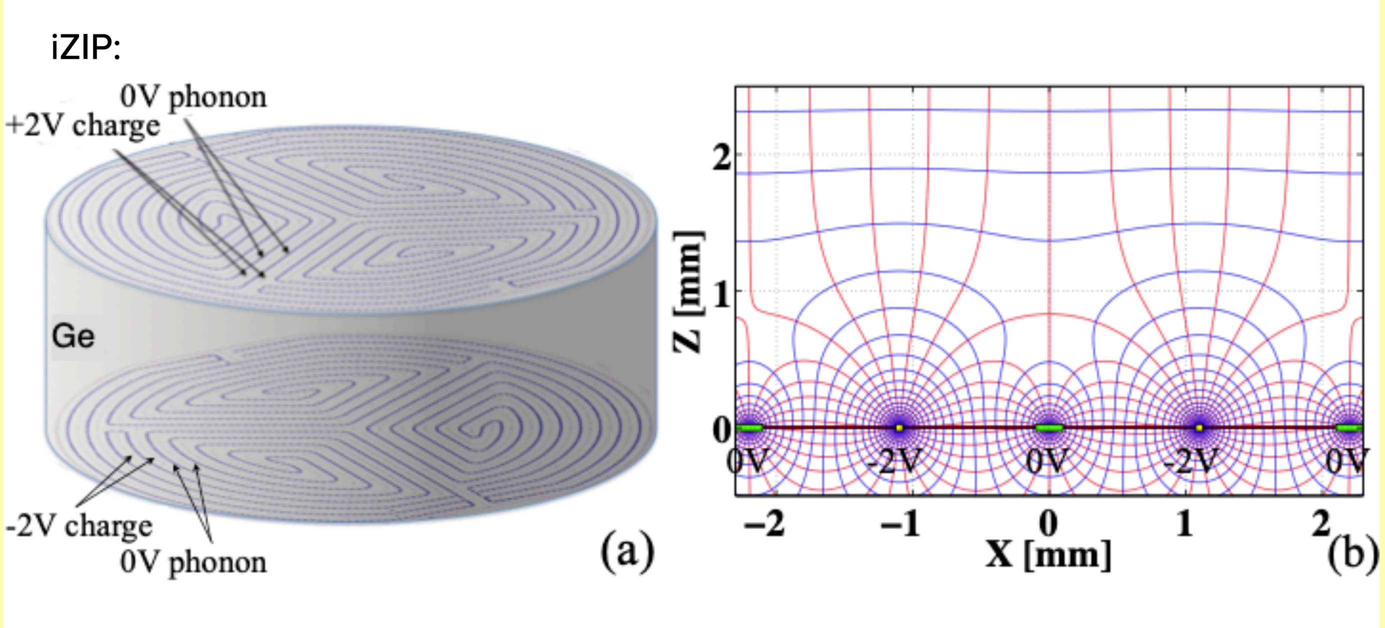
CRYSTALS: CDMS

- SuperCDMS uses two run modes:
- The CDMSlite mode uses a high amplification voltage to lower the energy threshold
  - Under a higher drift field, the charge carriers drifted through the detector emit additional phonons, which are then read out
  - Downside: lower ER/NR discrimination capability
- The interleaved mode (iZIP) reads out charge as well as phonons
  - Rejects ER events based on charge/phonon ratio
  - Surface backgrounds are also reduced with a positive bias on the ionisation channels, funnelling the charges

R. Agnese et al. Projected Sensitivity of the SuperCDMS SNOLAB experiment. Phys. Rev. D, 95(8):082002, 2017. doi: 10.1103/PhysRevD.95.082002.



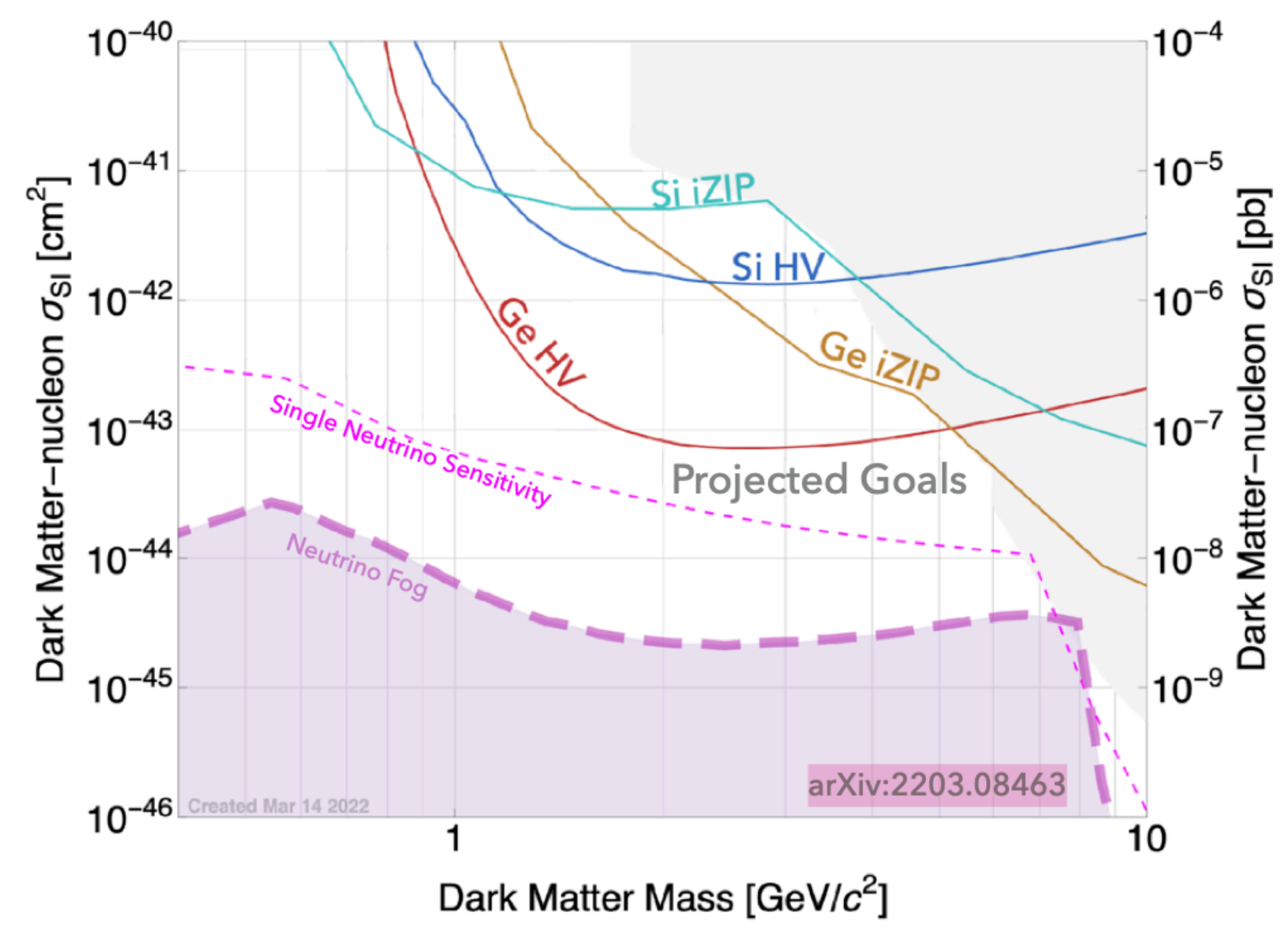
Phonon channel segmentation shown with color



R. Agnese et al. Demonstration of Surface Electron Rejection with Interleaved Germa- nium Detectors for Dark Matter Searches. Appl. Phys. Lett., 103:164105, 2013. doi: 10.1063/1.4826093.

CRYSTALS: CDMS

- **CDMSLite modules have reached energy thresholds of $0.3\ \mathrm{keV}_{nr}$, but high backgrounds limits sensitivity below $1.6\ \mathrm{keV}_{nr}$**
- **SuperCMDS, with target exposures of $\sim 40\mathrm{kg}-\mathrm{years}$ for Ge and $4-8\mathrm{kg}-\mathrm{years}$ for Si will start commissioning this year**
- **will constrain WIMPs down to $0.3\ \mathrm{GeV}/c^2$, and electronic recoils to $1\mathrm{eV}$**

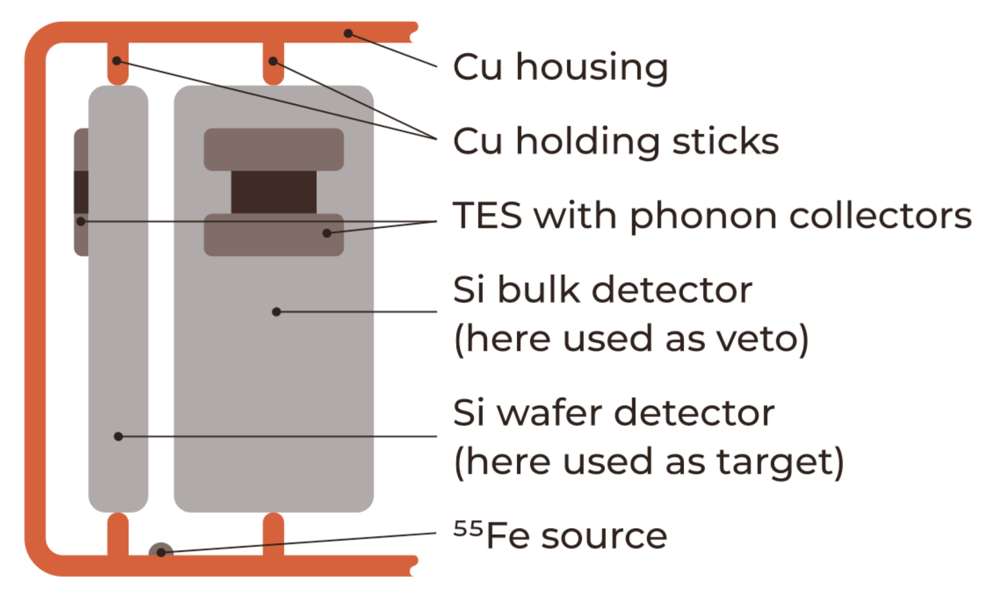


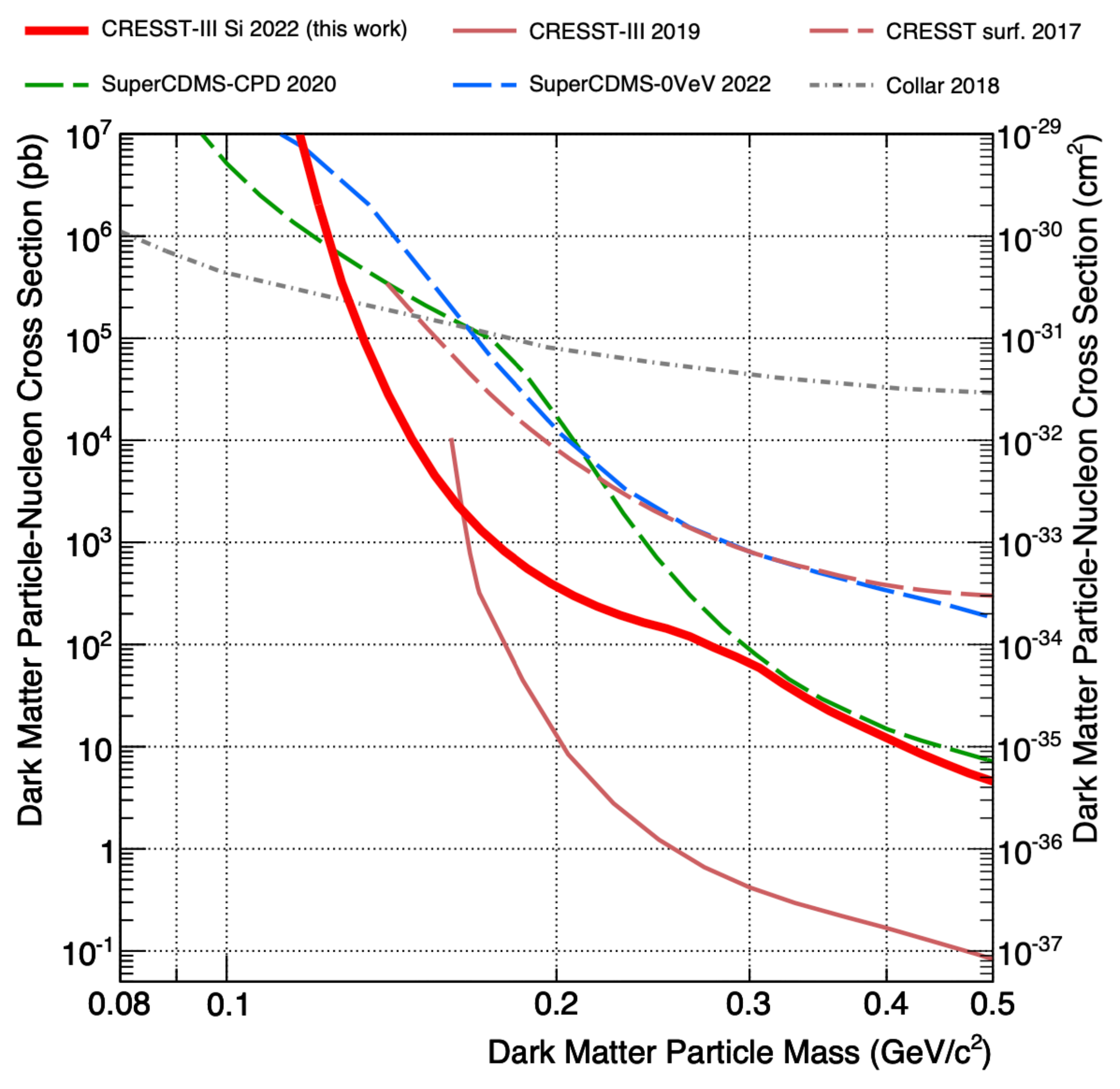
Plot from Matthew Wilson, Overview of the SuperCDMS Experiment IDM2022 Vienna

M. F. Albakry et al. A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS SNOLAB Facility. In 2022 Snowmass Summer Study, 3 2022.

CRYSTALS: CRESST-III

- **A range of crystal targets;** $\mathrm{CaWO_4}$, $\mathrm{Al_2O_3}$ $\mathrm{LiAlO_2}$, Si **held at** $10\ \mathrm{mK}$**, and operating as calorimeters read out by a transition-edge sensor**
- **Observables: phonons and (for scintillators) scintillation light, which provides ER/NR discrimination**
- **Choosing a specific low-noise crystal, CRESST-III was able to put limits down to** $0.115\ \mathrm{GeV/c^2}$ **with an energy threshold of** $10\ \mathrm{eV}$

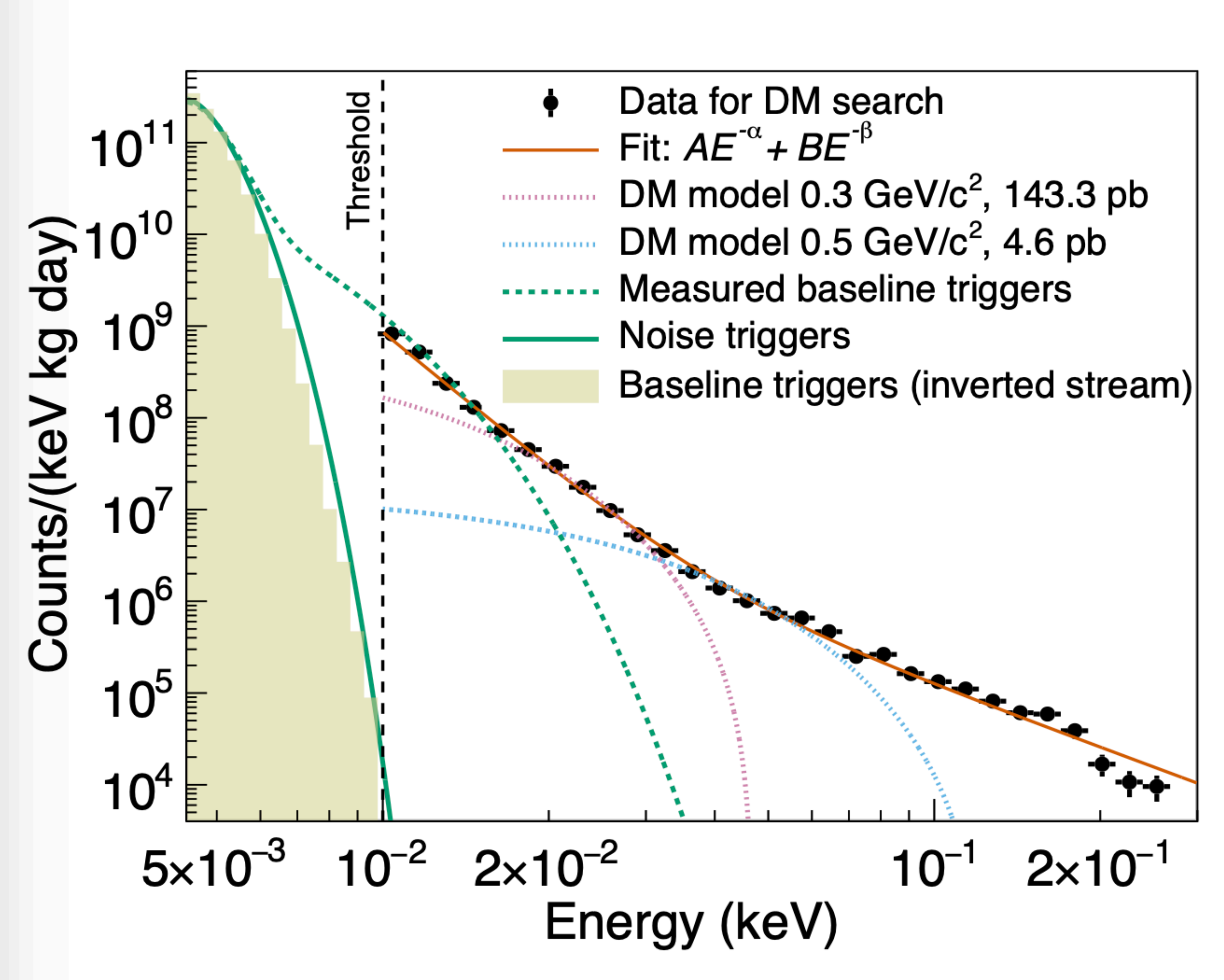




G. Angloher et al. Results on sub-GeV Dark Matter from a 10 eV Threshold CRESST-III Silicon Detector. 12 2022.

STRESS?

- A unexpected background component has been reported by a range of experiments at the lowest energies, varying between target modules
  - CRESST-III, EDELWEISS, NUCLEUS, SuperCDMS
- At least a significant component of this noise has been identified with microscopic stresses in the target materials
  - Mitigation strategies include careful mounting and clamping strategies,
  - Or moving to liquid targets

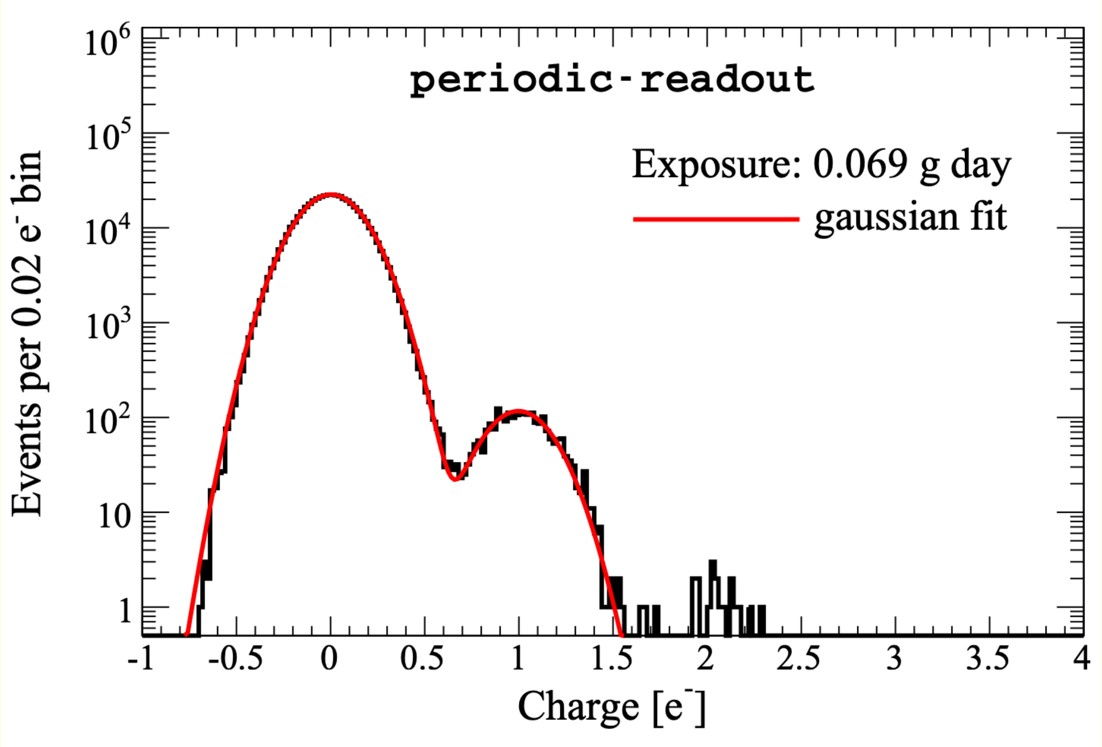


Abdelhameed, A. H. et al. (CRESST). First results from the CRESST-III low-mass dark matter program. Phys. Rev. D, 100(10):102002, 2019. doi: 10.1103/Phys- RevD.100.102002.

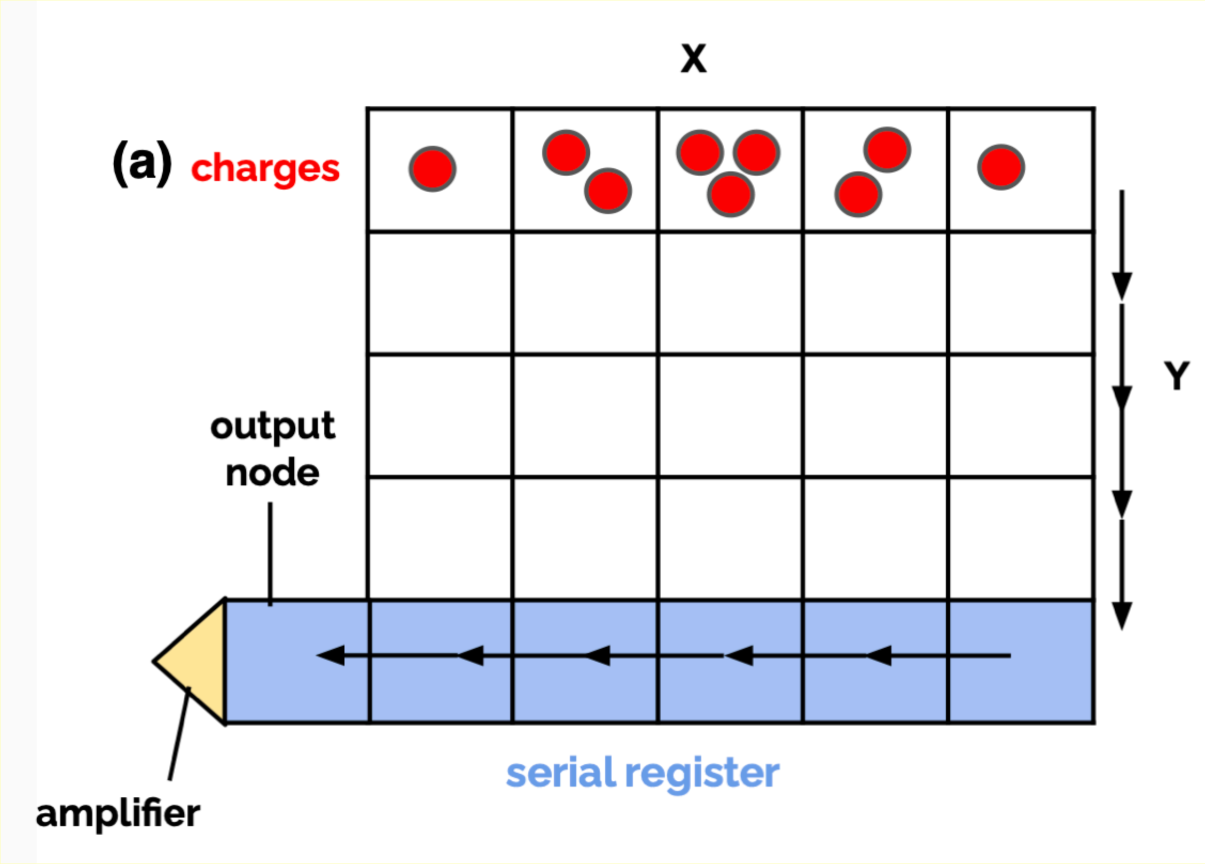
G. Angloher et al. Results on sub-GeV Dark Matter from a 10 eV Threshold CRESST-III Silicon Detector. 12 2022.

CCDs

- DAMIC-M and SENSEI, using CCD sensors, have achieved energy thresholds of $\sim 50\text{eV}$
  - Requires very low comsogenic activation and Rn contamination— limit time aboveground
  - Very low dark current achieved: $\sim 10^{-4} e^{-}/\text{pixel/day}$
- “Skipper” amplifiers read out the charge in a single pixel repeatedly, which gives single-electron resolution
- Scientific targets: DM-nucleon to $\sim 1\text{Gev}/c^2$ as well as DM-e^- scattering and full absorption (e.g. dark photon)



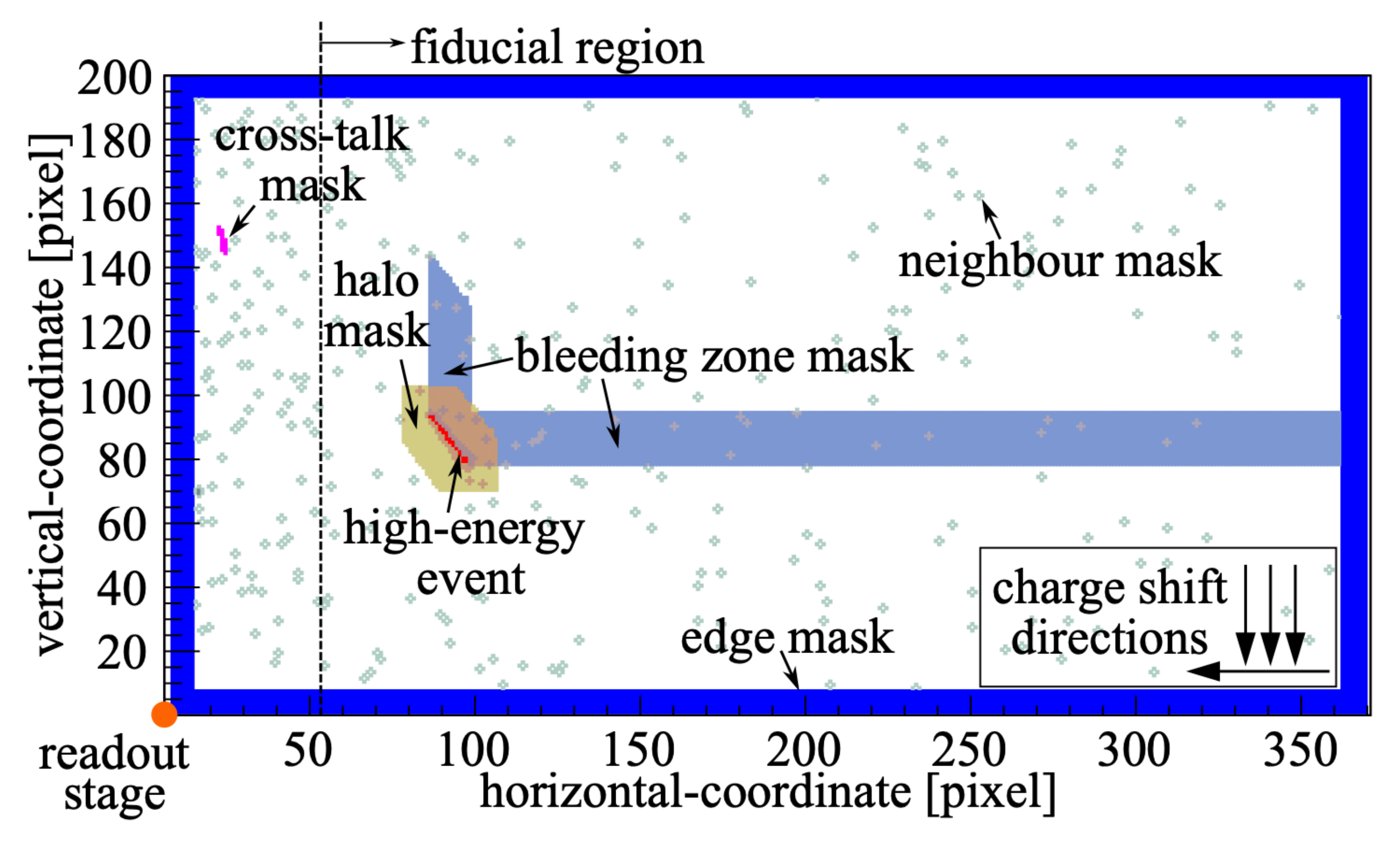
Orr Abramoff et al. SENSEI: Direct-Detection Constraints on Sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper-CCD. Phys. Rev. Lett., 122(16):161801, 2019. doi: 10.1103/PhysRevLett.122.161801.



I. Arnquist et al. The DAMIC-M Experiment: Status and First Results. In 14th International Workshop on the Identification of Dark Matter 2022, 10 2022.

CCDs

- Event candidates are classified based on the topology of the pixel hits
  - Low-energy events will be a small blob, and a limited amount of depth information can be gained by the diffusion of the charge
  - hits close to a high energy or near hot pixels are excluded



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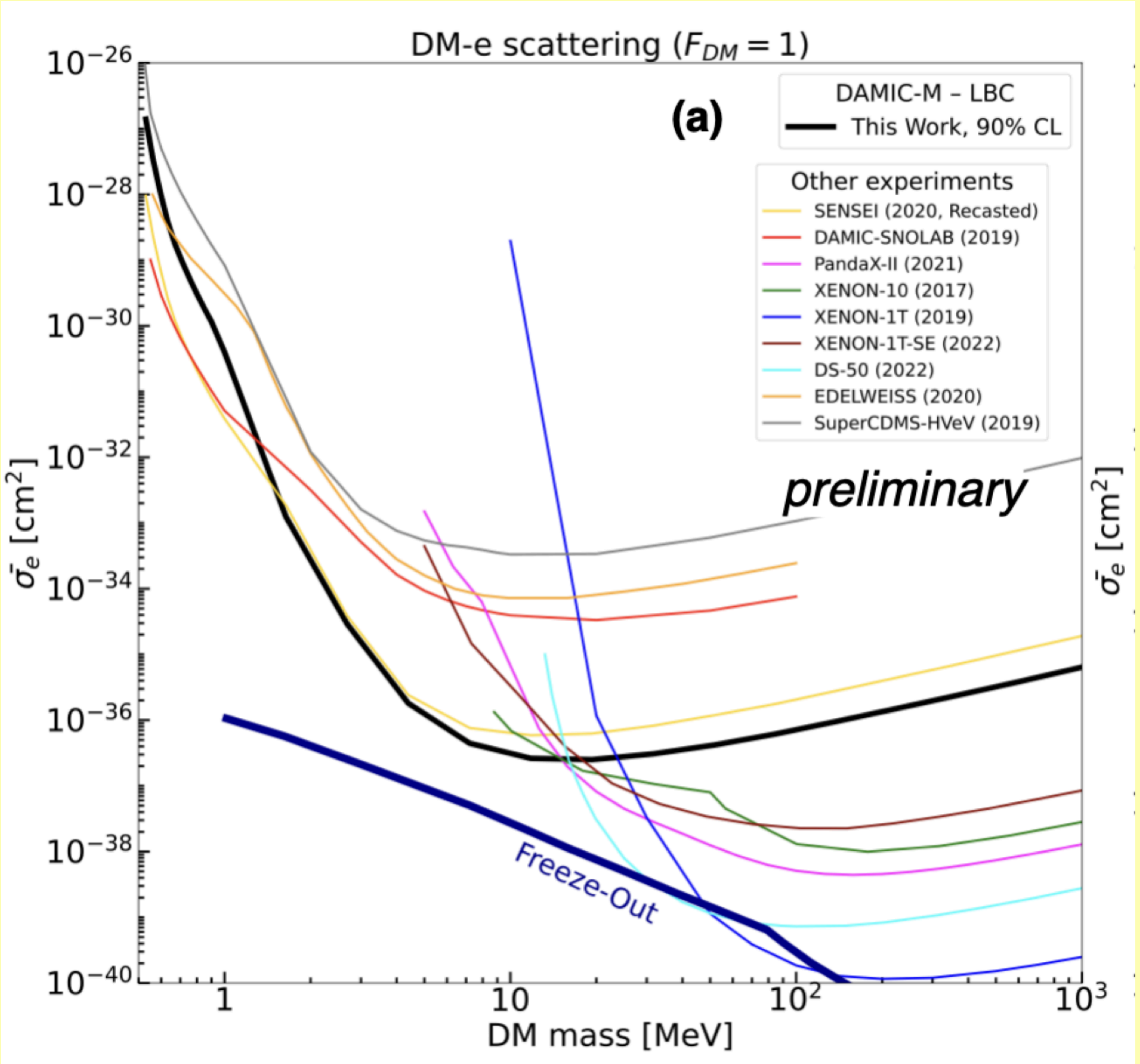
CCDs

- **Skipper CCDs have already delivered competitive constraints on light dark matter scattering on electrons**
  - **Limited exposures**
  - **Some exposures taken above-ground**
- **Current DAMIC results are reported for a pathfinder experiment:**
  - $115\mathrm{g} - \mathrm{days}$
  - **background** $\sim 10\ \mathrm{counts/kg/d/keV}$
- **Full DAMIC target:**
  - $1\mathrm{kg} - \mathrm{year}$
  - **background** $\sim 0.1\ \mathrm{counts/kg/d/keV}$
  - **energy threshold** $\sim 5\ \mathrm{keV}$



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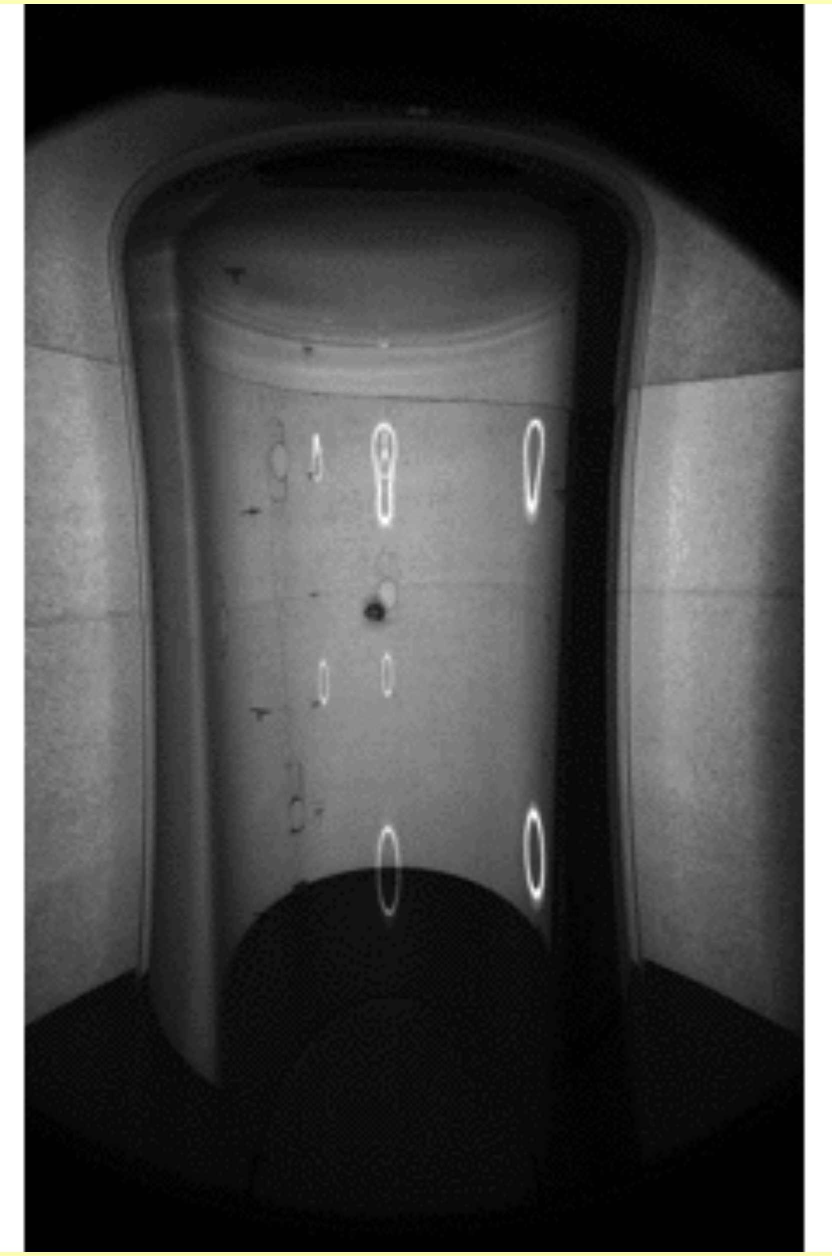
BUBBLE CHAMBERS/ PICO

- The PICO (PICASSO+COUPP) series of experiments use supercritical fluid bubble chambers to detect nuclear recoil heat depositions
- Electronic recoils produce less dense energy depositions, and do not form bubbles— intrinsic NR/ER discrimination
- Observables: images of bubbles, and the sound as the bubble bursts
  - neutrons can be distinguished by multiple tracks or spatially
  - Alpha bubbles are louder—99+% discrimination
- $\sim 3\mathrm{keV}$ energy thresholds in science mode, lower thresholds of $1.2 \pm 0.08\mathrm{keV}$ can be achieved if you accept some ER leakage



Single-bubble event captured during PICO-40L commissioning courtesy of the PICO experiment

F. Aubin et al. Discrimination of nuclear recoils from alpha particles with superheated liquids. New J. Phys., 10:103017, 2008. doi: 10.1088/1367-2630/10/10/103017.

C. Amole et al. Dark Matter Search Results from the Complete Exposure of the PICO- 60 C_3F_8 Bubble Chamber. Phys. Rev. D, 100(2):022001, 2019. doi: 10.1103/PhysRevD.100.022001.

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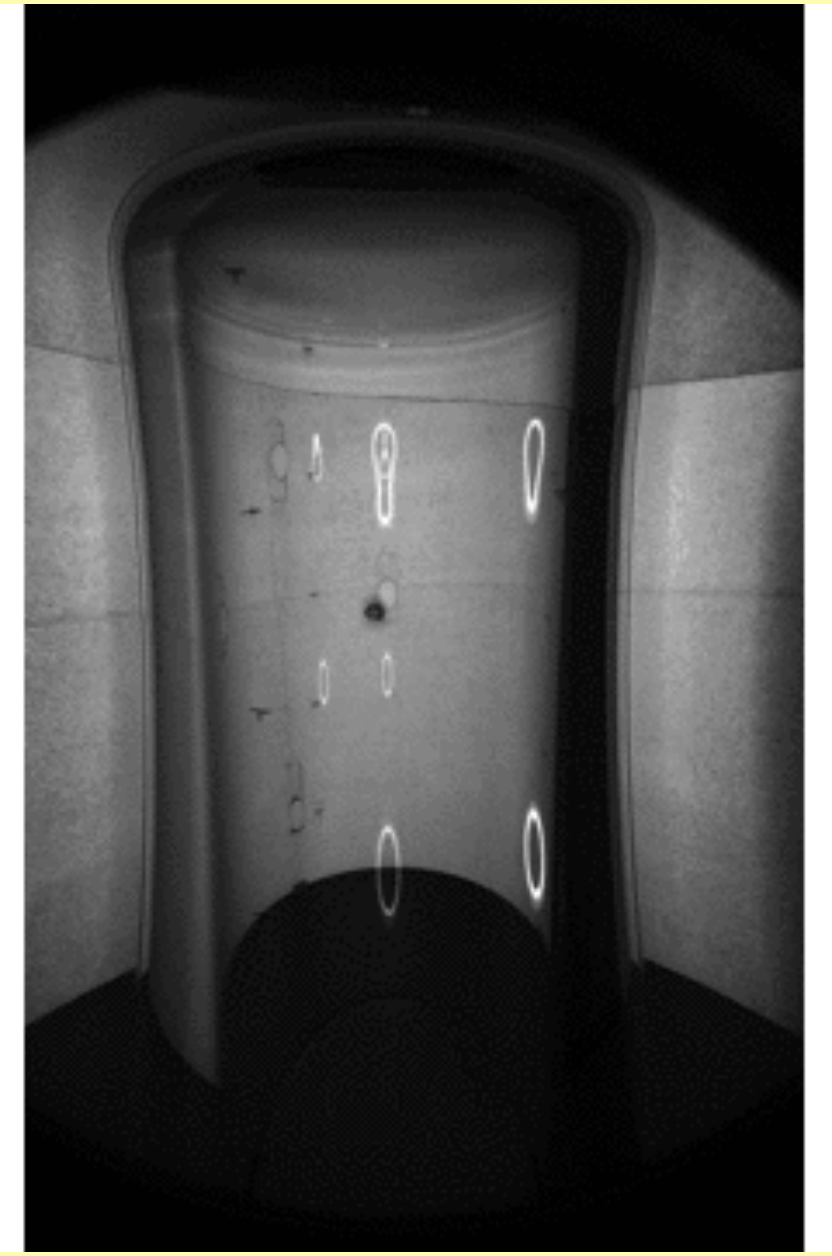

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BUBBLE CHAMBERS

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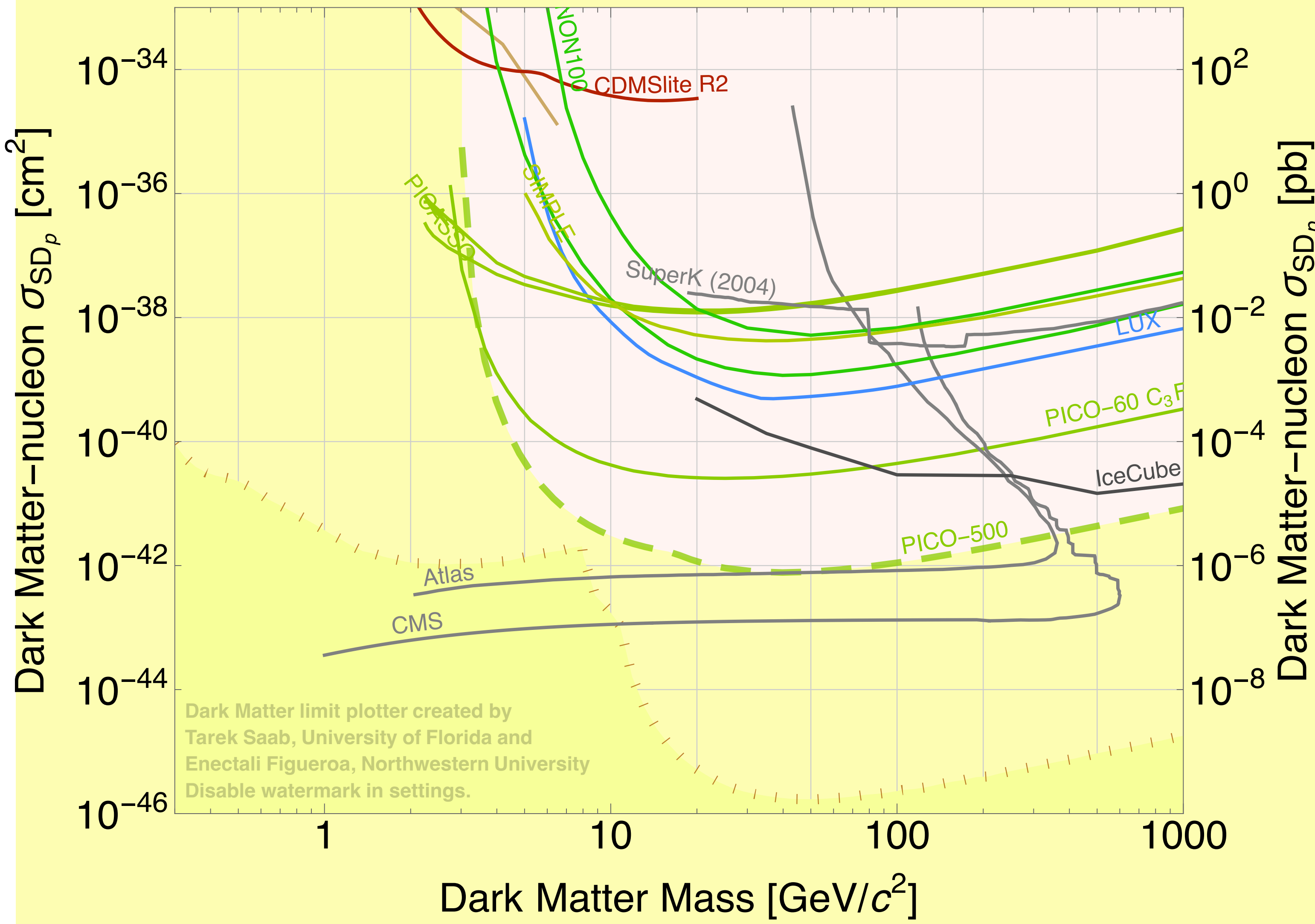
Plot from Dark Matter Limit Plotter (Sep 12 2022) https://supercdms.slac.stanford.edu/dark-matter-limit-plotter by Tarek Saab et al

- **Fluorine is a particularly good target for searches for spin-dependent WIMP-nucleon interactions, and PICO produces leading limits here (model dependence determines if collider bounds are even better)**
  - **Several nuclei can be used—can probe the nature of the WIMP-nucleon coupling**
- **Previous PICO generations (PICO-60) had the target hung under the bellows, PICO-40, in preparation for PICO-500 is “right side up”**
- **PICO-40L is commissioning, with a particular focus on background reduction, PICO-500 under construction**

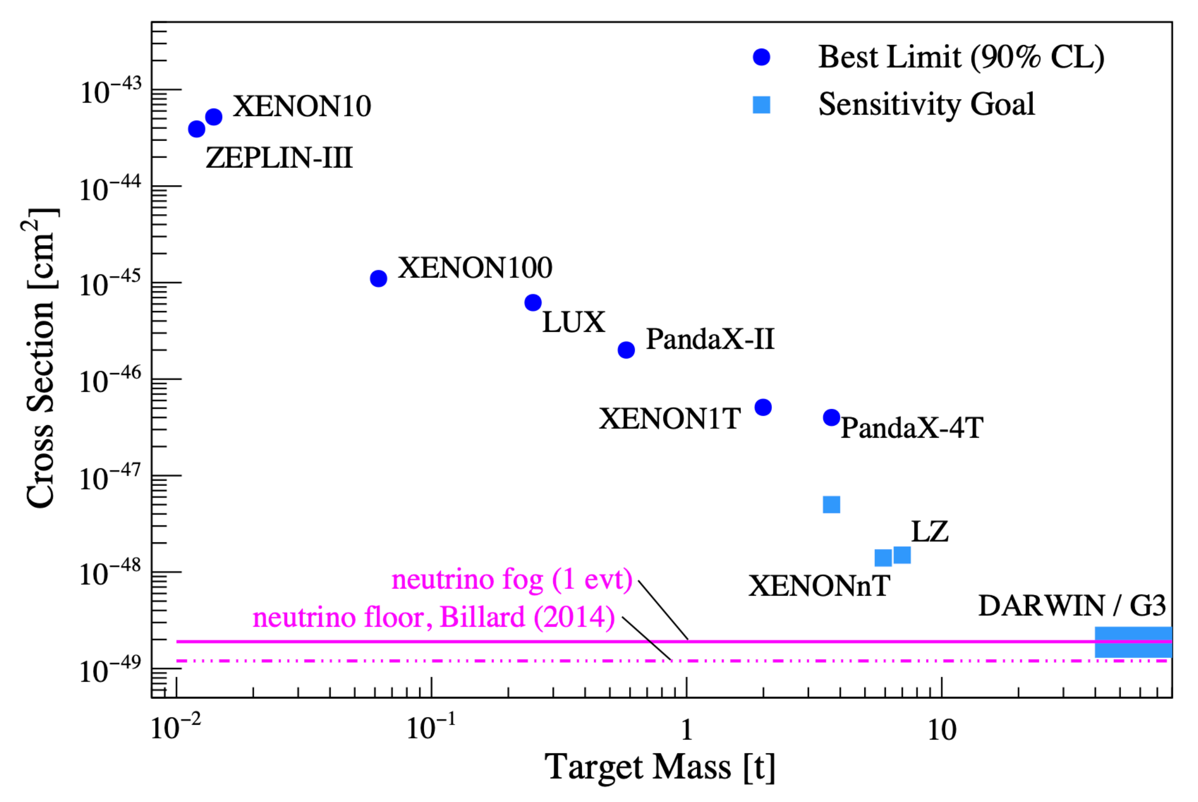


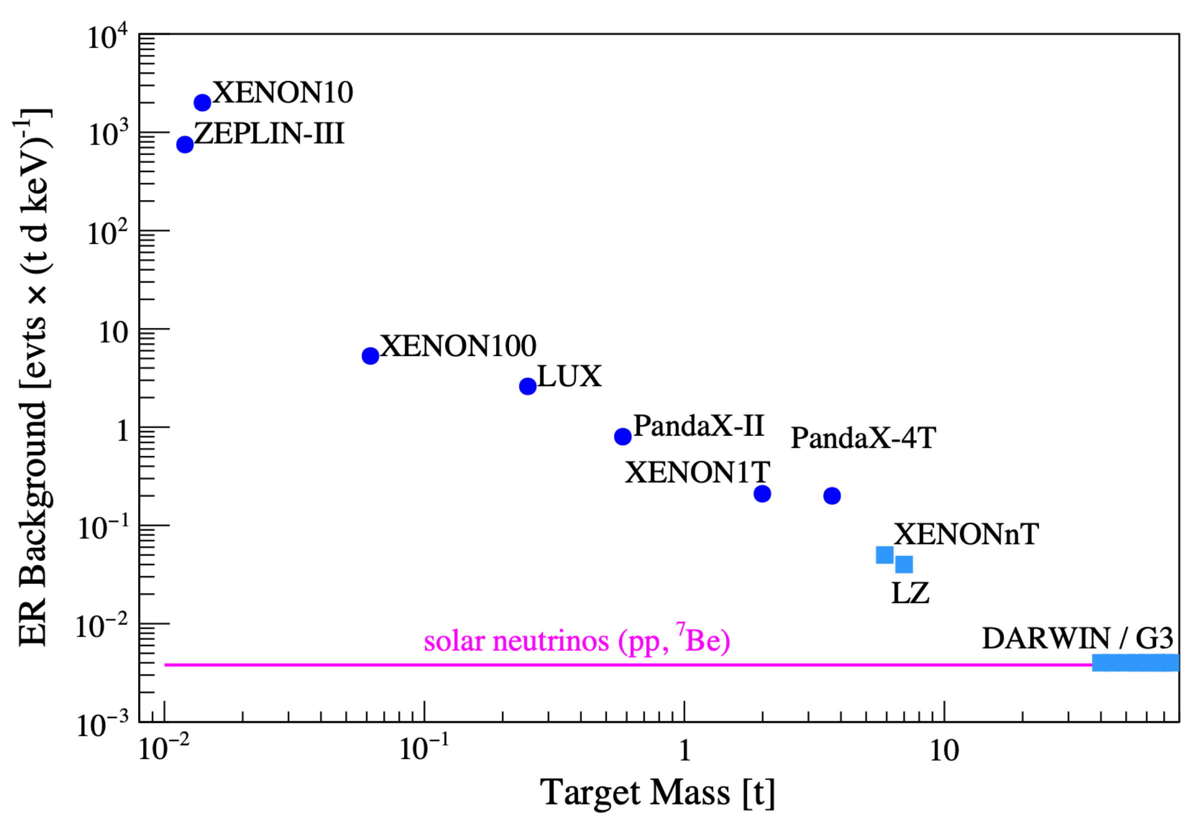
Caution: Combining collider and direct detection bounds like this involves some model dependence.

Liquid Xenon TPCs

BENEFITS OF XENON

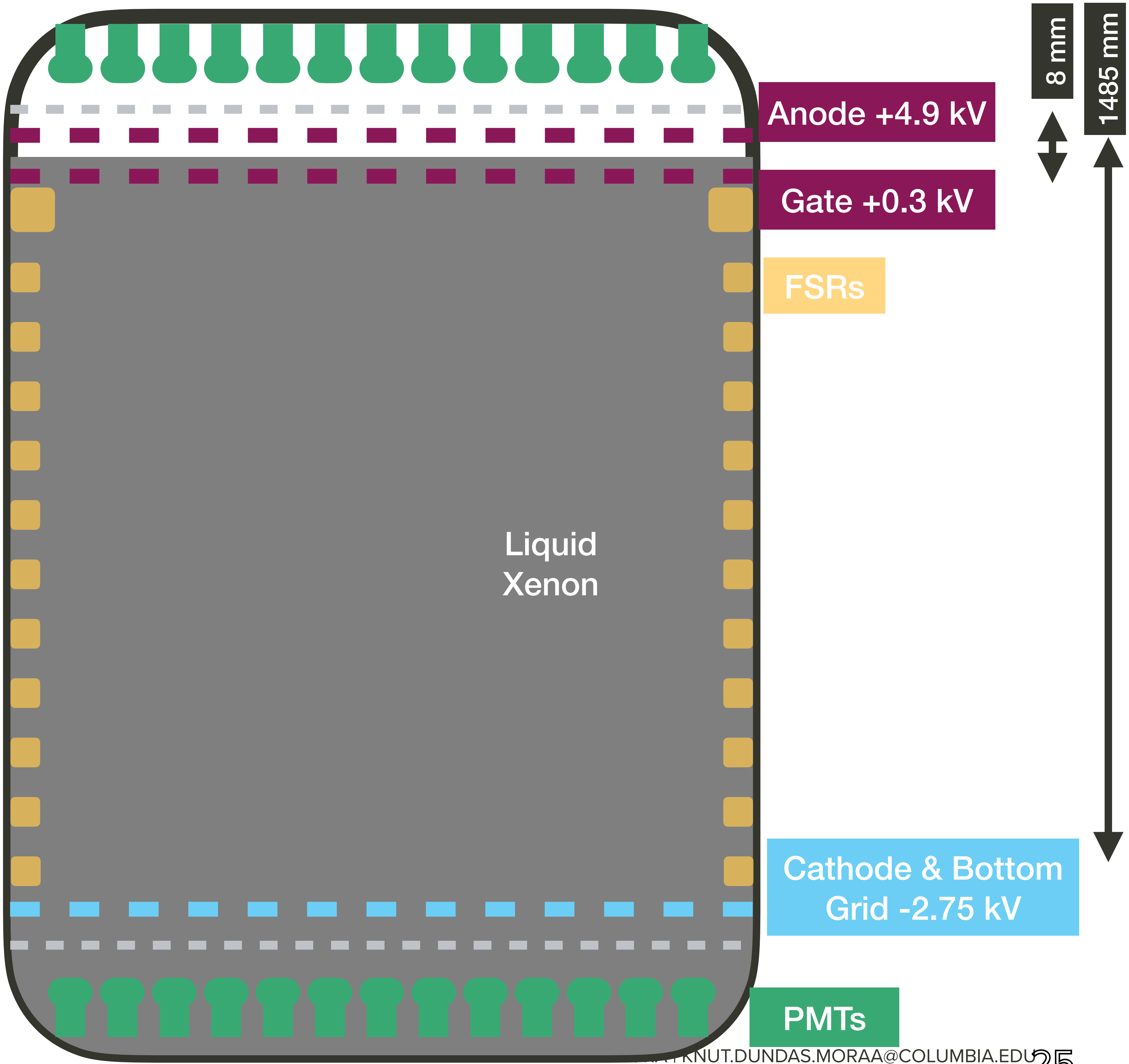
- For weak-scale dark matter (plots show $50\ \mathrm{GeV}/c^2$ limits), xenon-based detectors set the strongest limits, with a rapid improvement in sensitivity over the last 15 years or so
- Benefits of xenon include:
  - It scintillates in response to nuclear (and electronic) recoils
  - It is dense, allowing compact detectors with good self-shielding
  - It is nonreactive, and has few radioactive isotopes and little of them
  - A high atomic number gives a coherent enhancement of spin-independent WIMP-nucleus interactions





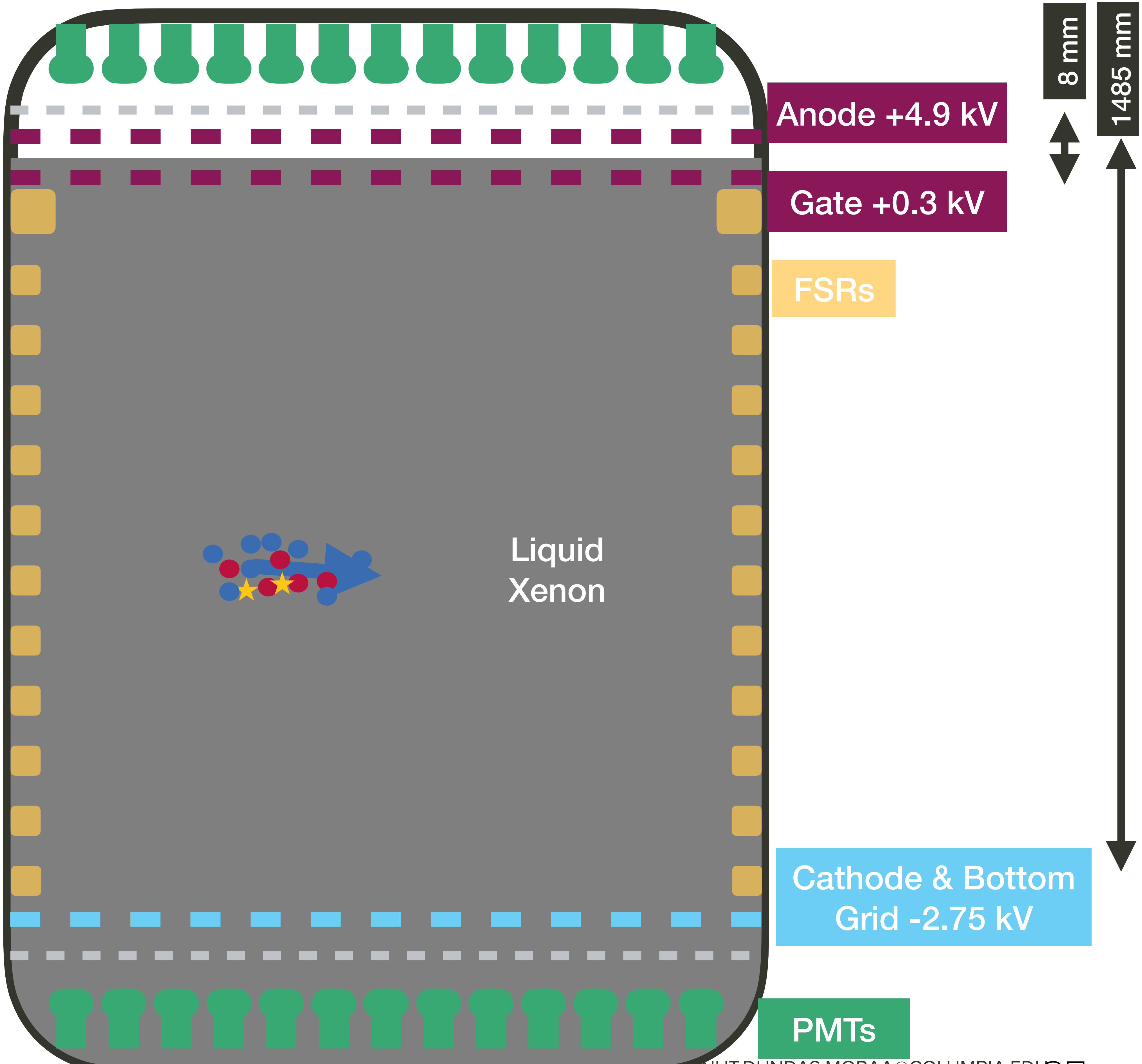
Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog. In 2022 Snowmass Summer Study, 3 2022.

WORKING PRINCIPLE



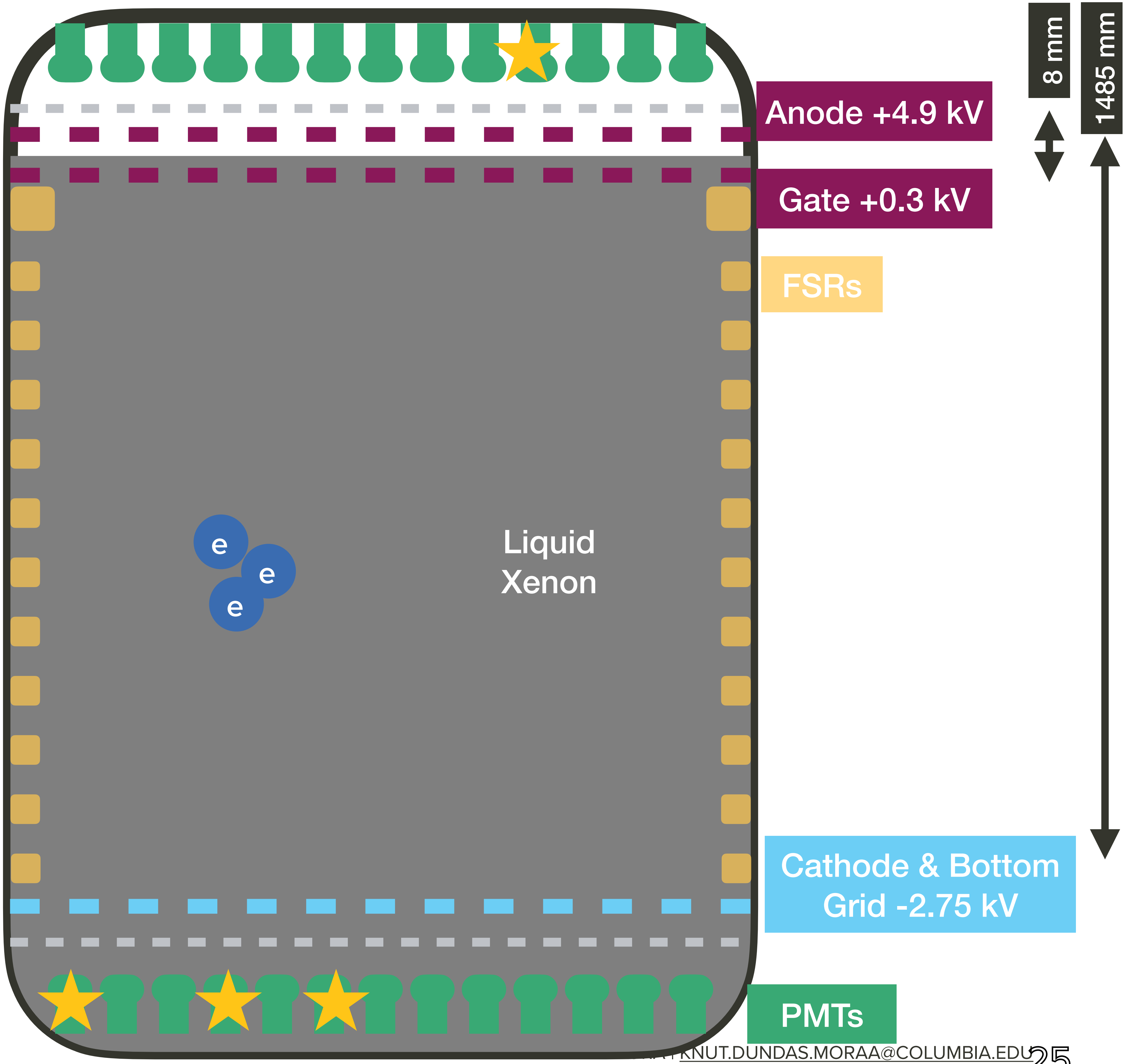
WORKING PRINCIPLE

- An Interaction deposits energy, scintillation light and charge is liberated



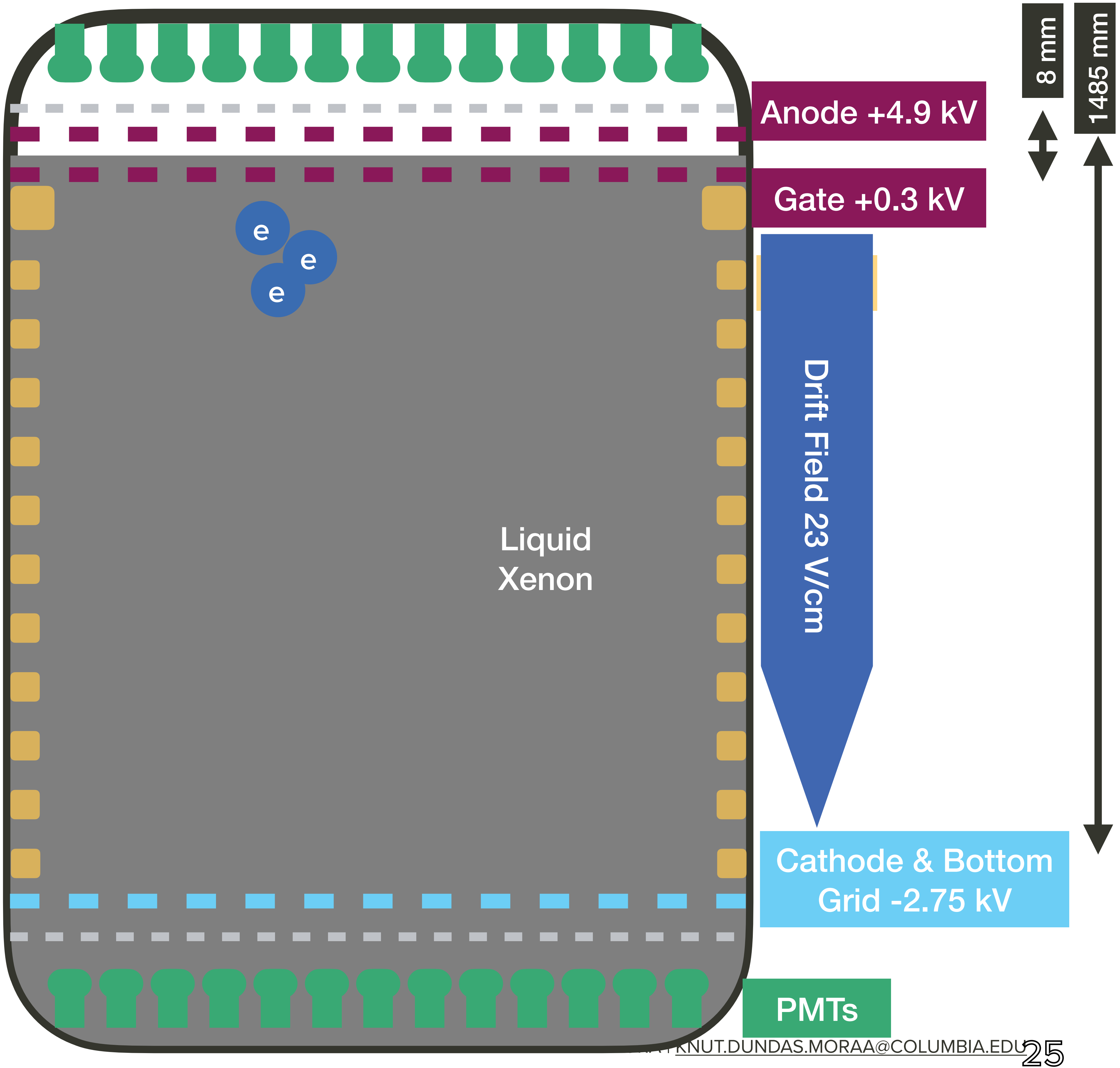
WORKING PRINCIPLE

- An Interaction deposits energy, scintillation light and charge is liberated
- S1 signal reaches photomultipliers



WORKING PRINCIPLE

- An Interaction deposits energy, scintillation light and charge is liberated
- S1 signal reaches photomultipliers
- Electrons drift to the surface



Anode +4.9 kV

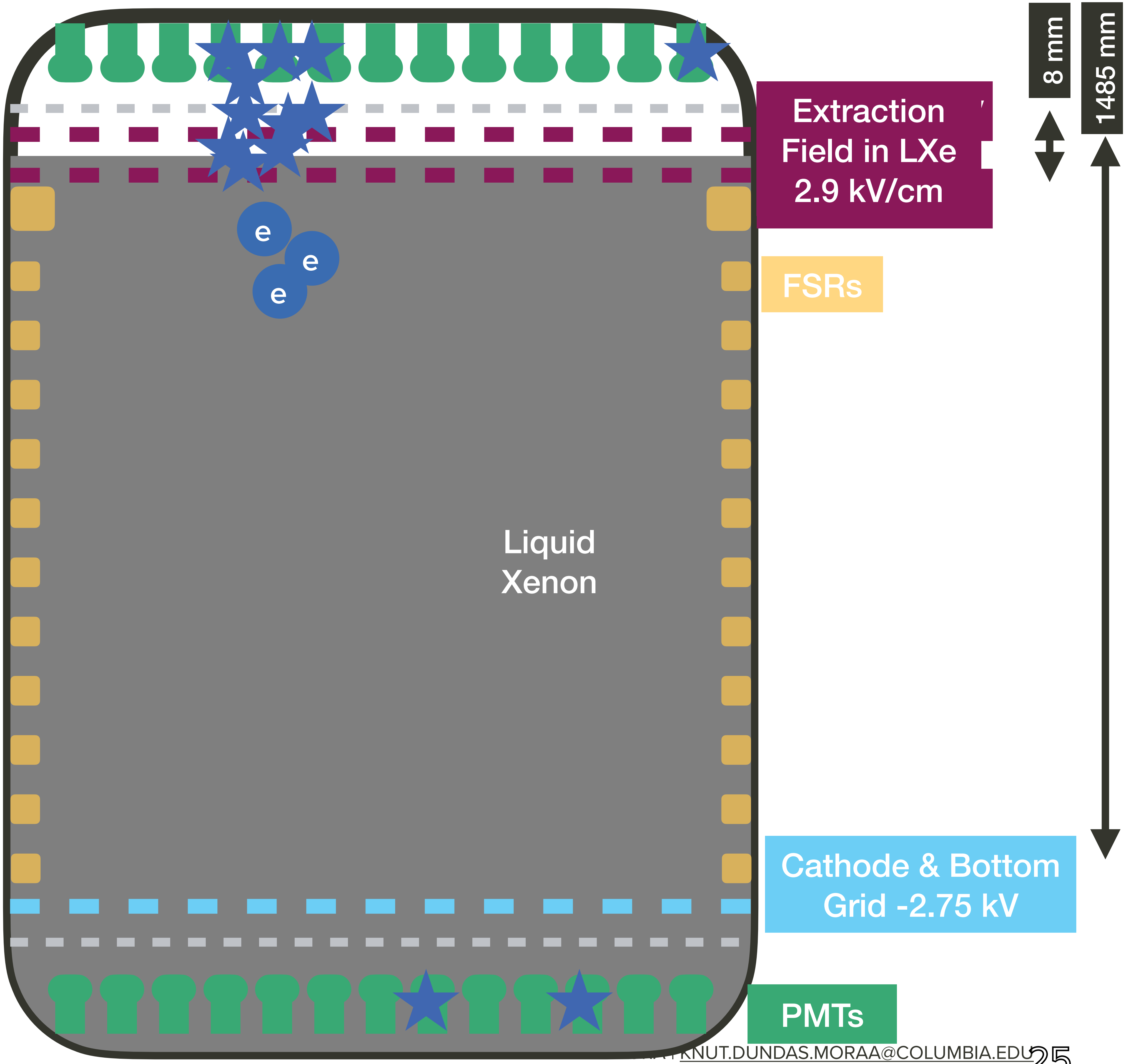
Gate +0.3 kV

Cathode & Bottom Grid -2.75 kV

PMTs

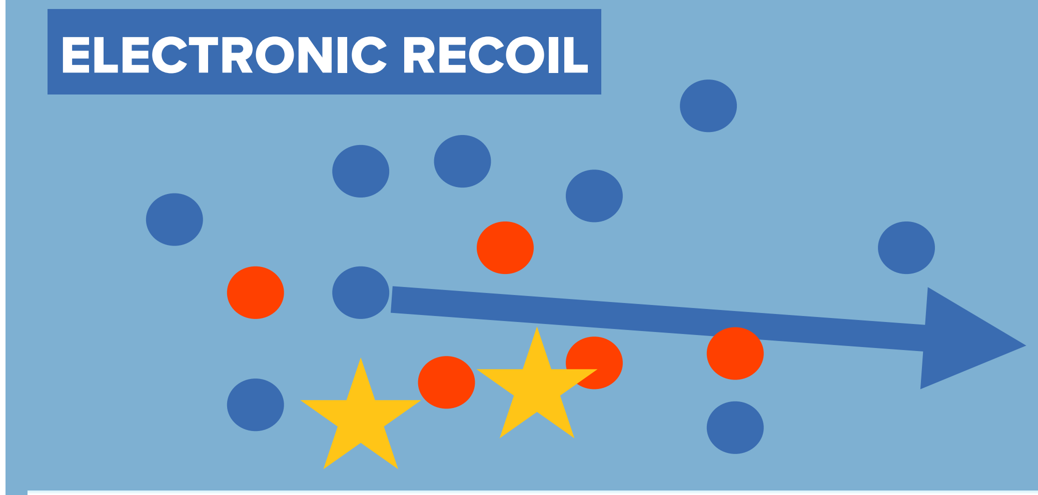
WORKING PRINCIPLE

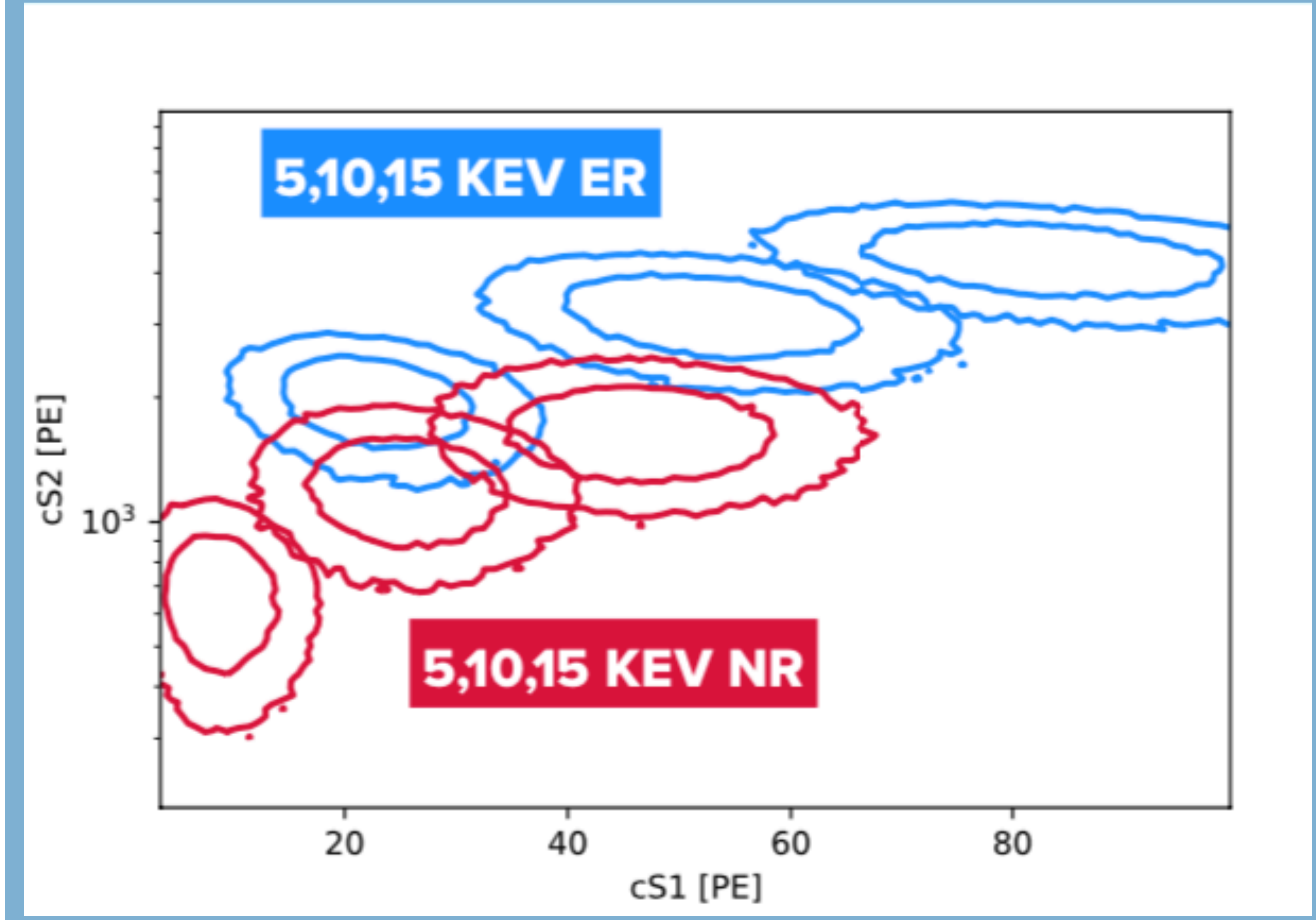
- **An Interaction deposits energy, scintillation light and charge is liberated**
- **S1 signal reaches photomultipliers**
- **Electrons drift to the surface**
- **The extraction field pulls the electrons to the gas phase where they make more scintillation light**



ELECTRONIC AND NUCLEAR RECOILS

- Energy deposited in liquid xenon results in:
- VuV scintillation light, released on ~10ns timescales: S1
- ionisation, which we measure after a drift period: an S2
- heat/atomic motion— not detected
- Nuclear recoils (NRs)
  - Energy (about 80%) is lost to heat
  - Higher light-to-charge ratio
- Recoils on electrons (ERs)
  - A recoiling electron deposits little or no energy as heat
  - A larger portion of the energy as ionization

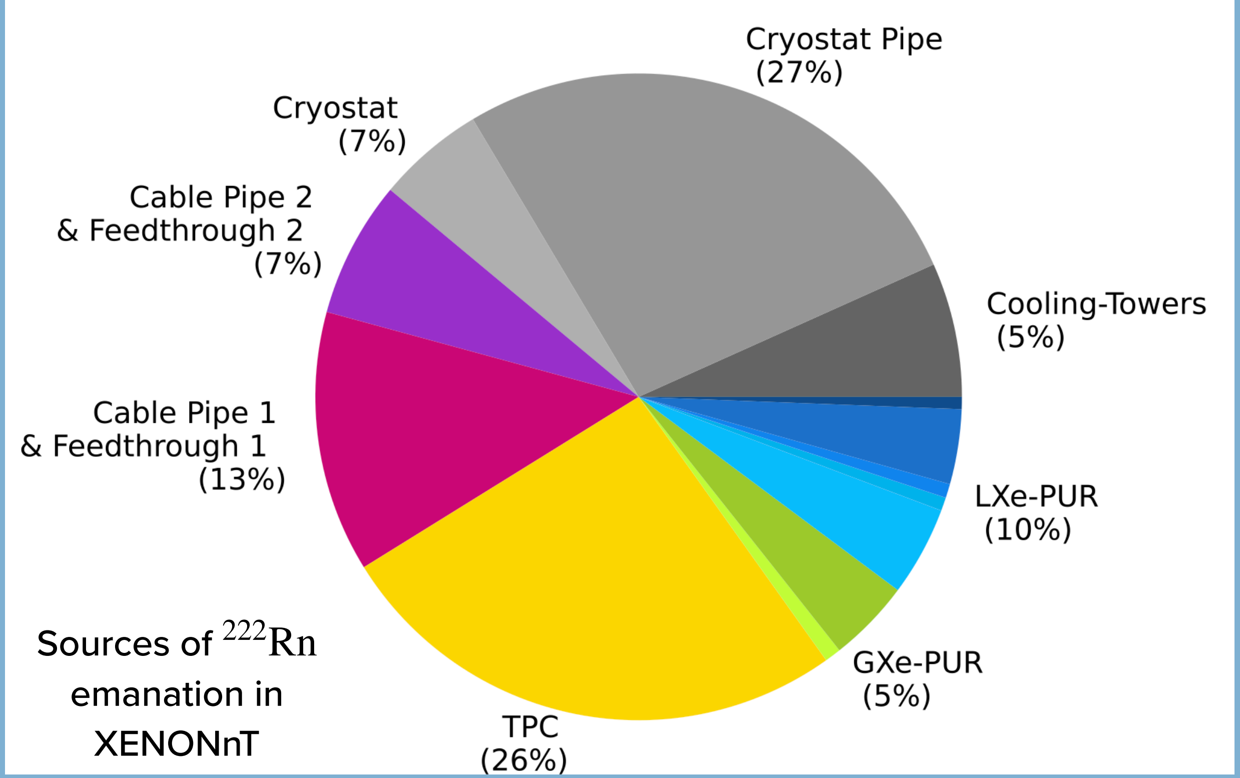




MATERIAL SCREENING, SELECTION

- **Every piece of the detector is assayed; e.g. LZ had a 6 year campaign**
- **^{226}Rn present in most materials (part of the ^{238}U chain) decays and produces ^{222}Rn as one of its daughter, which can emanate into the LXe**
  - **Etching, diamond shaving and cleaning steps used to reduce emanation**
- **Radioactive isotopes contribute both to ER background from surfaces, and to signal-like neutron signals**
  - **O(80) samples assayed at several detectors**
- **Detectors are assembled in cleanrooms, but the operations do introduce dust— LZ estimates (0.64 ± 0.05)g in their TPC**

E. Aprile et al. Material radiopurity control in the XENONnT experiment. Eur. Phys. J. C, 82(7):599, 2022. doi: 10.1140/epjc/s10052-022-10345-6.



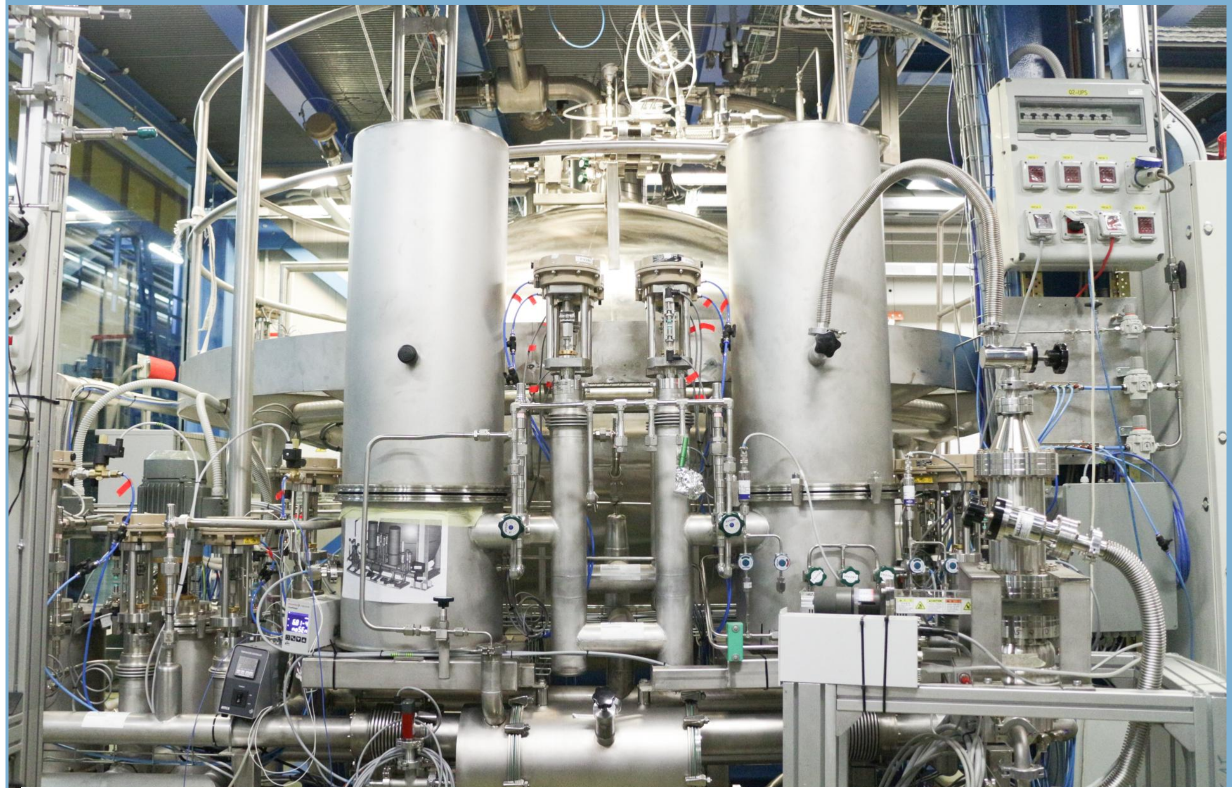
D. S. Akerib et al. The LUX-ZEPLIN (LZ) radioactivity and cleanliness control pro- grams. Eur. Phys. J. C, 80(11):1044, 2020. doi: 10.1140/epjc/s10052-020-8420-x.

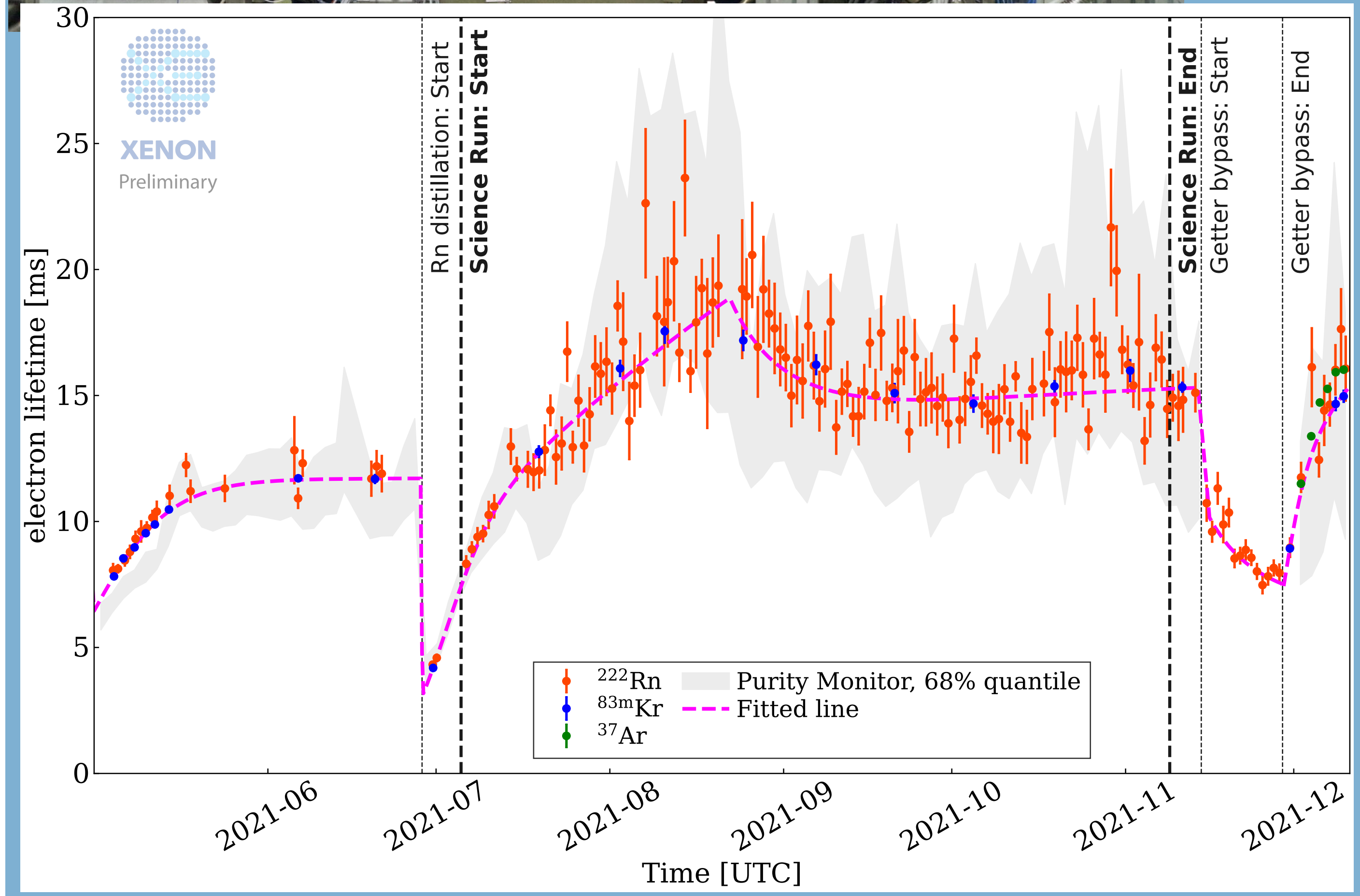
REMOVING ELECTRONEGATIVE IMPURITIES

- The 1.5 times longer drift length demands improvements in removing electronegative impurities that dampen the S2 signal
- XENONnT uses a new liquid purification technique with replaceable filter units with extremely low radon emanation (in the science run mode).
- High flow of 2 liters liquid xenon / minute— reach very high purity in less than a week — 18 h to exchange the entire volume

	Full TPC drift time	electron lifetime	electrons surviving a full drift length
XENON1T	0.67 ms	0.65 ms	30 %
XENONnT	2.2 ms	10+ ms	86 % @ 15 ms

G. Plante, E. Aprile, J. Howlett, and Y. Zhang. Liquid-phase purification for multi-tonne xenon detectors. Eur. Phys. J. C, 82(10):860, 2022. doi: 10.1140/ep jc/s10052-022-10832-w.

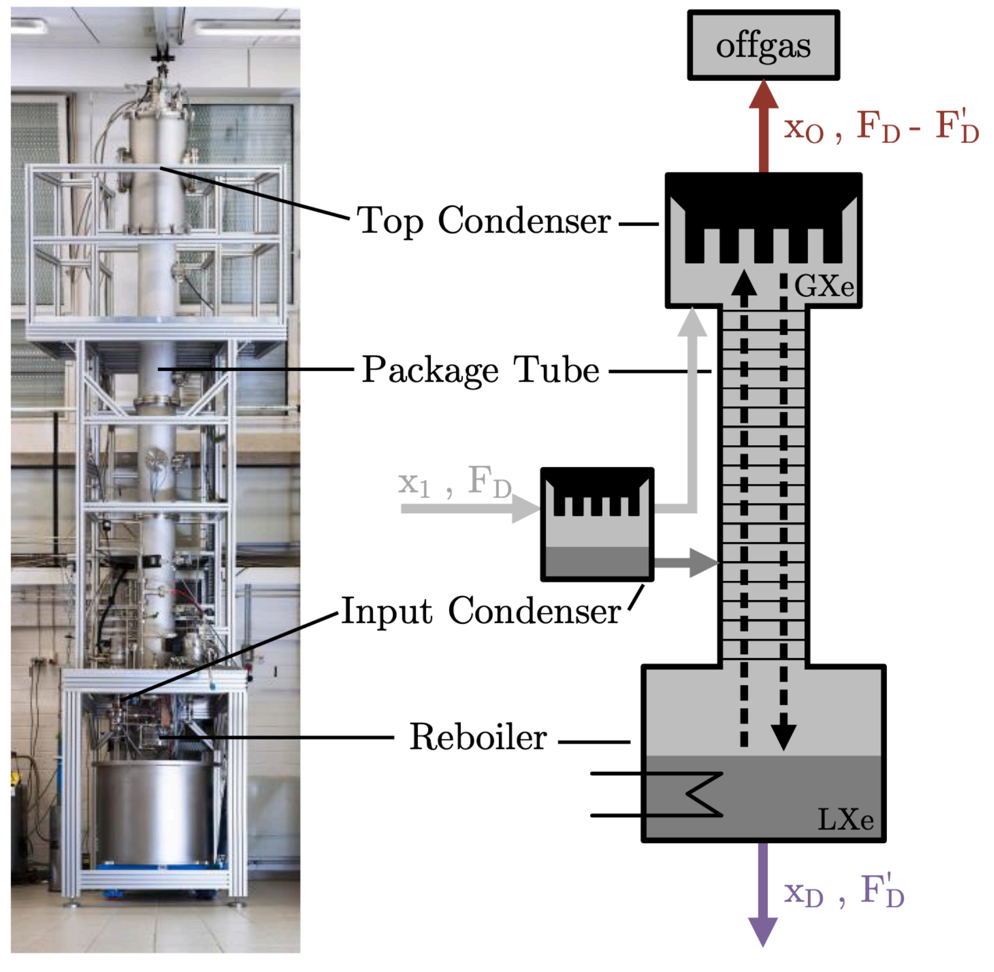


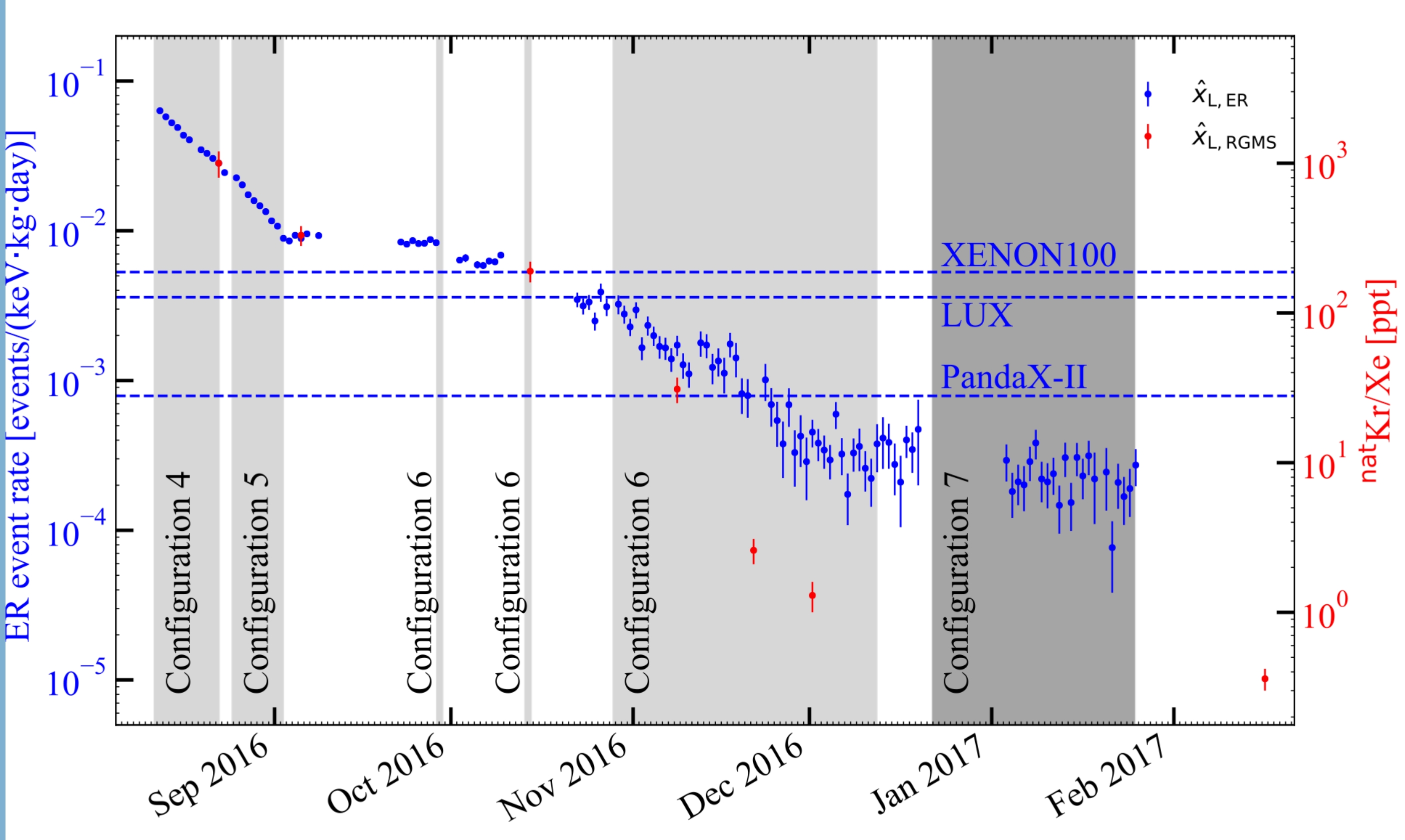


REMOVING KRYPTON

- ^{85}Kr from reactors and nuclear testing will be around $10^{-20}\frac{\text{mol }^{85}\text{Kr}}{\text{mol Xe}}$ in the best case.
  - Tonne-scale lXeTPCs require a further reduction of three orders of magnitude.
- The conventional method to remove this is offline reduction—take the xenon out of your detector and use distillation or gas chromatography
- XENON has demonstrated online cryogenic krypton distillation, where Kr and Ar are removed as the experiment is running
- If ^{37}Ar can be removed, it is a very useful calibration source with a 2.8 keV line. This experiment demonstrated a removal $\tau_{\text{removal}} = 1.7\text{d}$ vs the decay $\tau = 35\text{d}$

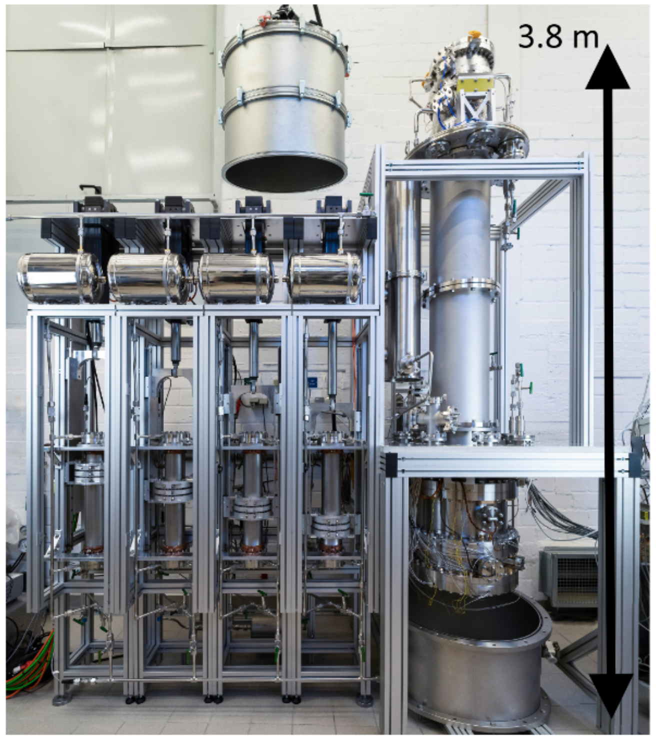
E. Aprile et al. Application and modeling of an online distillation method to reduce krypton and argon in XENON1T. PTEP, 2022(5):053H01, 2022. doi: 10.1093/ptep/ptac074.





REMOVING RADON

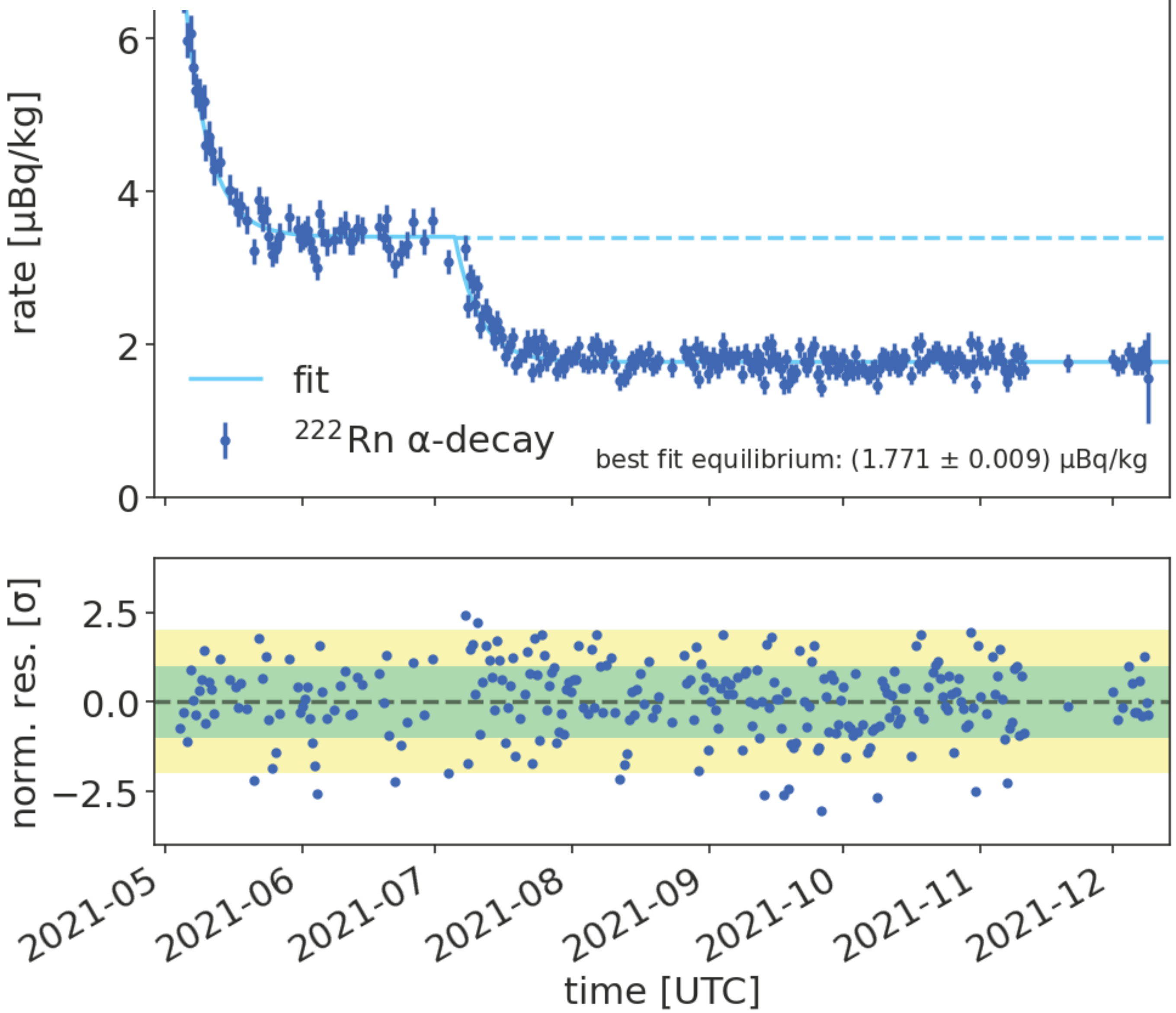
- $^{220}\mathrm{Rn}$ is the primary source of signal-like background events in XENONnT (as well as in PandaX and LZ although they had other contaminants during their first commissioning runs)
  - In the first XENONnT run: ~ 0.5 of the total background for low-energy ERs
- For XENONnT, a newly developed Rn column can handle large xenon flows using radon-free compressors and heat exchangers
- First science run used gas-only meeting, with $7\ \mathrm{kg/h}$ to enhance electron lifetime
  - further runs will use LXe mode with ten times the flow to achieve the goal concentration



M. Murra, D. Schulte, C. Huhmann, and C. Weinheimer. Design, construction and commissioning of a high-flow radon removal system for XENONnT. Eur. Phys. J. C, 82(12):1104, 2022. doi: 10.1140/epjc/s10052-022-11001-9.

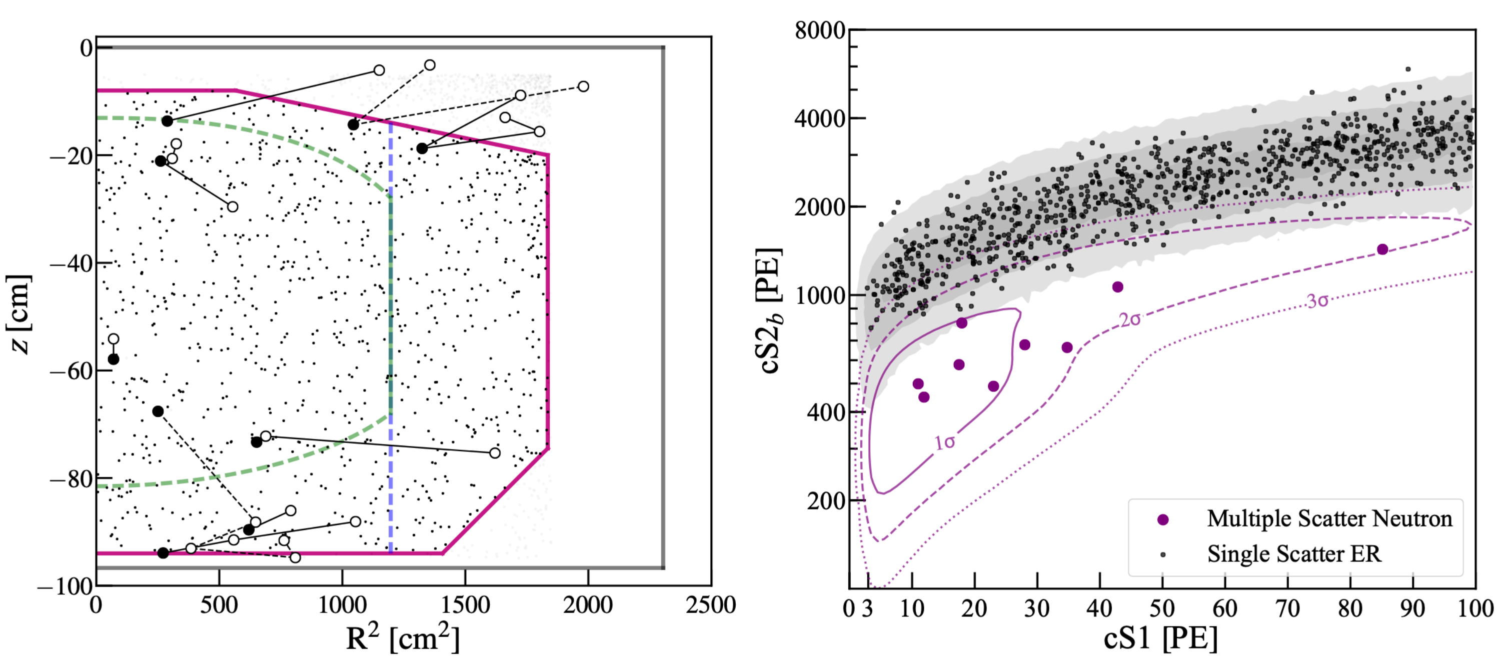
SR0: $1.77 \pm 0.01 \mu\mathrm{Bq/kg}$

SR1+: $< 1\ \mu\mathrm{Bq/kg}$

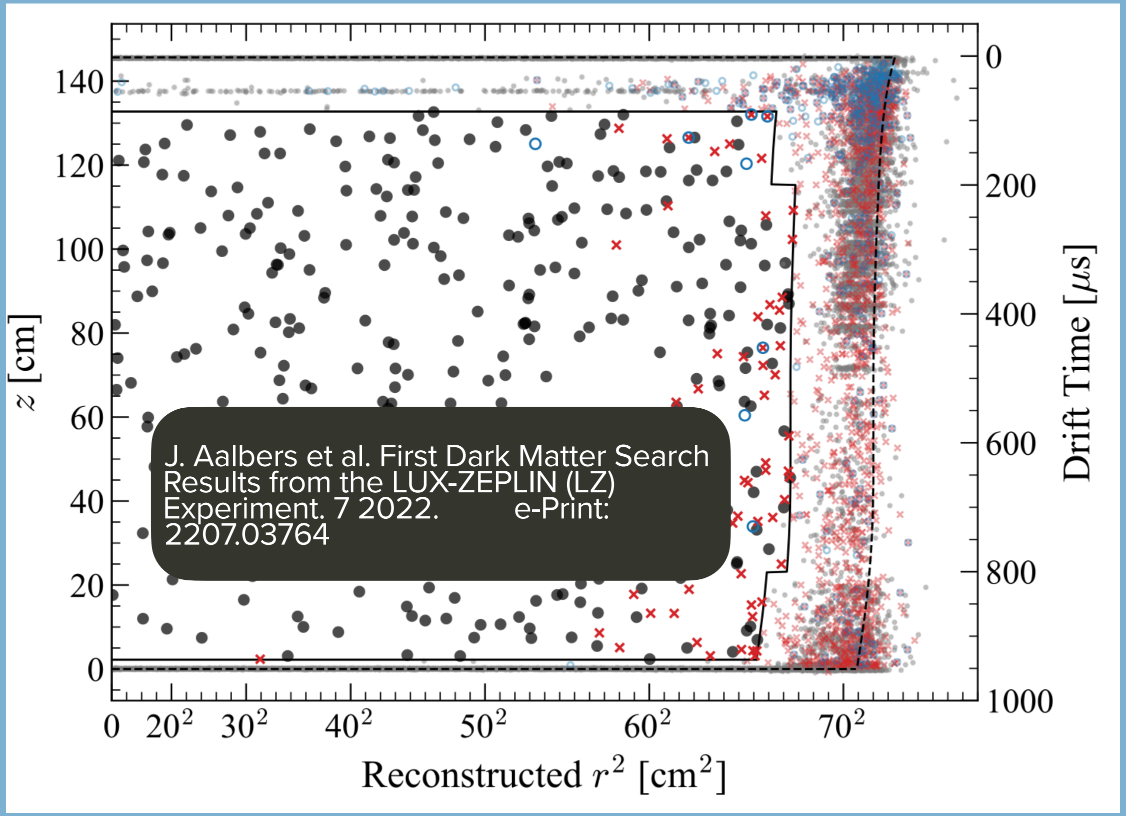


REJECTING NEUTRONS

- **Neutrons are distinguishable from WIMPs statistically via their spatial distribution, and directly either when they scatter multiple times or via neutron vetos:**
- **XENONnT uses a denser instrumented TPC array in its muon water tank, and plans to dope the water with Gd**
  - **Current tagging efficiency: 0.68, with Gd projected 0.87**
- **LZ surrounds the detector with blocks filled with 17 tonnes liquid scintillator + Gd (blue circles are vetoed events)**
  - **Tagging efficiency 0.88 in calibration**



E. Aprile et al. XENON1T dark matter data analysis: Signal and background models and statistical inference. Phys. Rev. D, 99(11):112009, 2019. doi: 10.1103/PhysRevD.99.112009.

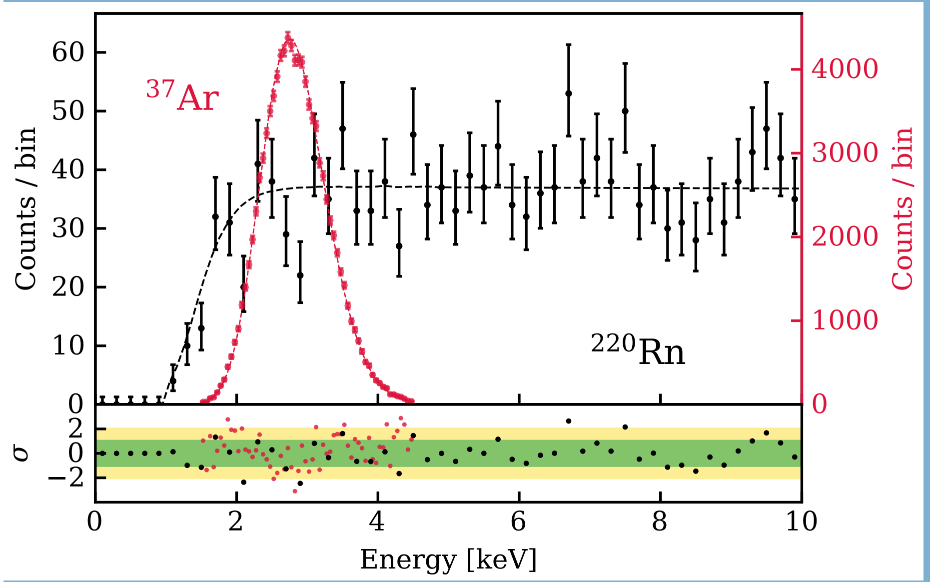


J. Aalbers et al. First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment. 7 2022. e-Print: 2207.03764

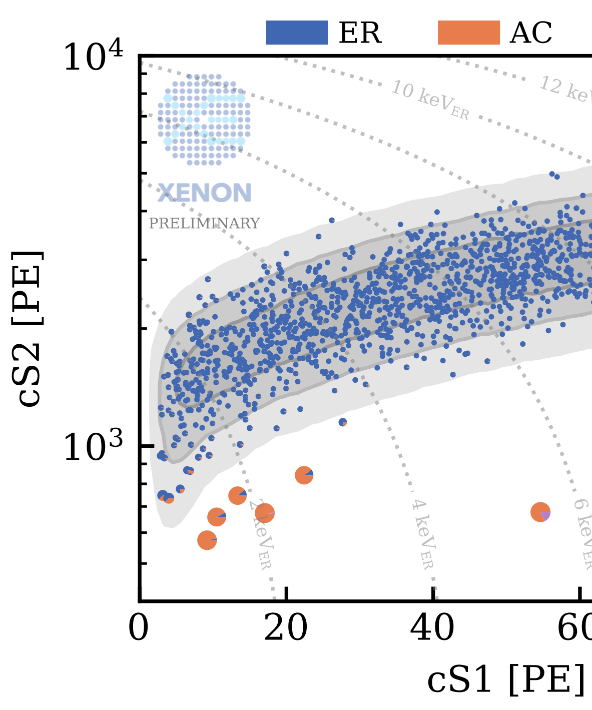
CALIBRATION

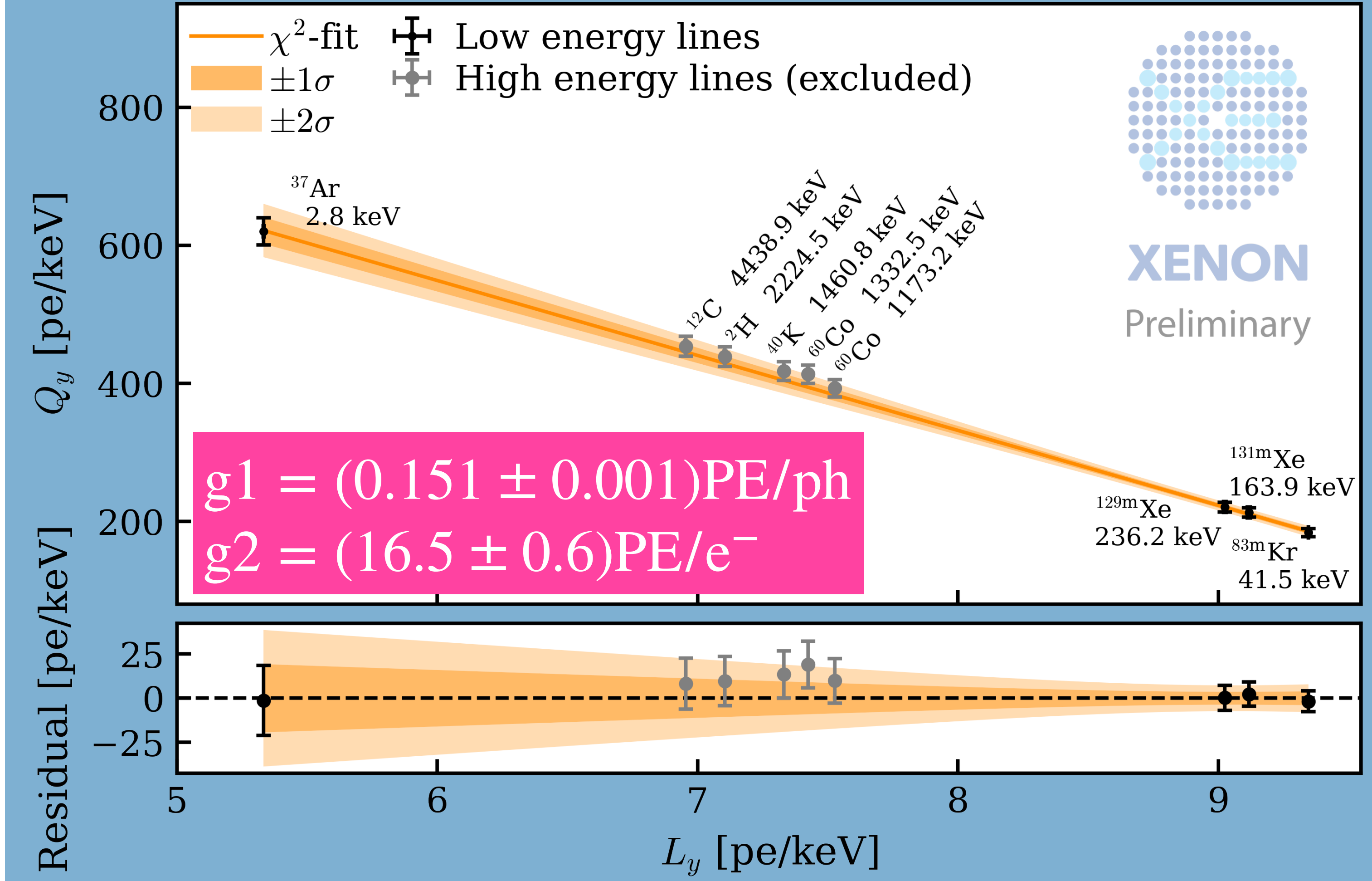
- **Spatial variations in the detector response is calibrated with ^{83m}Kr (^{37}Ar):**
    - **Varying gains, electron lifetime**
- **The detector energy scale is fit to mono-energetic decays: ^{37}Ar, ^{83m}Kr. ^{129m}Xe and ^{131m}Xe**
- **^{220}Rn yields an approximately flat β-spectrum at low energies**
- **AmBe or neutron generators are used to constrain the detector response to nuclear recoils,**
- **PandaX and LUX have used tritiated methane as an additional ER calibration source, but this is long-lived, and removing it not always trouble-free**

Rn and Ar calibration in reconstructed energy



^{220}Rn calibration in cS1, cS2

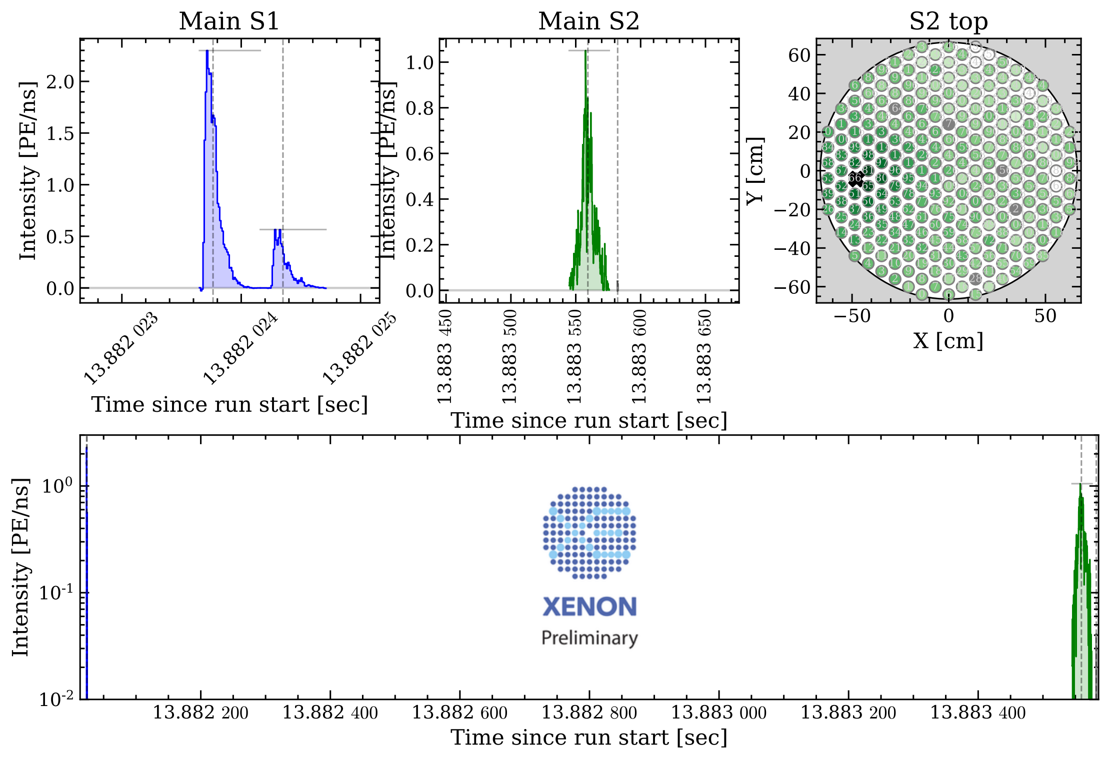


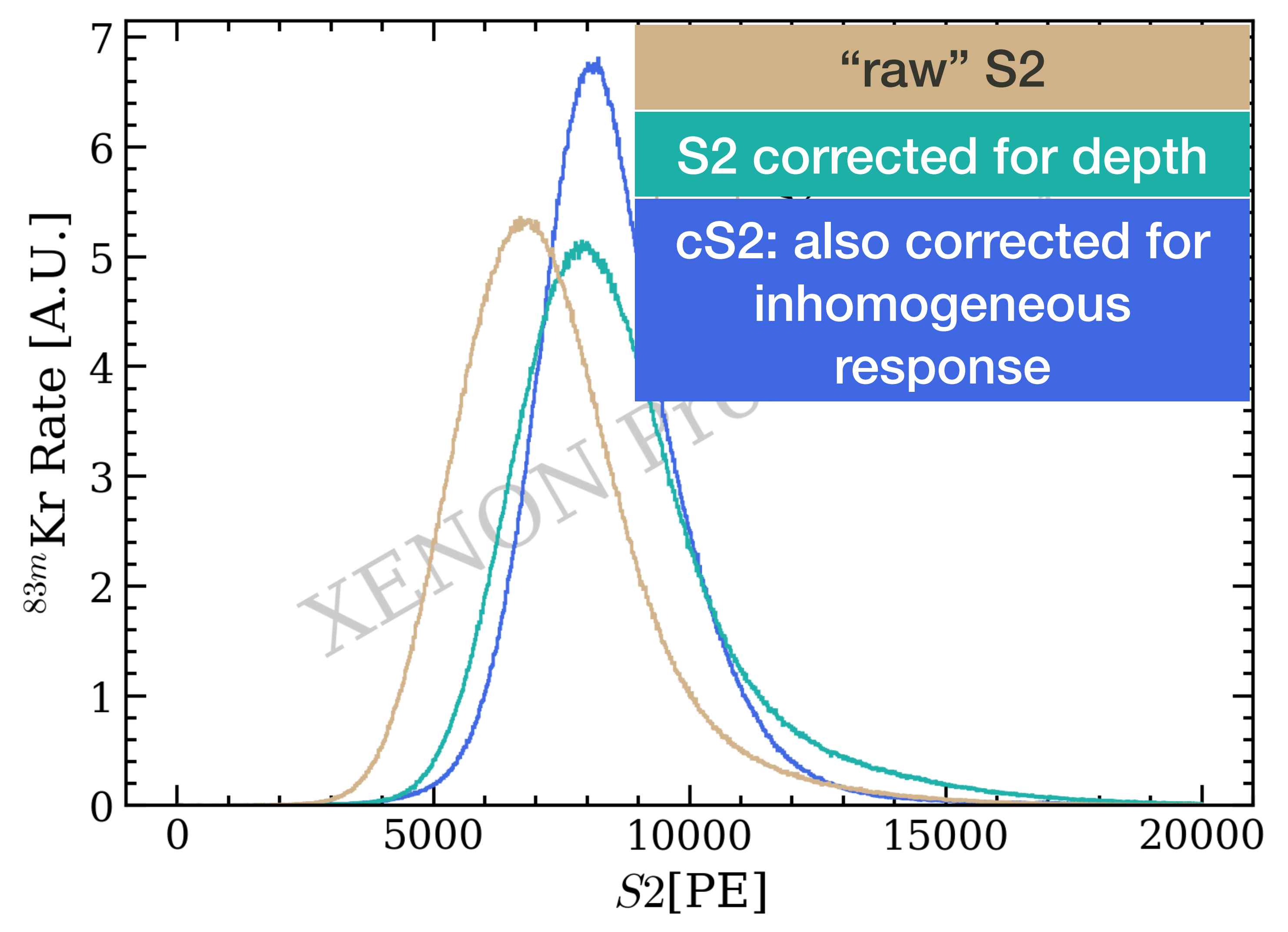


$g1 = (0.151 \pm 0.001)$PE/ph
$g2 = (16.5 \pm 0.6)$PE/e$^-$

TYPICAL ANALYSIS

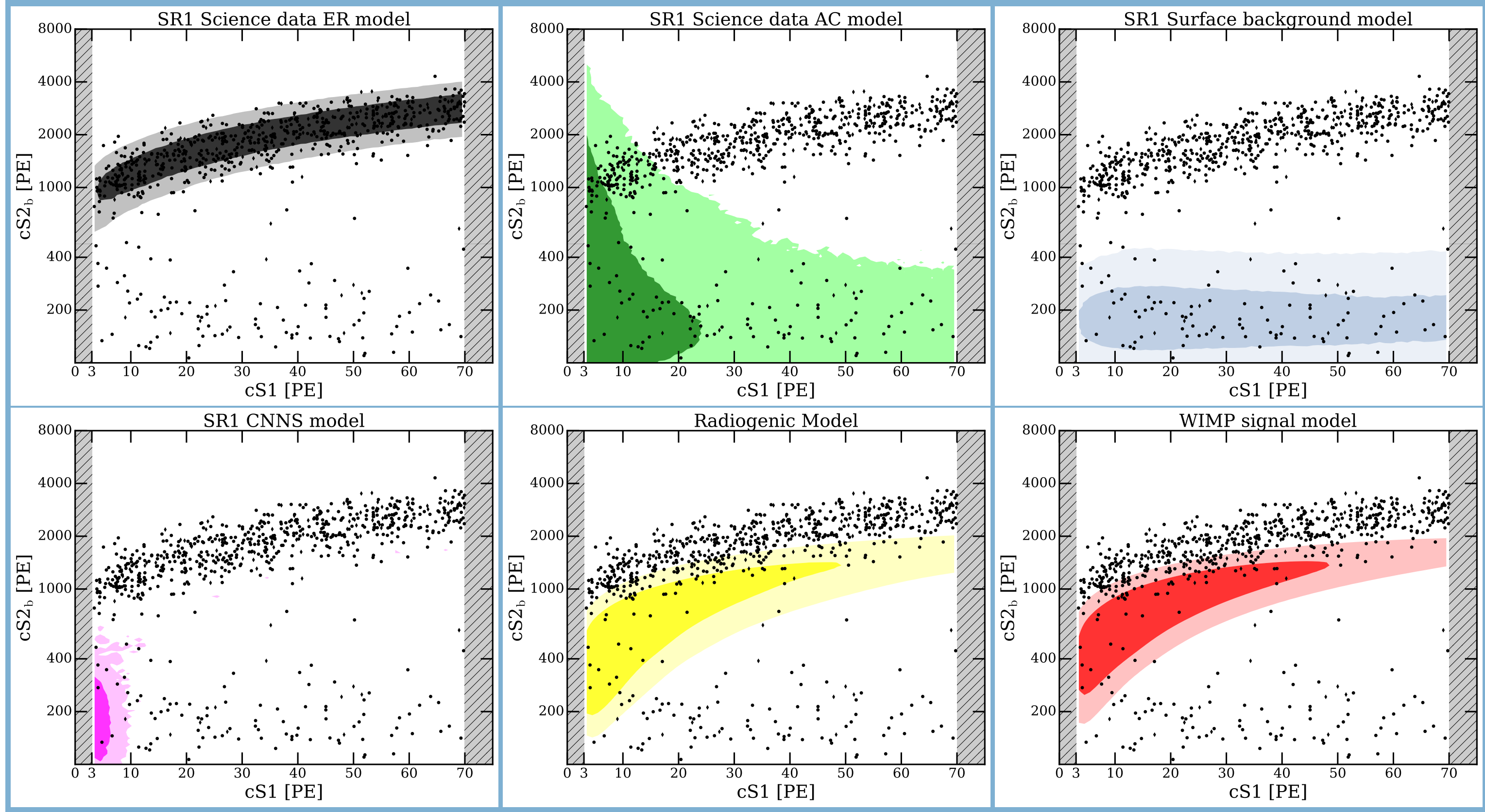
- **The data is recorded as "waveforms"— signals over time for each PMT (494 in XENONnT)**
    - **Some experiments use triggered readout, XENONnT uses an arbitrary-threshold per-channel readout**
- **Main job of analysis: go from this signal to well-reconstructed events**
    - **Peak clustering, peak classification and reconstruction steps to get to Events**
    - **Validated with (matched) simulations and calibration data**
    - **The final detector variables are corrected for detector losses and distortions: electron losses with depth, varying S2 gain across the surface, varying S1 gain with position and distortions due to the drift field**

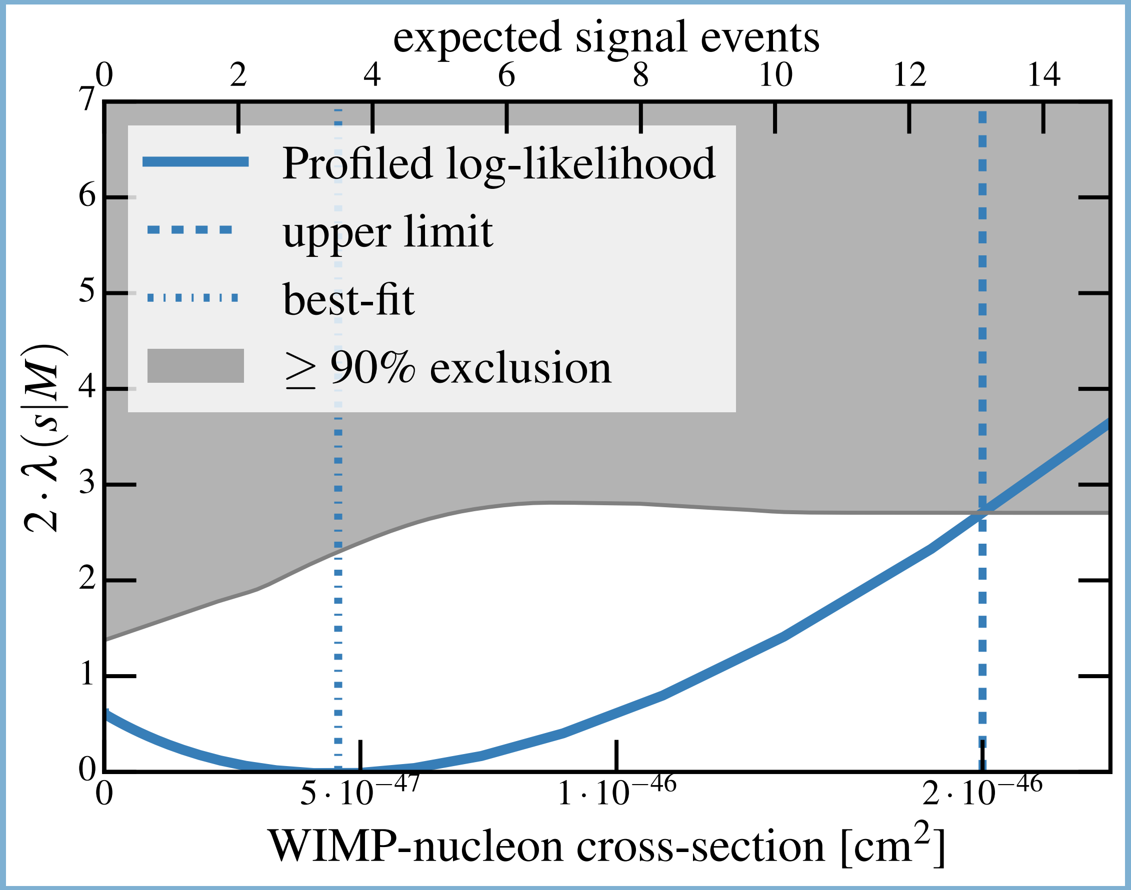




TYPICAL ANALYSIS

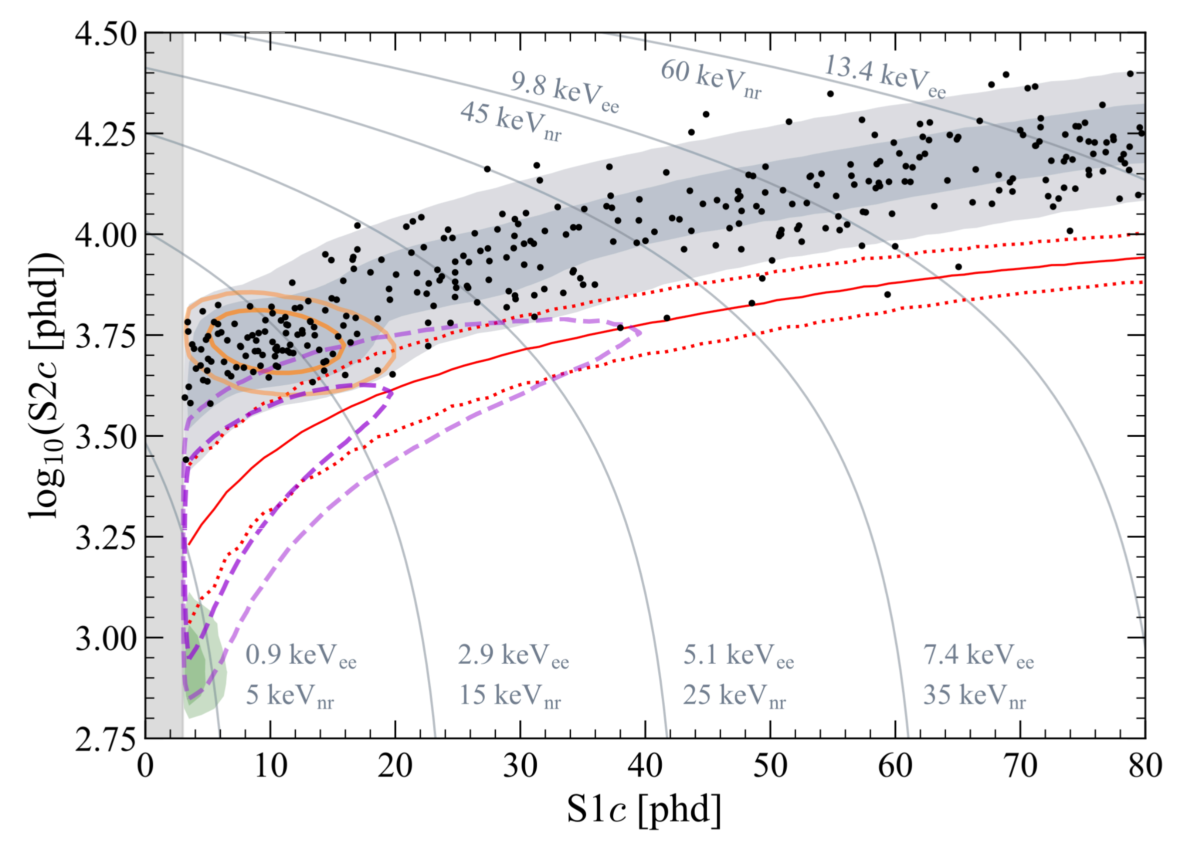
- Typical analysis space: cS1, cS2 and spatial variables (e.g. cS1, cS2 and R for XENON1T)
- Models for signal and background from:
    - data-driven fits or synthetic data
    - simulation and calibration fits for NR response
    - Detector response fit to ER calibration data including nuisance parameters — difficult to be confident in the signal-like tail.
- Produce frequentist unified intervals and discovery significance using profile log likelihood ratio + toyMC-calibrated Neyman thresholds

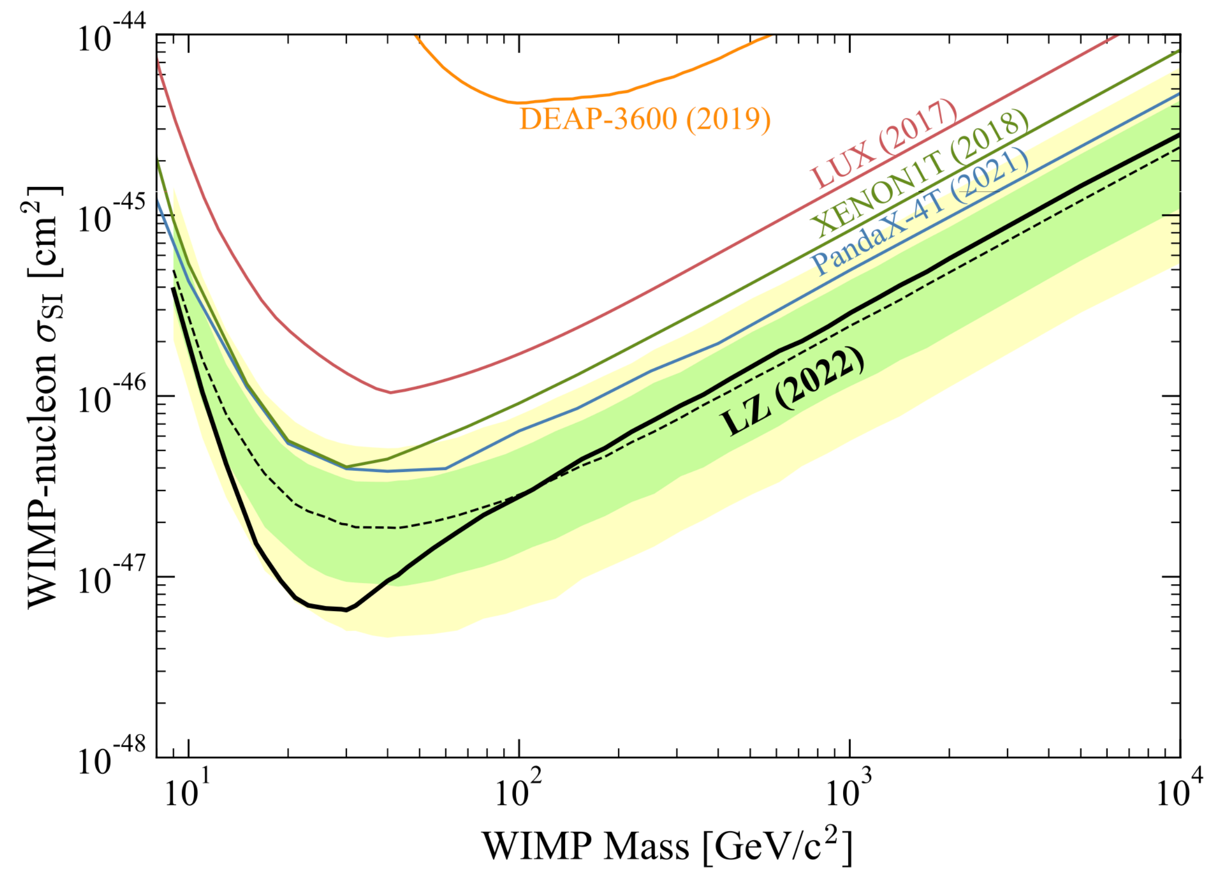




CURRENT LIMITS

- Currently, the best limits are set by LZ
  - Commissioning run, with a significant $^{37}\mathrm{Ar}$ contamination, and no blinding attempted
  - $\sim 5.5\ \mathrm{keV}$ threshold
  - $0.9\ \mathrm{tonne-year}$ exposure
  - Downwards fluctuation at low mass hits the “power-constraint” (experiments resolved to not report limits where there was not at least a minimal discovery power





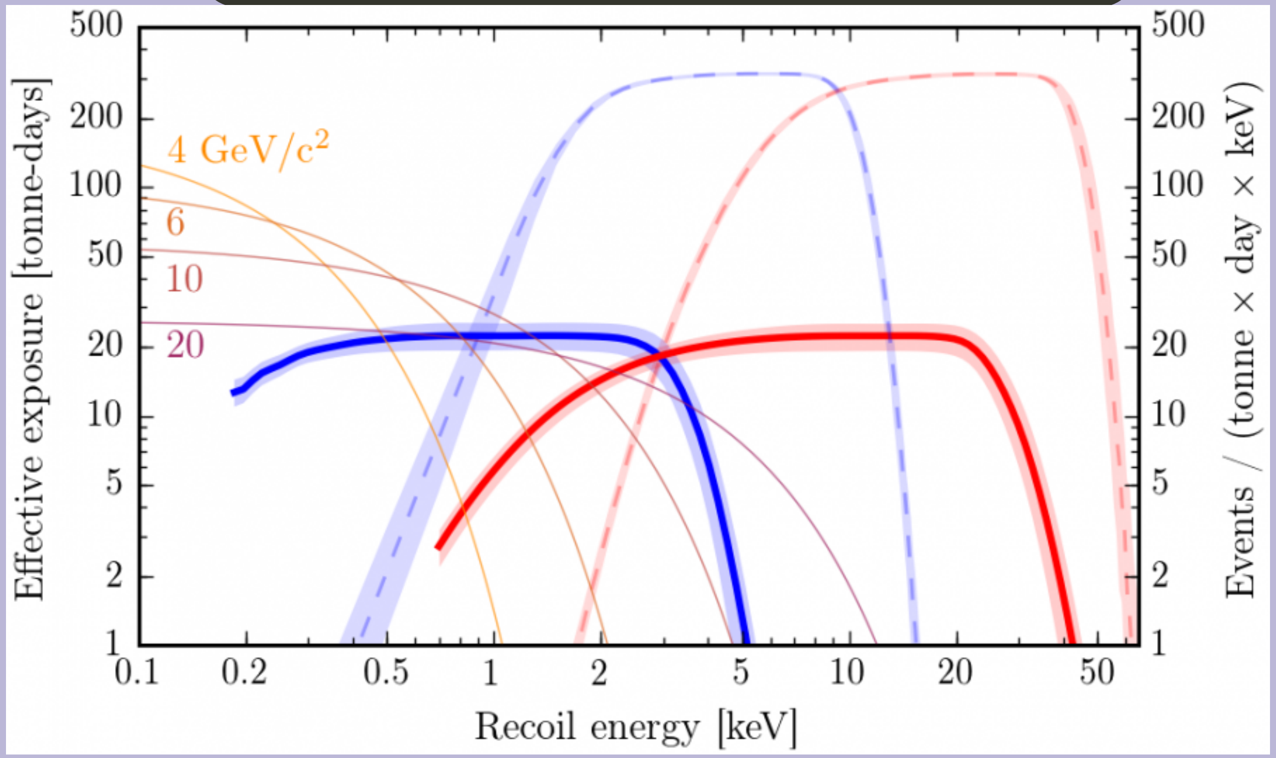
J. Aalbers et al. First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment. 7 2022. e-Print: 2207.03764

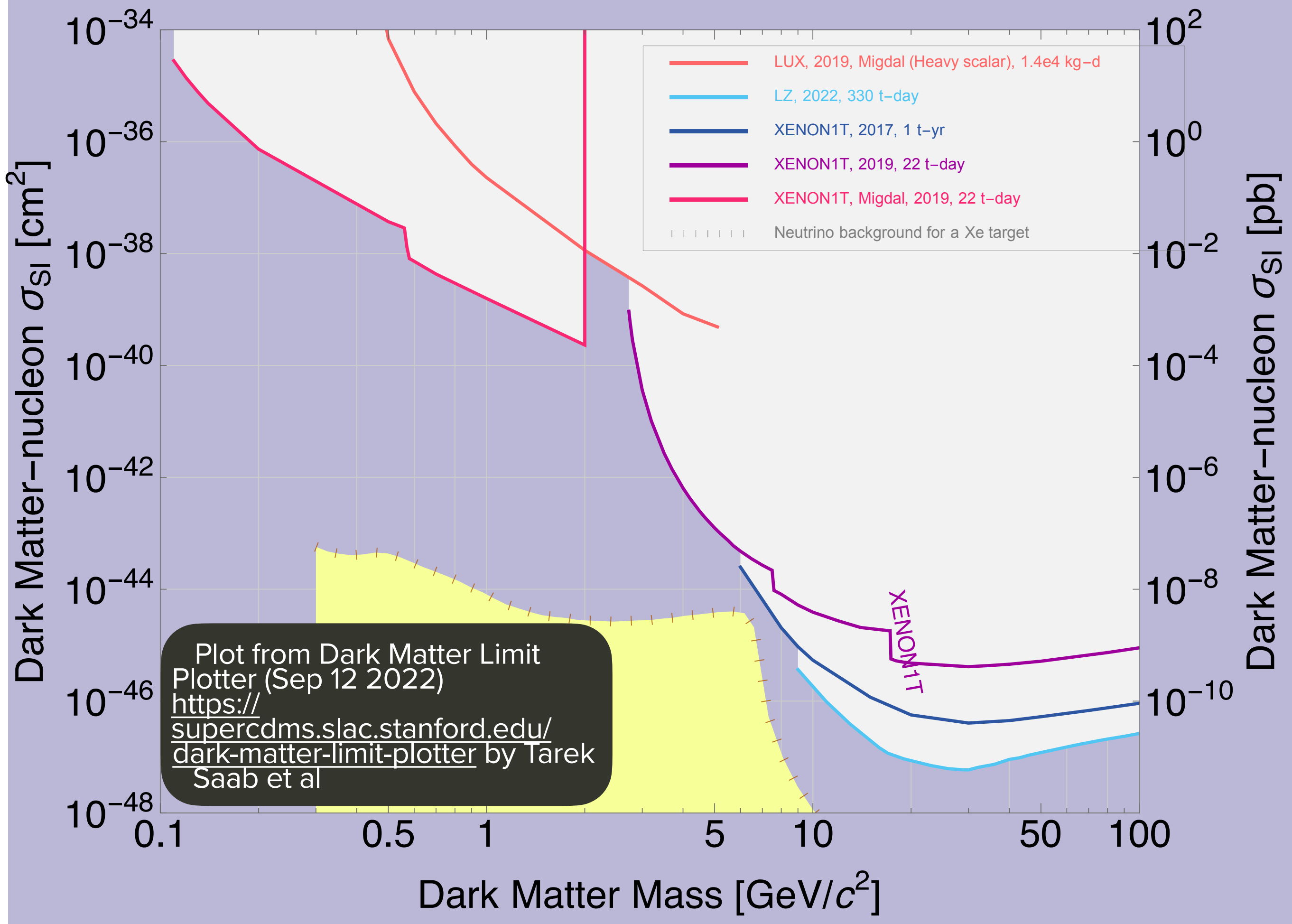
S2ONLY

- **The low-energy threshold of lXe TPCs is driven by the requirement to see 2-3 photons in the S1 signal**
- **Alternative analyses, for example with XENON1T have relaxed this requirement**
  - **Upside: much lower energy thresholds—** $0.2\ \mathrm{keV}$**(ERs) and** $\sim 1\ \mathrm{keV}$**(NRs)**
  - **Drawbacks: worse or incomplete event reconstruction, and new + unknown backgrounds**
- **Gives limits down to** $\sim 0.1 \mathrm{GeV}/c^2$ **if the Migdial effect — the small probability for WIMP nuclear recoils to also deposit energy**

E. Aprile et al. Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T. Phys. Rev. Lett., 123(24):241803, 2019. doi: 10.1103/Phys-

E. Aprile et. al (XENON). Light Dark Matter Search with Ionization Signals in XENON1T. Phys. Rev. Lett., 123(25):251801, 2019. doi: 10.1103/PhysRevLett.123.251801.

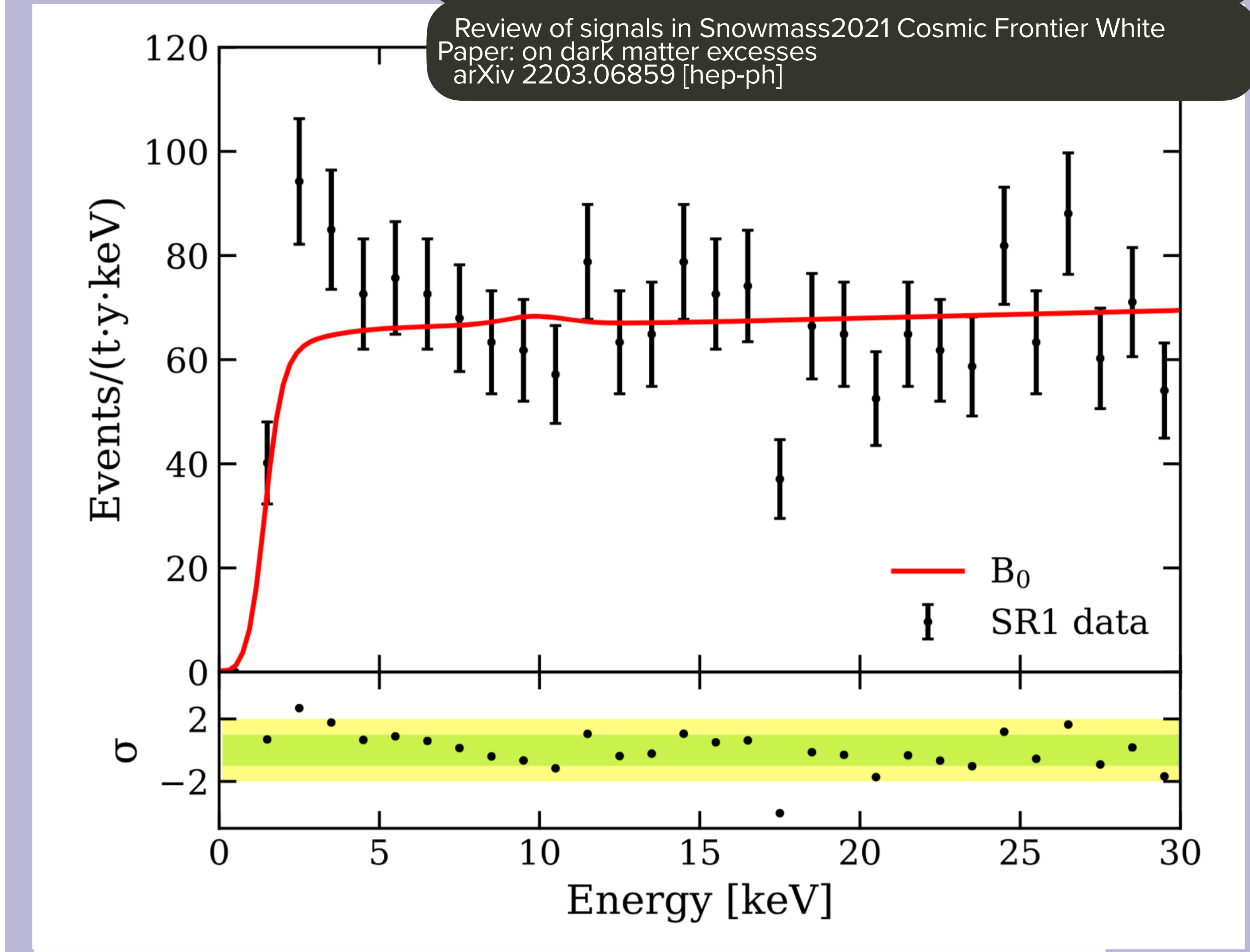




Plot from Dark Matter Limit Plotter (Sep 12 2022) https://supercdms.slac.stanford.edu/dark-matter-limit-plotter by Tarek Saab et al

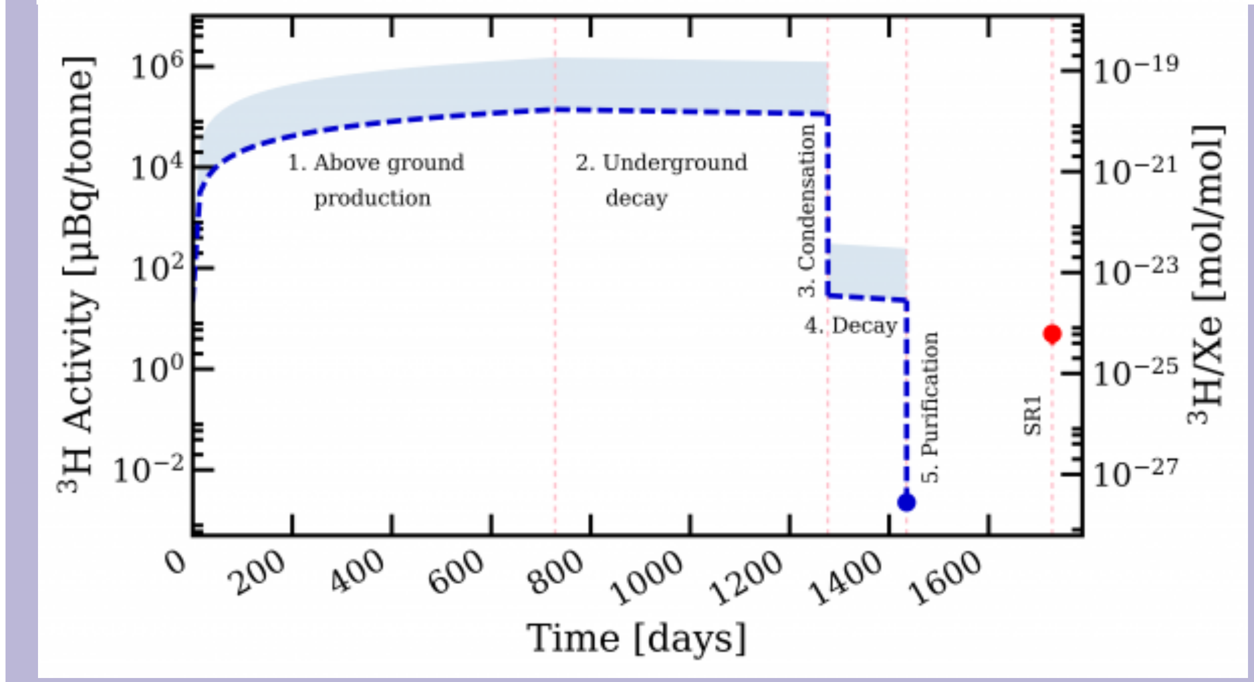
SEARCHES FOR ER SIGNATURES

- **XENON1T observed a peak in its ER spectrum below $\sim 7\ \mathrm{keV}$**
- **Excess fit to $2.3\ \mathrm{keV}$ peak, .**
- **$^{37}\mathrm{Ar}$ would be removed by the online Kr distillation. The necessary air leak to explain the excess is > 13 l/y, upper limit is 0.9 l/year**
- **$^{3}\mathrm{H}$ is possible— not as water but as tritiated hydrogen. Required rate much greater than expected from purification.**
- **A range of new physics could be compatible with the peak: solar axions, dark photons, a neutrino magnetic moment and many more**



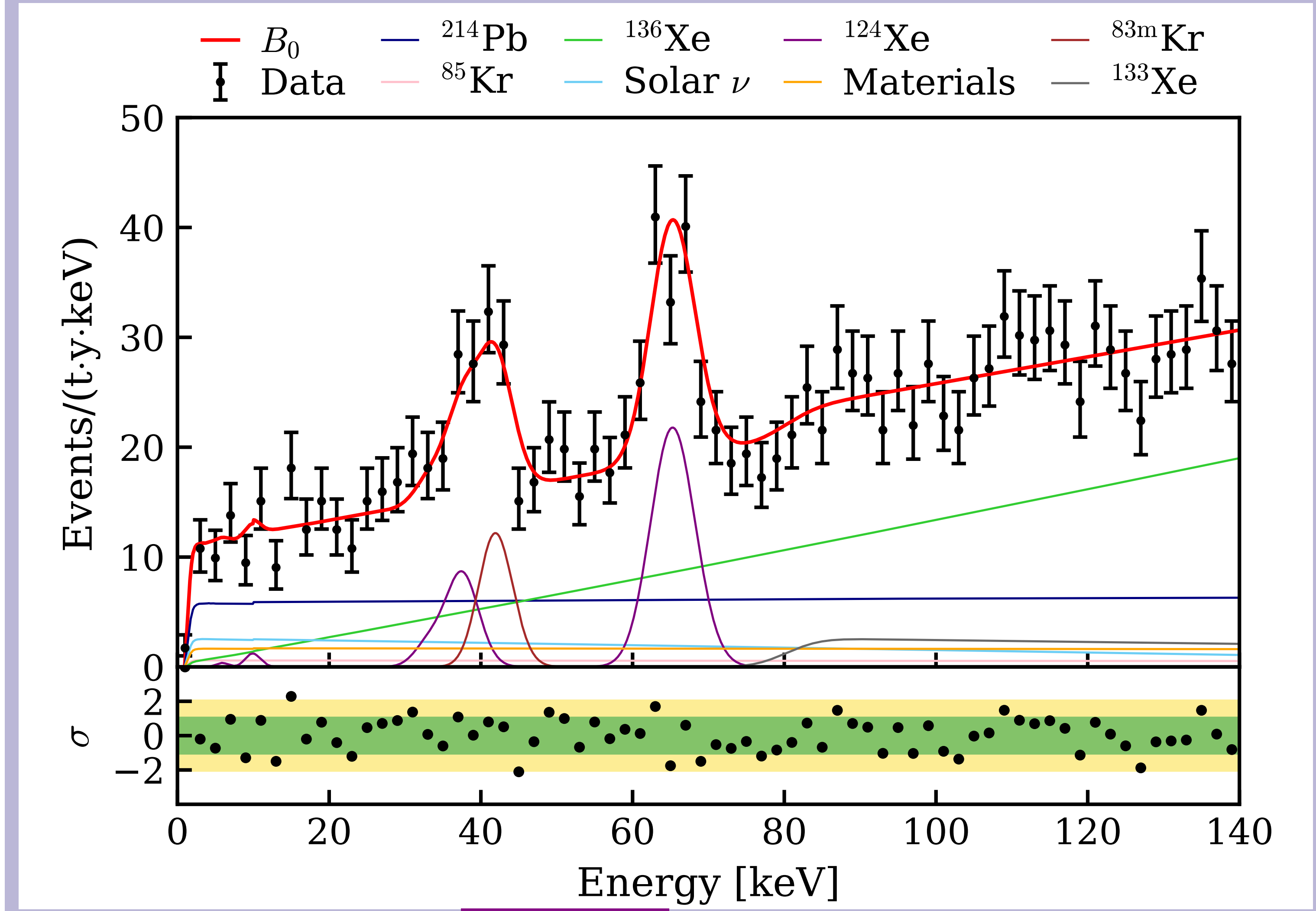
Excess electronic recoil events in XENON1T
Phys.Rev.D 102 (2020) 7, 072004

Review of signals in Snowmass2021 Cosmic Frontier White Paper: on dark matter excesses
arXiv 2203.06859 [hep-ph]



SEARCHES FOR ER SIGNATURES

- **XENONnT performed a blind analysis of a $1 \text{ tonne} - \text{year}$ exposure to test this excess**
- **Significant effort was made to reduce the possible sources of the excess, in particular hydrogen**
- **At low energies, the intrinsic background is dominated by βs from ^{214}Pb decays, itself a daughter of ^{222}Rn, with a level of $1.77 \pm 0.01 \mu\text{Bq/kg}$**
- **XENON1T first observed the double-electron capture signature from — longest half-life directly detected, in XENONnT it is evident by eye, and was used to validate the energy reconstruction.**



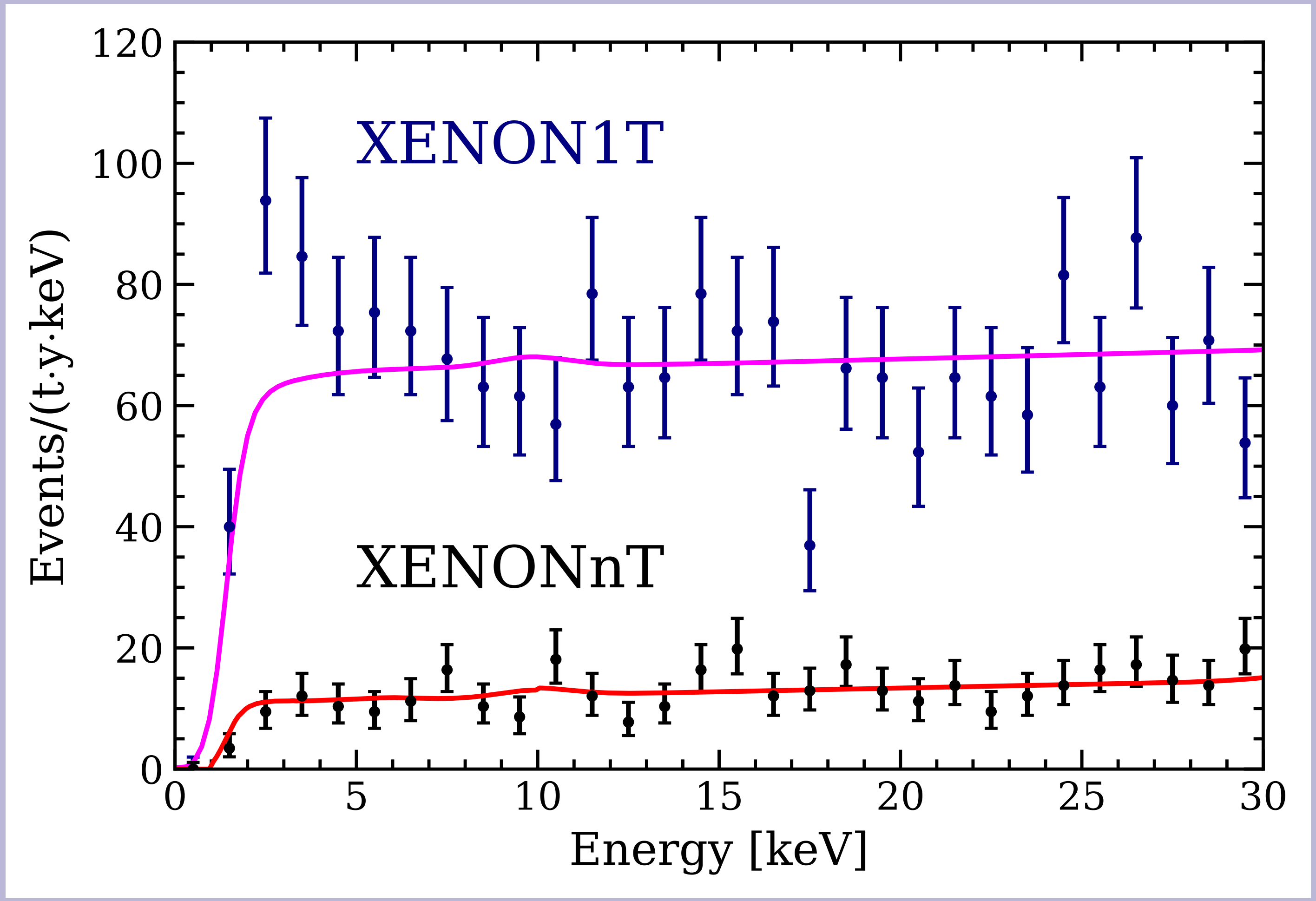
^{124}Xe
2νECEC

^{136}Xe
$2\nu\beta\beta$

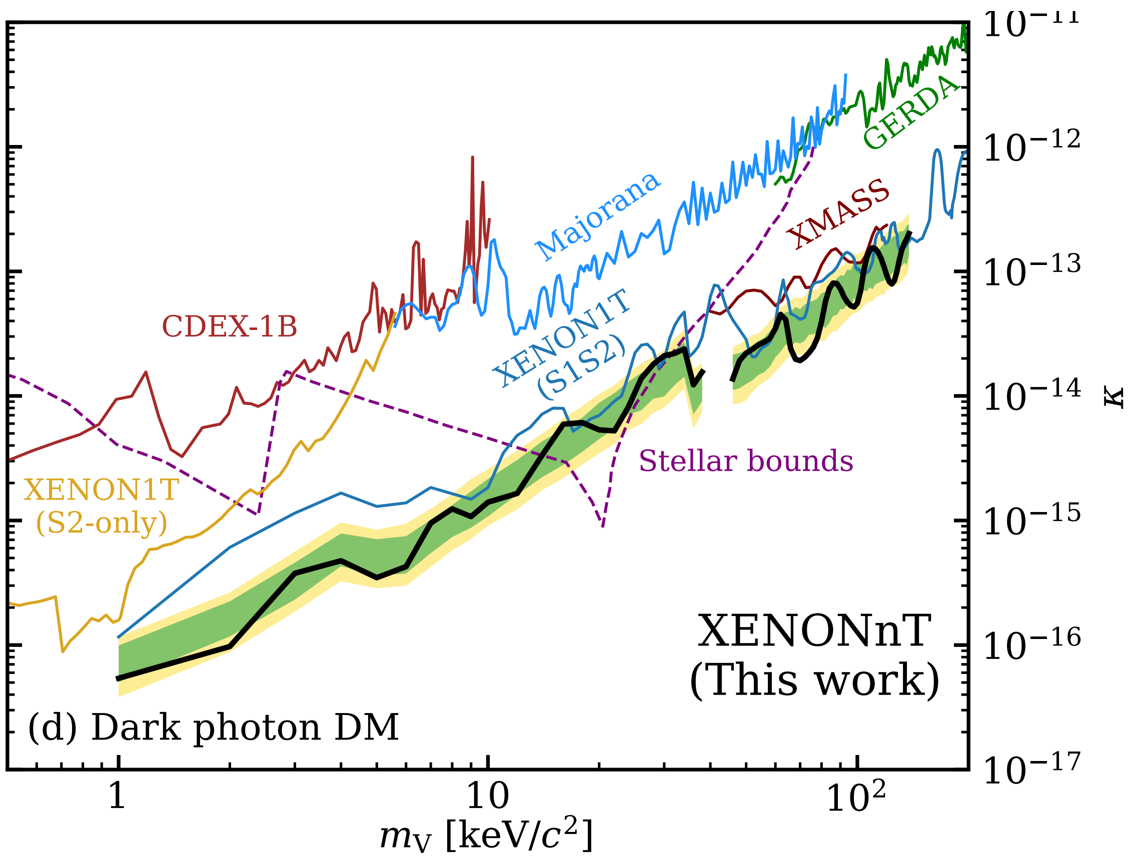
E. Aprile et al. Search for New Physics in Electronic Recoil Data from XENONnT. Phys. Rev. Lett., 129(16):161805, 2022. doi: 10.1103/PhysRevLett.129.161805.

SEARCHES FOR ER SIGNATURES

- **With a higher exposure and sixfold reduction in background, XENONnT observes no excess, and places stringent constraints on ALPs and dark photons**



Exposure: 1.16 tonne – years	$\sim \times 2$ XENON1T ER search (0.65 tonne-years)
Background rate: (16.1 ± 0.3) events/(t × yr × keV)	$\sim \times 0.2$ XENON1T
Best-fit signal strength: 0	XENONnT rejects a XENON1T-size peak at 8.6σ
Exclusion of XENON1T excess (2.3 keV) peak.	Measurements incompatible at ~4σ

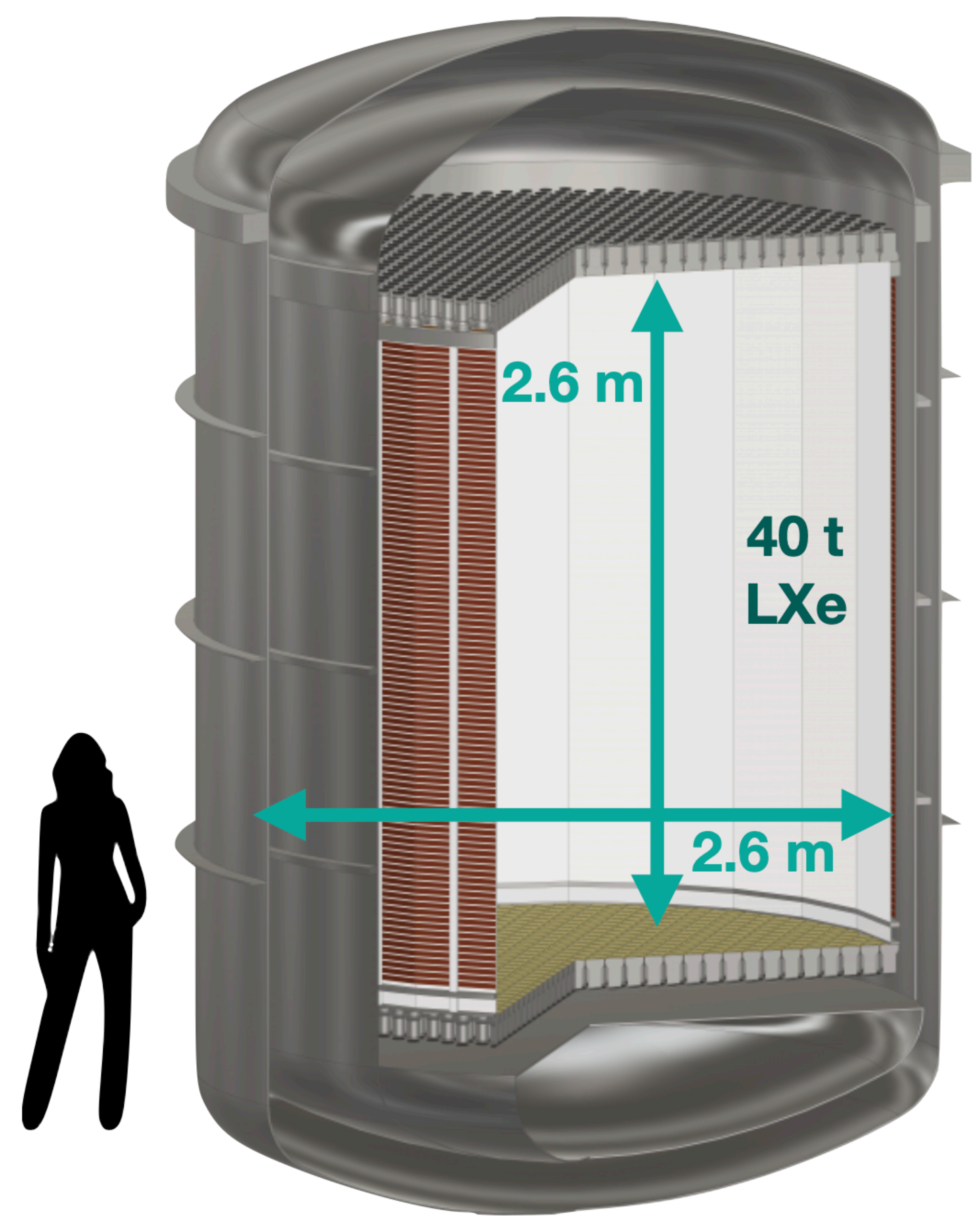


E. Aprile et al. Search for New Physics in Electronic Recoil Data from XENONnT. Phys. Rev. Lett., 129(16):161805, 2022. doi: 10.1103/PhysRevLett.129.161805.

UPCOMING EXPERIMENTS

DARWIN/XLZD

- After XENONnT and LZ finish their exposures in ~ 4 y the unimaginative next step is bigger
- Darwin envisions a ~ 50t detector
  - 2.6m length and diameter
  - Would need 1800 XENON-style PMTs
  - Will use all the innovations in previous generations: active vetos, continuous purification
- Size comes with sizeable challenges:
  - Cryogenic handling of extreme amounts of LXe
  - Field shaping and electrode stability
  - xenon procurement

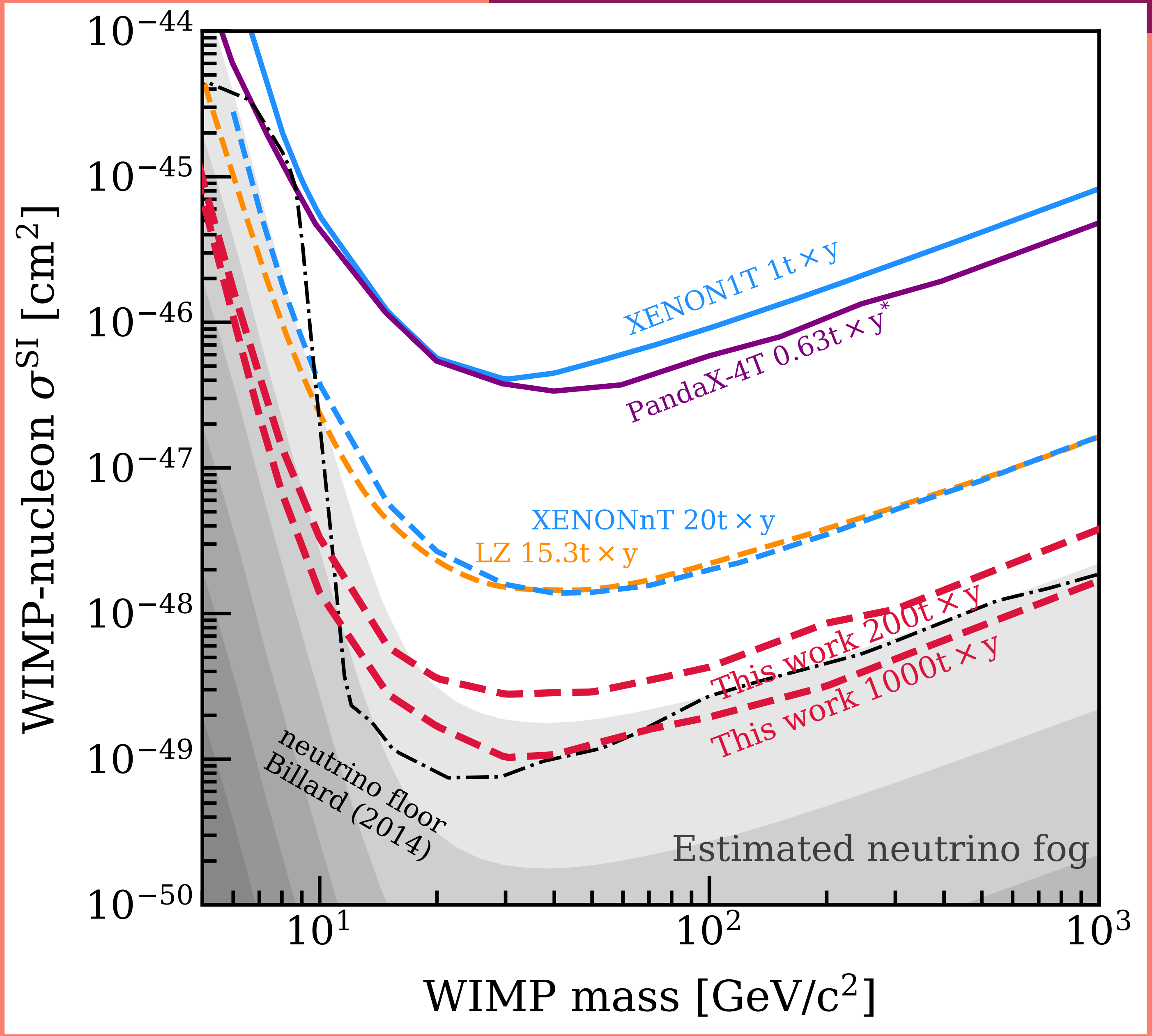


KNUT DUNDAS MORÅ | KNUT.DUNDAS.MORAA@COLUMBIA.EDU

DARWIN/XLZD

xlzd.org

- **LZ and Darwin + XENON have signed a memorandum for a consortium planning the next generation of lXe detector**
- **Using continuous purification and material selection, hope to bring the ER background down to where it is dominated by solar neutrinos (~ 0.25 of the XENONnT ER background)**
- **A larger TPC gives neutrons more length to scatter more than once—Darwin projects $2/200\ \mathrm{tonne-years}$ radiogenic neutrons**
- **In addition to WIMPs, many other science targets:**
  - **ER signatures $> 1\mathrm{keV}$: ALPs. dark photons**
  - **Neutrinos: from the sun, from supernovae**
  - **Nucleon to invisible decays**
  - **Neutrinoless double-beta decay of $^{136}\mathrm{Xe}$ to $T \sim 2 \times 10^{27}\mathrm{y}$**
  - **etc**



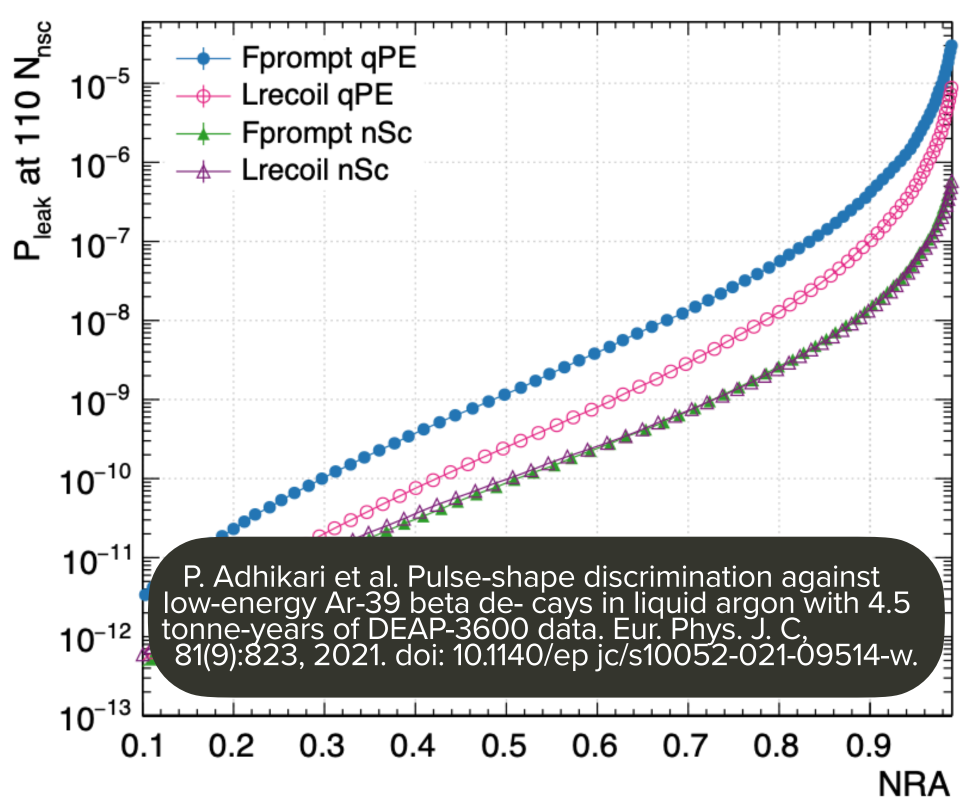
J. Aalbers et al. A next-generation liquid xenon observatory for dark matter and neutrino physics. J. Phys. G, 50(1):013001, 2023. doi: 10.1088/1361-6471/ac841a.

600 authors

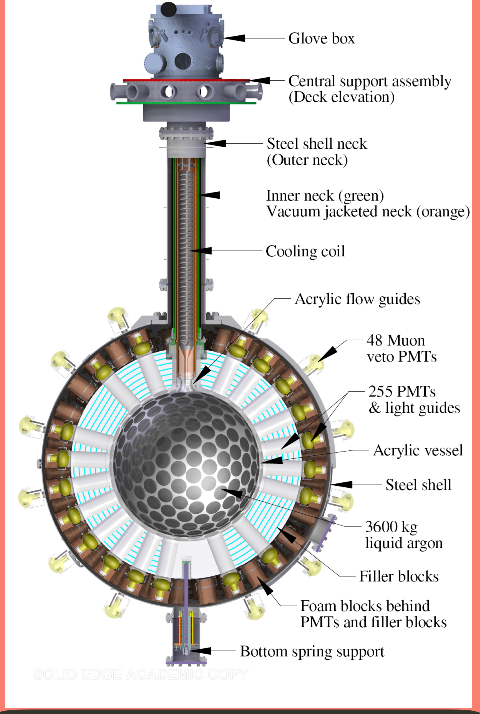
ARGON: DEAP AND DARKSIDE

- **Observable: scintillation light (and charge for 2-phase TPCs)**
- **Unlike xenon, the triplet and singlet excited states of argon decays with detectable difference in timescale $(7,\ 1600\ \mathrm{ns})$**
    - **NRs excite preferentially to singlet states, with excellent $(10^{-7}$ demonstrated by DEAP-3600**
- **Darkside-20K aims to achieve a nearly background-free $(\mu_{\mathrm{bkg}} << 1)$ 100 tonne-year exposure**
    - **20 tonne fiducial volume (surface background observed with Darkside-50)**
    - **Underground argon will reduce the $^{39}\mathrm{Ar}$ background, but projections still assume an ER-limited threshold of $30\ \mathrm{keV}$**

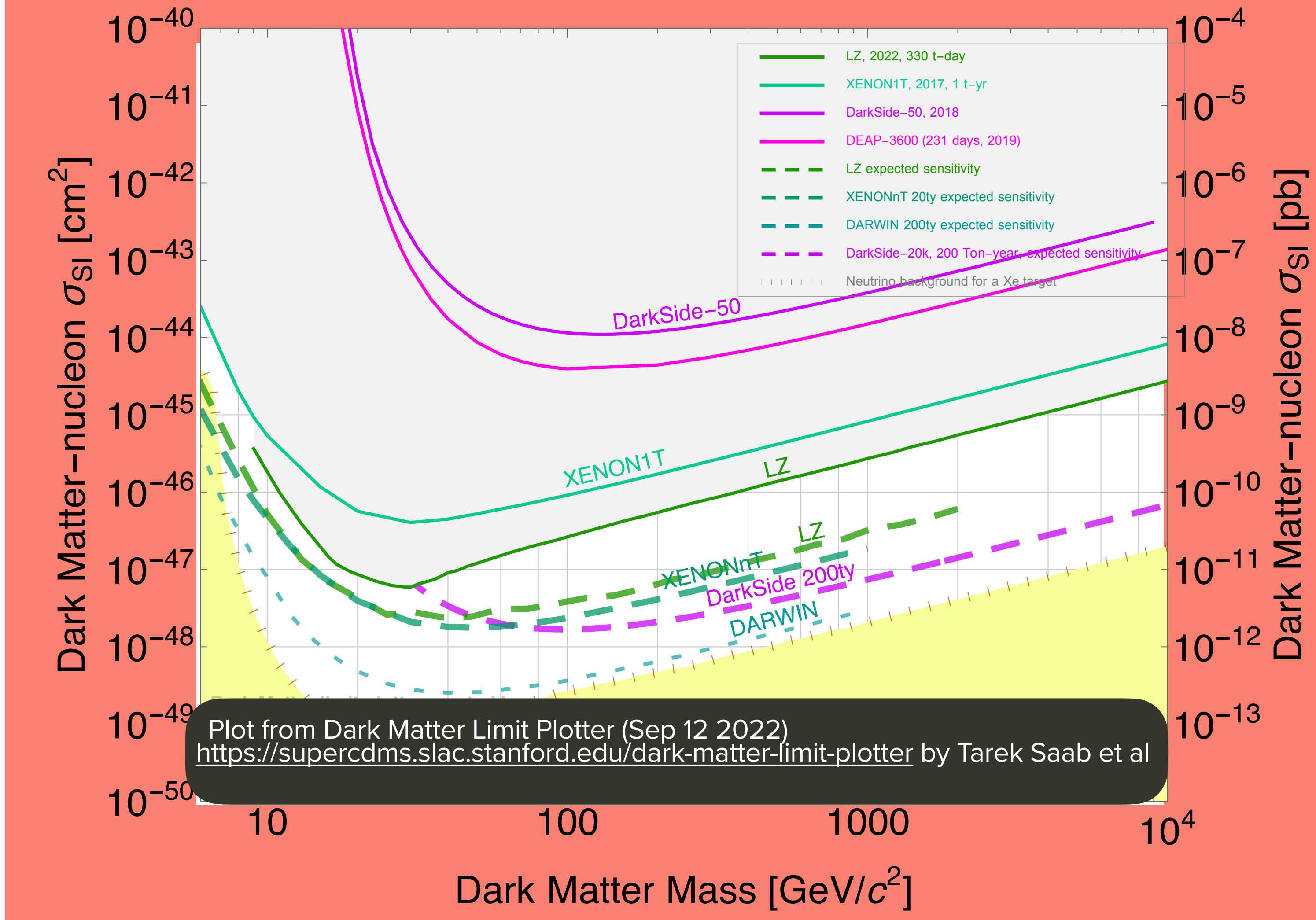
C. E. Aalseth et al. DarkSide-20k: A 20 tonne two-phase LAr TPC for direct dark matter detection at LNGS. Eur. Phys. J. Plus, 133:131, 2018. doi: 10.1140/epjp/i2018-11973-4.



P. Adhikari et al. Pulse-shape discrimination against low-energy Ar-39 beta de- cays in liquid argon with 4.5 tonne-years of DEAP-3600 data. Eur. Phys. J. C, 81(9):823, 2021. doi: 10.1140/ep jc/s10052-021-09514-w.



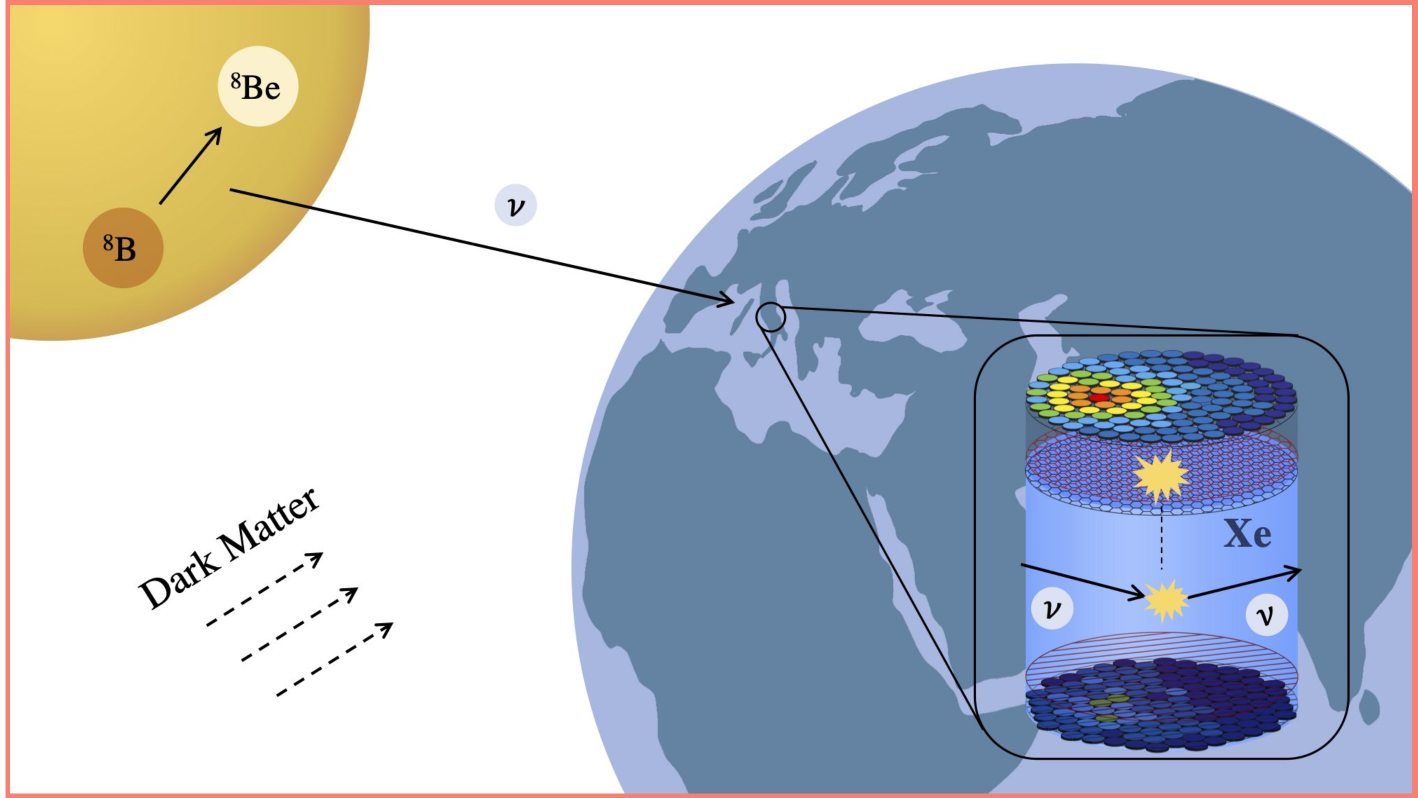
Schematic courtesy of DEAP-3600

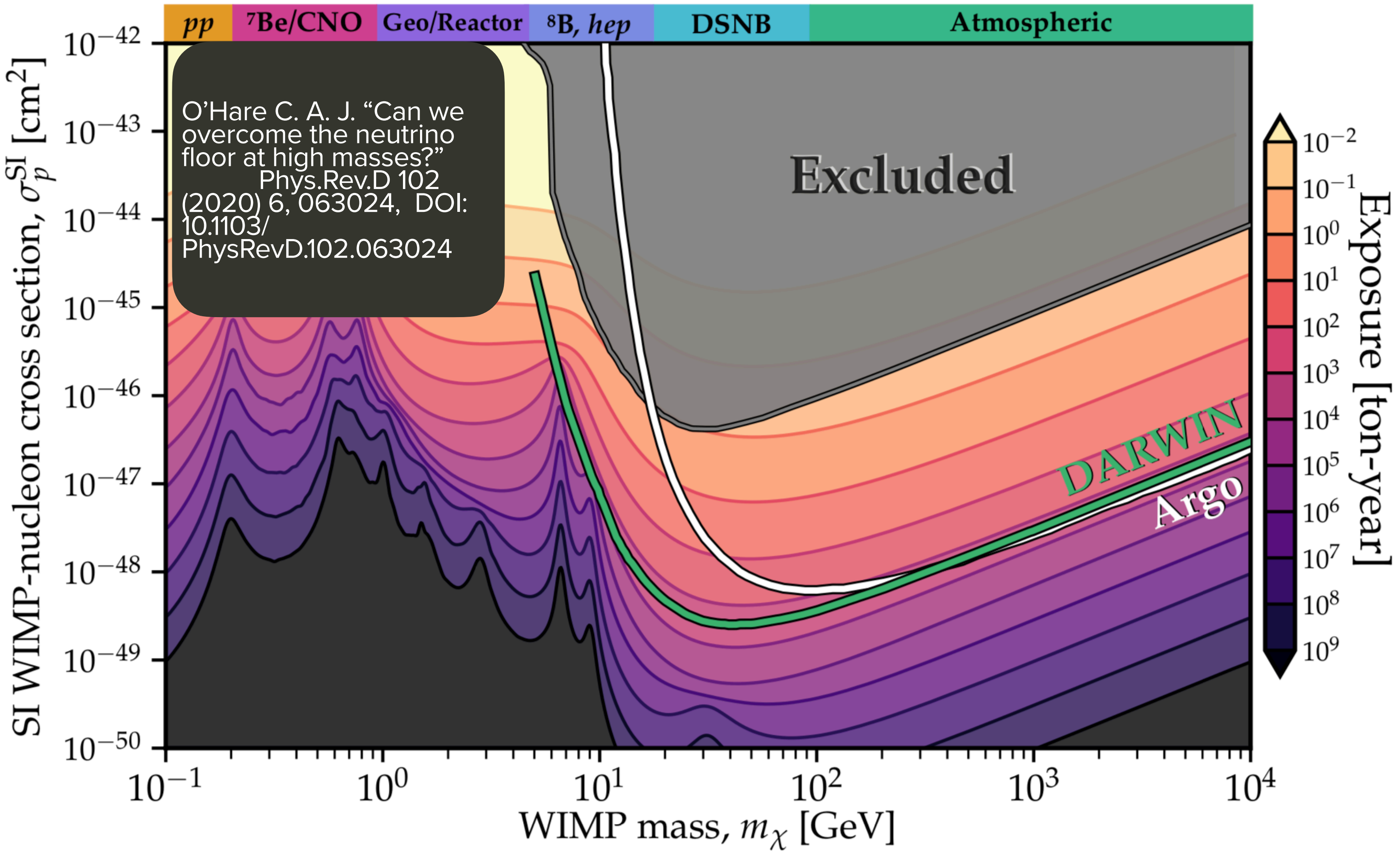


Plot from Dark Matter Limit Plotter (Sep 12 2022) https://supercdms.slac.stanford.edu/dark-matter-limit-plotter by Tarek Saab et al

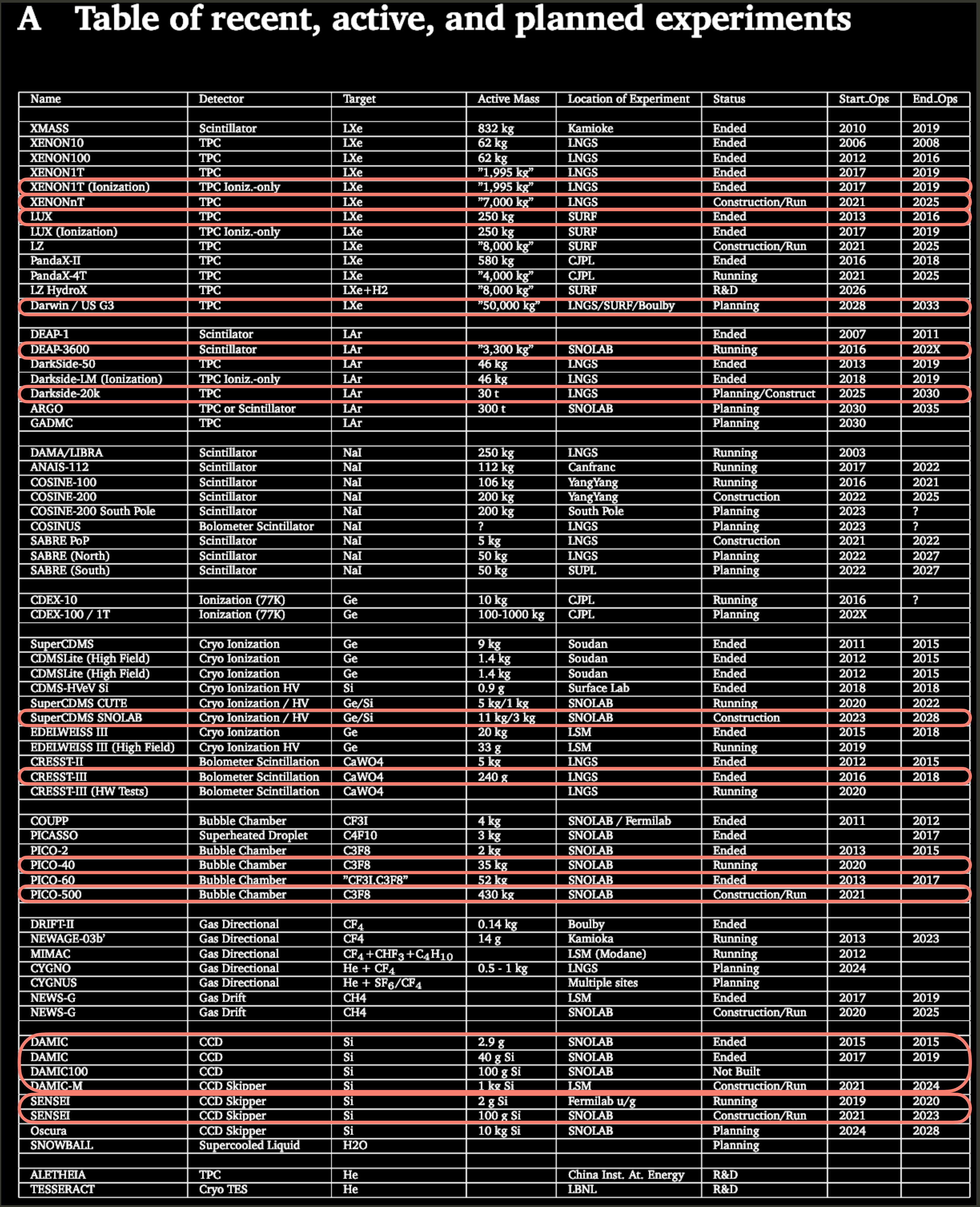
THE ν-FOG

- Neutrinos tick all the boxes of the WIMP acronym, and astrophysical neutrinos will yield recoils indistinguishable from dark matter scattering
- Solar neutrinos from ${}^8B$ are in reach of XENONnT/LZ
- Spectral information still helps if your exposure is big enough, directional information is lost in most direct detection experiments.
- The first spectrum expected to be observed is coherent elastic scattering of solar 8B neutrinos, which have a recoil spectrum nearly indistinguishable from a 6 GeV/c2 WIMP with cross-section ~2 10-45 cm2
  - Right at the lower threshold of the signals the standard WIMP search reach




O'Hare C. A. J. "Can we overcome the neutrino floor at high masses?" Phys.Rev.D 102 (2020) 6, 063024, DOI: 10.1103/PhysRevD.102.063024

SO LITTLE TIME, SO MANY EXPERIMENTS



A Table of recent, active, and planned experiments

Name	Detector	Target	Active Mass	Location of Experiment	Status	Start_Ops	End_Ops
XMASS	Scintillator	LXe	832 kg	Kamioke	Ended	2010	2019
XENON10	TPC	LXe	62 kg	LNGS	Ended	2006	2008
XENON100	TPC	LXe	62 kg	LNGS	Ended	2012	2016
XENON1T	TPC	LXe	”1,995 kg”	LNGS	Ended	2017	2019
XENON1T (Ionization)	TPC Ioniz.-only	LXe	”1,995 kg”	LNGS	Ended	2017	2019
XENONnT	TPC	LXe	”7,000 kg”	LNGS	Construction/Run	2021	2025
LUX	TPC	LXe	250 kg	SURF	Ended	2013	2016
LUX (Ionization)	TPC Ioniz.-only	LXe	250 kg	SURF	Ended	2017	2019
LZ	TPC	LXe	”8,000 kg”	SURF	Construction/Run	2021	2025
PandaX-II	TPC	LXe	580 kg	CJPL	Ended	2016	2018
PandaX-4T	TPC	LXe	”4,000 kg”	CJPL	Running	2021	2025
LZ HydroX	TPC	LXe+H2	”8,000 kg”	SURF	R&D	2026	
Darwin / US G3	TPC	LXe	”50,000 kg”	LNGS/SURF/Boulby	Planning	2028	2033
DEAP-1	Scintilator	LAr			Ended	2007	2011
DEAP-3600	Scintillator	LAr	”3,300 kg”	SNOLAB	Running	2016	202X
DarkSide-50	TPC	LAr	46 kg	LNGS	Ended	2013	2019
Darkside-LM (Ionization)	TPC Ioniz.-only	LAr	46 kg	LNGS	Ended	2018	2019
Darkside-20k	TPC	LAr	30 t	LNGS	Planning/Construct	2025	2030
ARGO	TPC or Scintillator	LAr	300 t	SNOLAB	Planning	2030	2035
GADMC	TPC	LAr			Planning	2030	
DAMA/LIBRA	Scintillator	NaI	250 kg	LNGS	Running	2003	
ANAIS-112	Scintillator	NaI	112 kg	Canfranc	Running	2017	2022
COSINE-100	Scintillator	NaI	106 kg	YangYang	Running	2016	2021
COSINE-200	Scintillator	NaI	200 kg	YangYang	Construction	2022	2025
COSINE-200 South Pole	Scintillator	NaI	200 kg	South Pole	Planning	2023	?
COSINUS	Bolometer Scintillator	NaI	?	LNGS	Planning	2023	?
SABRE PoP	Scintillator	NaI	5 kg	LNGS	Construction	2021	2022
SABRE (North)	Scintillator	NaI	50 kg	LNGS	Planning	2022	2027
SABRE (South)	Scintillator	NaI	50 kg	SUPL	Planning	2022	2027
CDEX-10	Ionization (77K)	Ge	10 kg	CJPL	Running	2016	?
CDEX-100 / 1T	Ionization (77K)	Ge	100-1000 kg	CJPL	Planning	202X	
SuperCDMS	Cryo Ionization	Ge	9 kg	Soudan	Ended	2011	2015
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	Soudan	Ended	2012	2015
CDMSLite (High Field)	Cryo Ionization	Ge	1.4 kg	Soudan	Ended	2012	2015
CDMS-HVeV Si	Cryo Ionization HV	Si	0.9 g	Surface Lab	Ended	2018	2018
SuperCDMS CUTE	Cryo Ionization / HV	Ge/Si	5 kg/1 kg	SNOLAB	Running	2020	2022
SuperCDMS SNOLAB	Cryo Ionization / HV	Ge/Si	11 kg/3 kg	SNOLAB	Construction	2023	2028
EDELWEISS III	Cryo Ionization	Ge	20 kg	LSM	Ended	2015	2018
EDELWEISS III (High Field)	Cryo Ionization HV	Ge	33 g	LSM	Running	2019	
CRESST-II	Bolometer Scintillation	CaWO4	5 kg	LNGS	Ended	2012	2015
CRESST-III	Bolometer Scintillation	CaWO4	240 g	LNGS	Ended	2016	2018
CRESST-III (HW Tests)	Bolometer Scintillation	CaWO4		LNGS	Running	2020	
COUPP	Bubble Chamber	CF3I	4 kg	SNOLAB / Fermilab	Ended	2011	2012
PICASSO	Superheated Droplet	C4F10	3 kg	SNOLAB	Ended		2017
PICO-2	Bubble Chamber	C3F8	2 kg	SNOLAB	Ended	2013	2015
PICO-40	Bubble Chamber	C3F8	35 kg	SNOLAB	Running	2020	
PICO-60	Bubble Chamber	”CF3I,C3F8”	52 kg	SNOLAB	Ended	2013	2017
PICO-500	Bubble Chamber	C3F8	430 kg	SNOLAB	Construction/Run	2021	
DRIFT-II	Gas Directional	CF_4	0.14 kg	Boulby	Ended		
NEWAGE-03b’	Gas Directional	CF4	14 g	Kamioka	Running	2013	2023
MIMAC	Gas Directional	$CF_4+CHF_3+C_4H_{10}$		LSM (Modane)	Running	2012	
CYGNO	Gas Directional	He + CF_4	0.5 - 1 kg	LNGS	Planning	2024	
CYGNUS	Gas Directional	He + SF_6/CF_4		Multiple sites	Planning		
NEWS-G	Gas Drift	CH4		LSM	Ended	2017	2019
NEWS-G	Gas Drift	CH4		SNOLAB	Construction/Run	2020	2025
DAMIC	CCD	Si	2.9 g	SNOLAB	Ended	2015	2015
DAMIC	CCD	Si	40 g Si	SNOLAB	Ended	2017	2019
DAMIC100	CCD	Si	100 g Si	SNOLAB	Not Built		
DAMIC-M	CCD Skipper	Si	1 kg Si	LSM	Construction/Run	2021	2024
SENSEI	CCD Skipper	Si	2 g Si	Fermilab u/g	Running	2019	2020
SENSEI	CCD Skipper	Si	100 g Si	SNOLAB	Construction/Run	2021	2023
Oscura	CCD Skipper	Si	10 kg Si	SNOLAB	Planning	2024	2028
SNOWBALL	Supercooled Liquid	H2O			Planning		
ALETHEIA	TPC	He		China Inst. At. Energy	R&D		
TESSERACT	Cryo TES	He		LBNL	R&D		

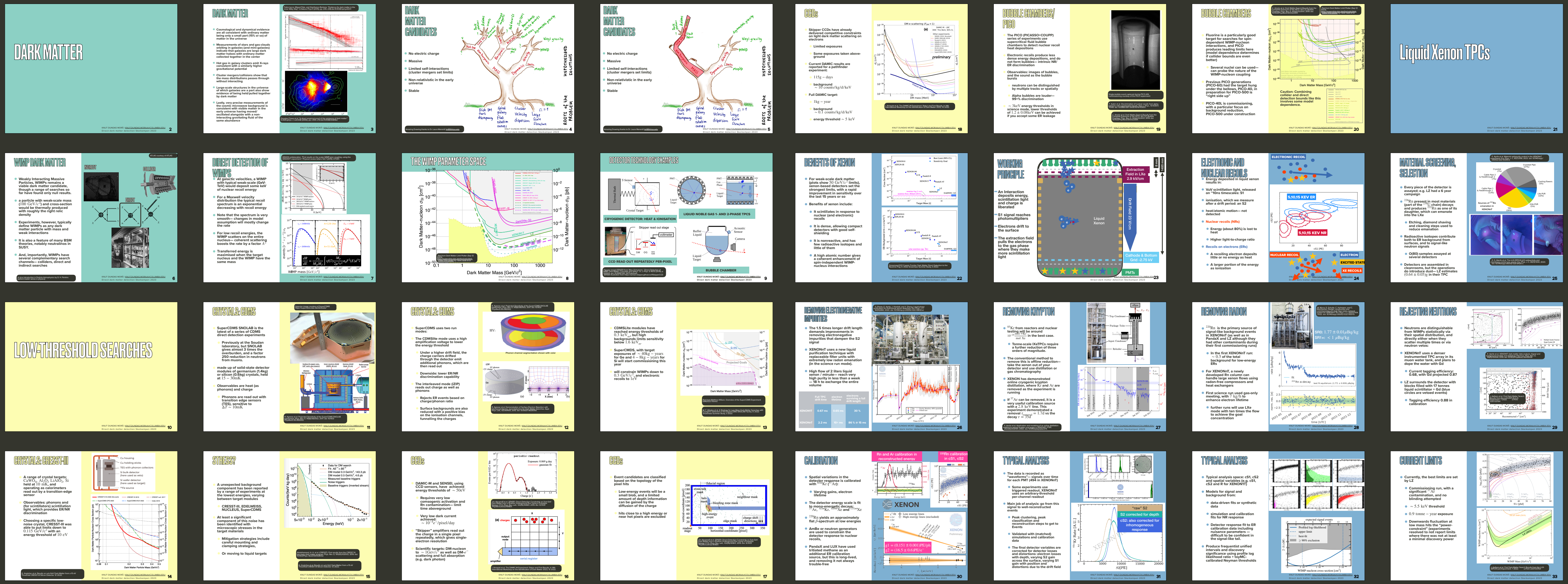
D. S. Akerib et al. Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog. In 2022 Snowmass Summer Study, 3 2022.

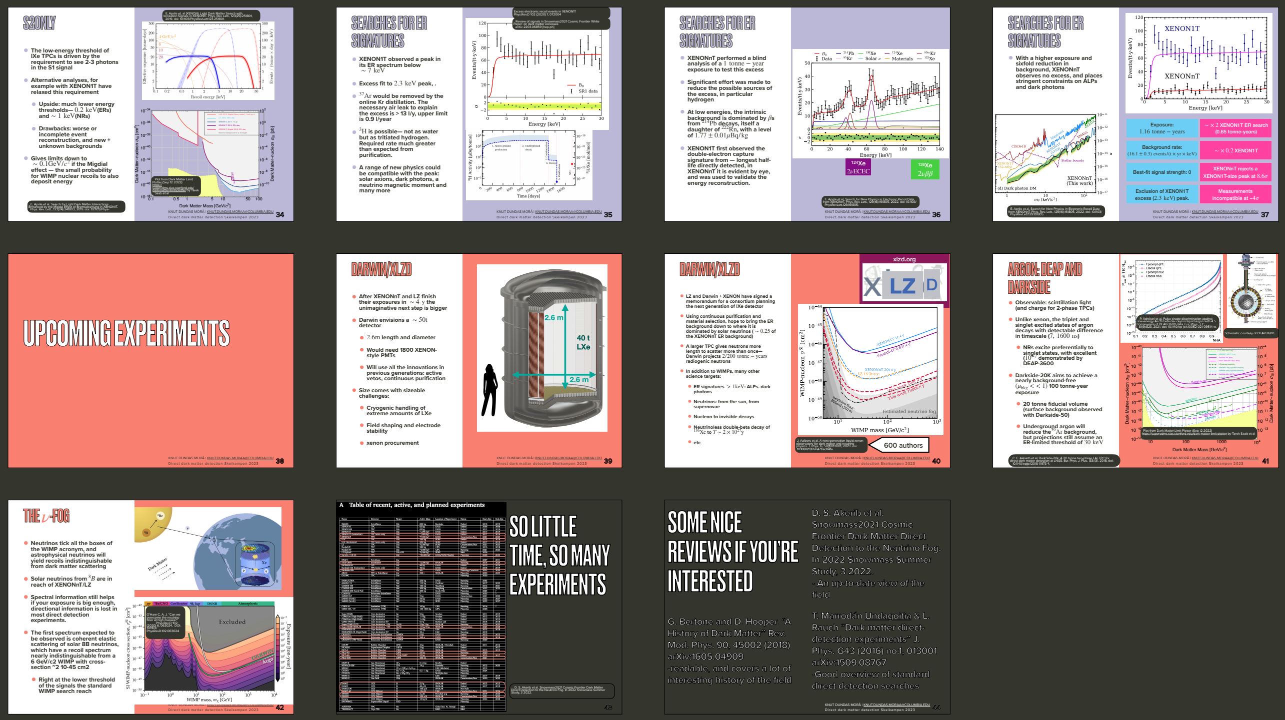
SOME NICE REVIEWS IF YOU'RE INTERESTED

G. Bertone and D. Hooper. “A History of Dark Matter” Rev. Mod. Phys. 90, 45002 (2018) arXiv:1605.04909
-readable, and covers a lot of interesting history of the field

D. S. Akerib et al. Snowmass2021 Cosmic Frontier Dark Matter Direct Detection to the Neutrino Fog. In 2022 Snowmass Summer Study, 3 2022.
- An up-to-date view of the field

T. Marrodán Undagoitia & L. Rauch “Dark matter direct-detection experiments” J. Phys. G43 (2016) no.1, 013001 arXiv:1509.08767
-Good overview of standard direct detection searches





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JUST BRAGGING