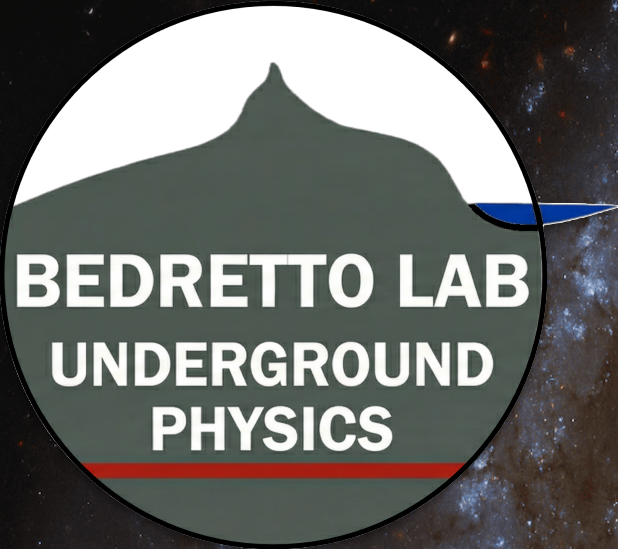


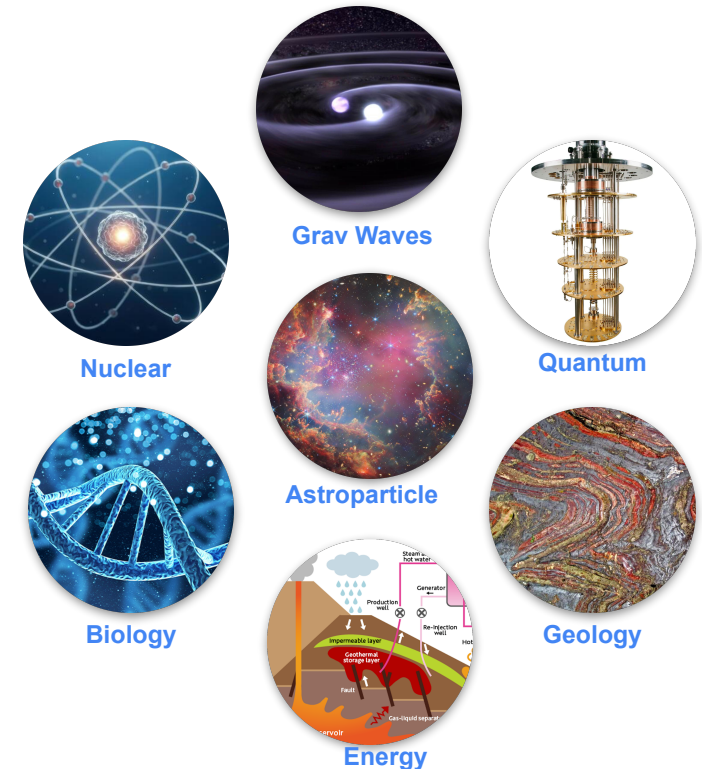
**DIVERSE: MORE UG LABS, ARGON,
MODULATION, DIRECTIONAL**

UNDERGROUND LABS, EXAMPLE: BEDRETTO

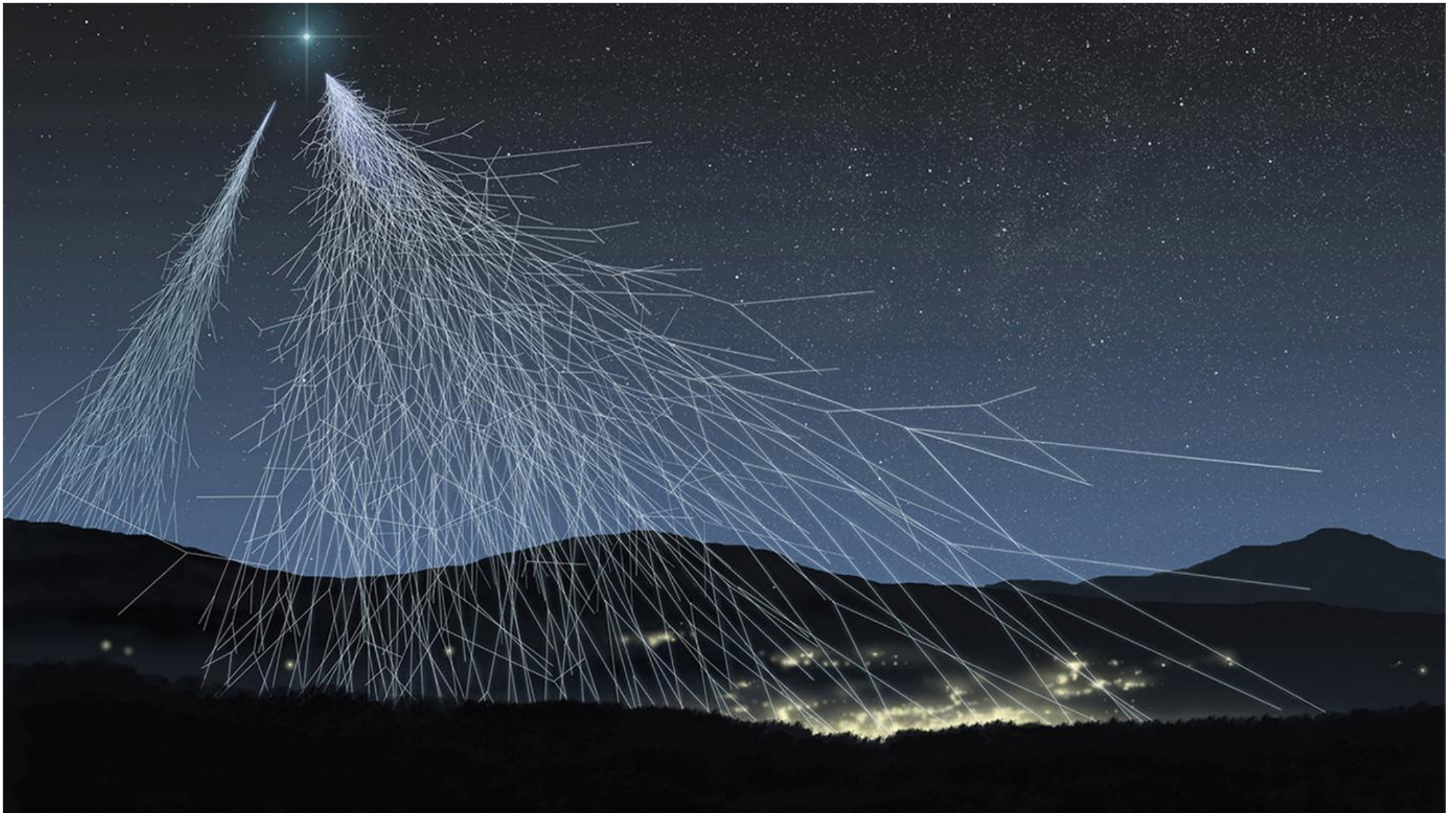


THE SCIENCE YOU CAN DO

- Underground laboratories are indispensable for many sciences
- Among others:
 - Astro Particle & Neutrino Physics
 - Gravitational Waves
 - Nuclear Monitoring & Assaying
 - Quantum Sensing & Computing
 - Biology & Extreme Life
 - Earth Sciences
 - Geothermal Energies
- Provide unique, background reduced-environments to explore the Precision Frontier

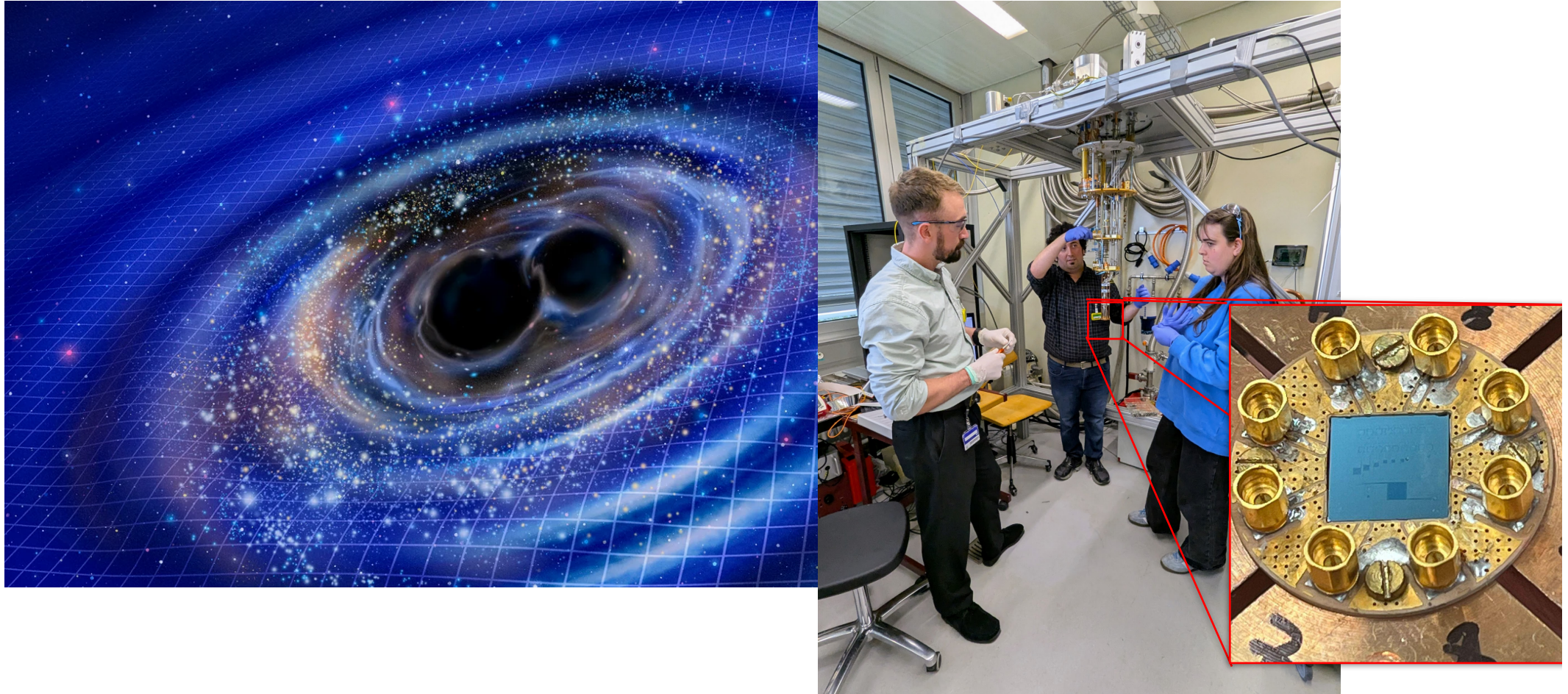


SPACE IS NOISY



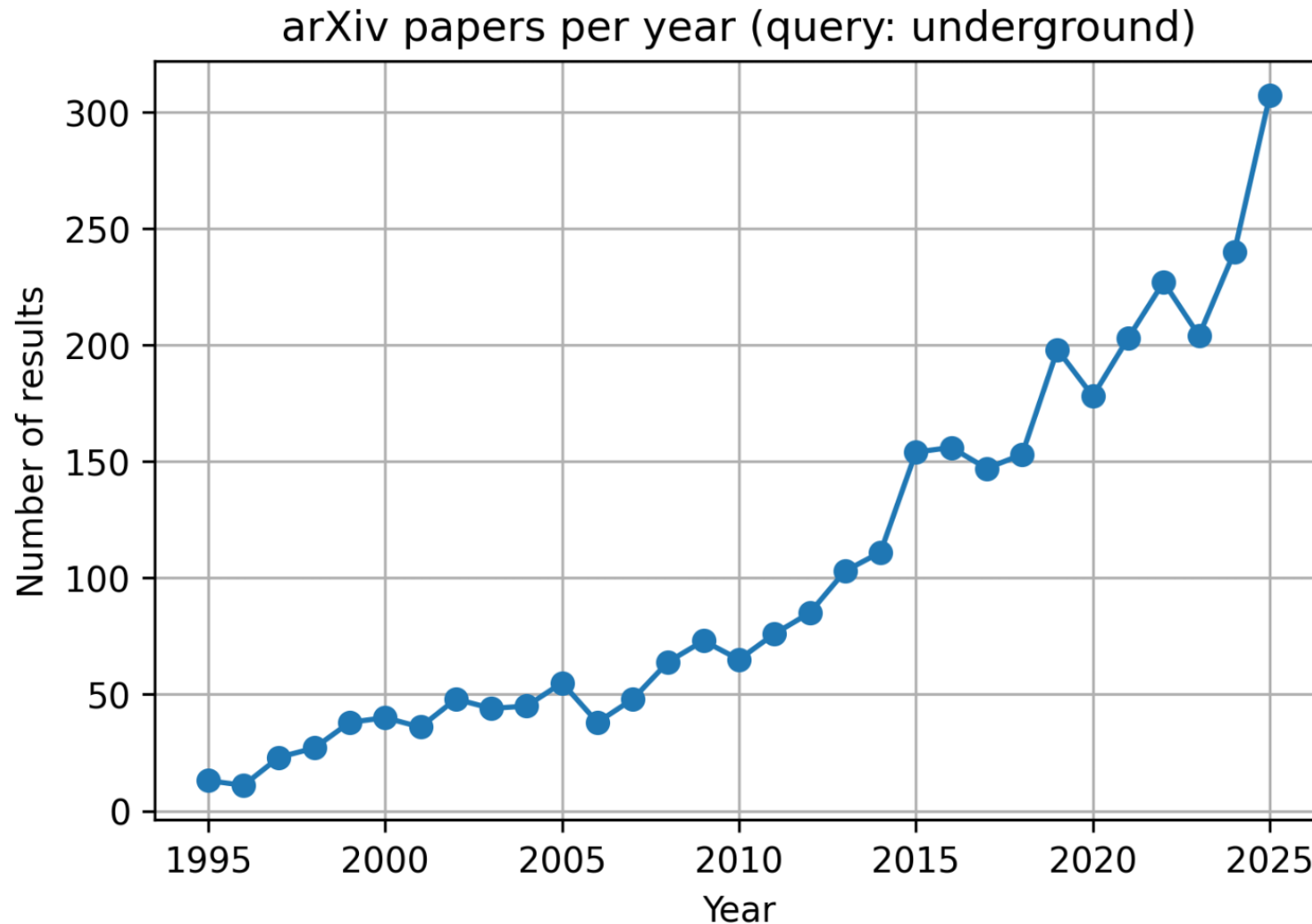
- Underground Labs allow us to shield cosmic rays that will interfere with our detectors

UNDERGROUND IS QUIETER



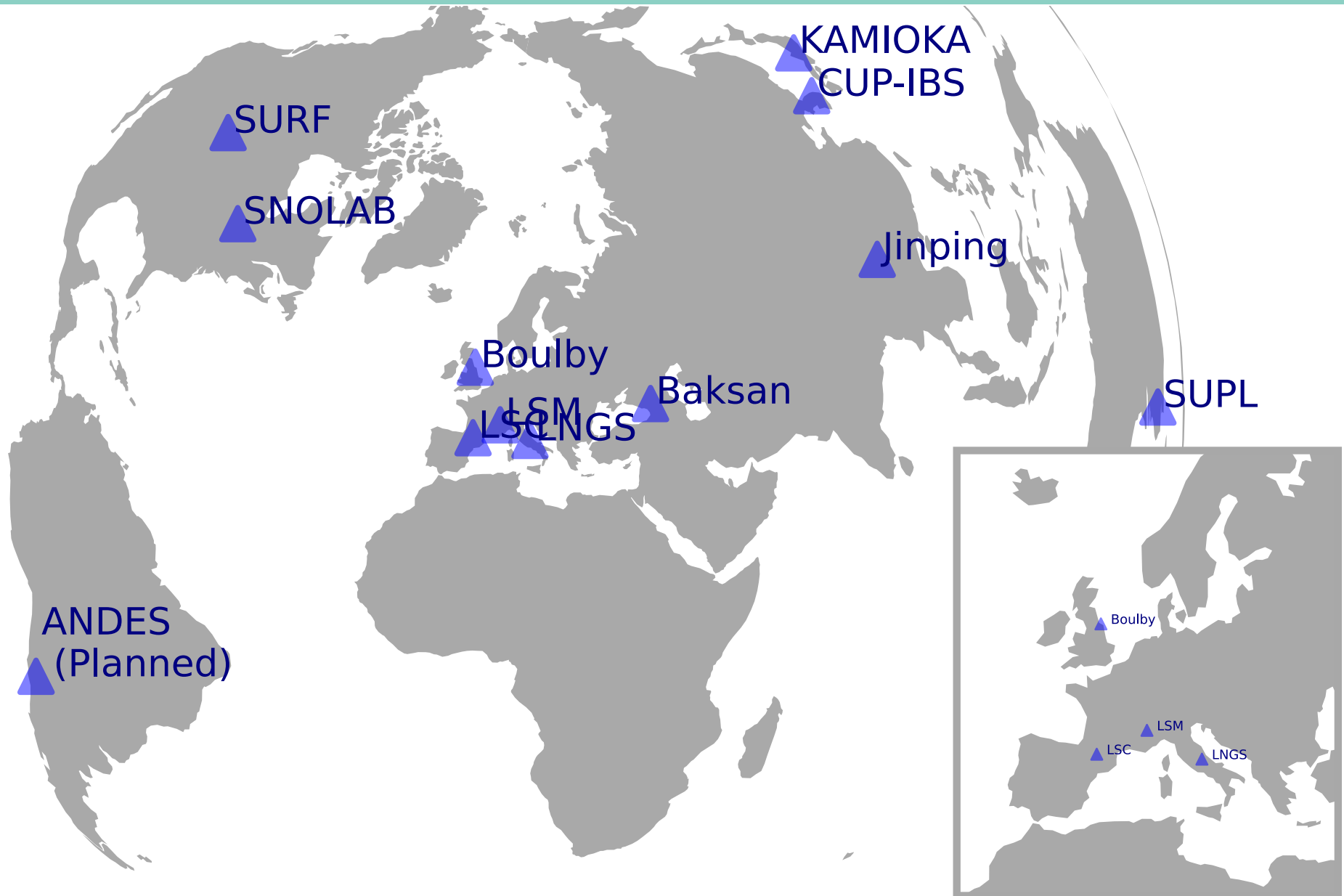
Underground labs are very quiet, minimizing vibrational noise and gravitational gradients, which enables gravitational wave searches & improves Quantum sensing

SIGNIFICANT SCIENTIFIC INTEREST

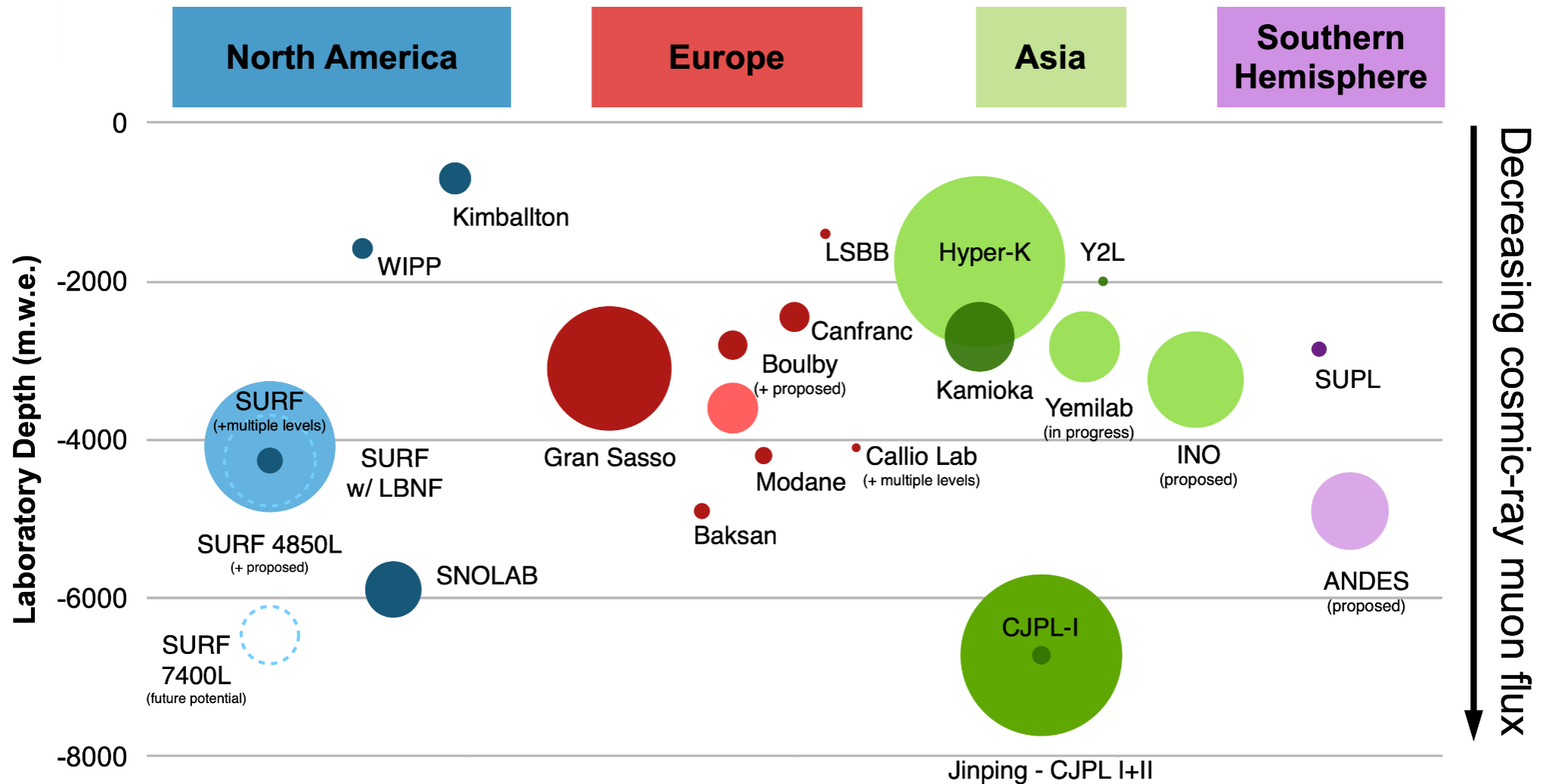


The size of our **community** has about **doubled** in the last decade, still **increases quickly** due **new fields** being explored such as **quantum sensing** and **gravitational waves**

LOCATION OF UNDERGROUND LABS



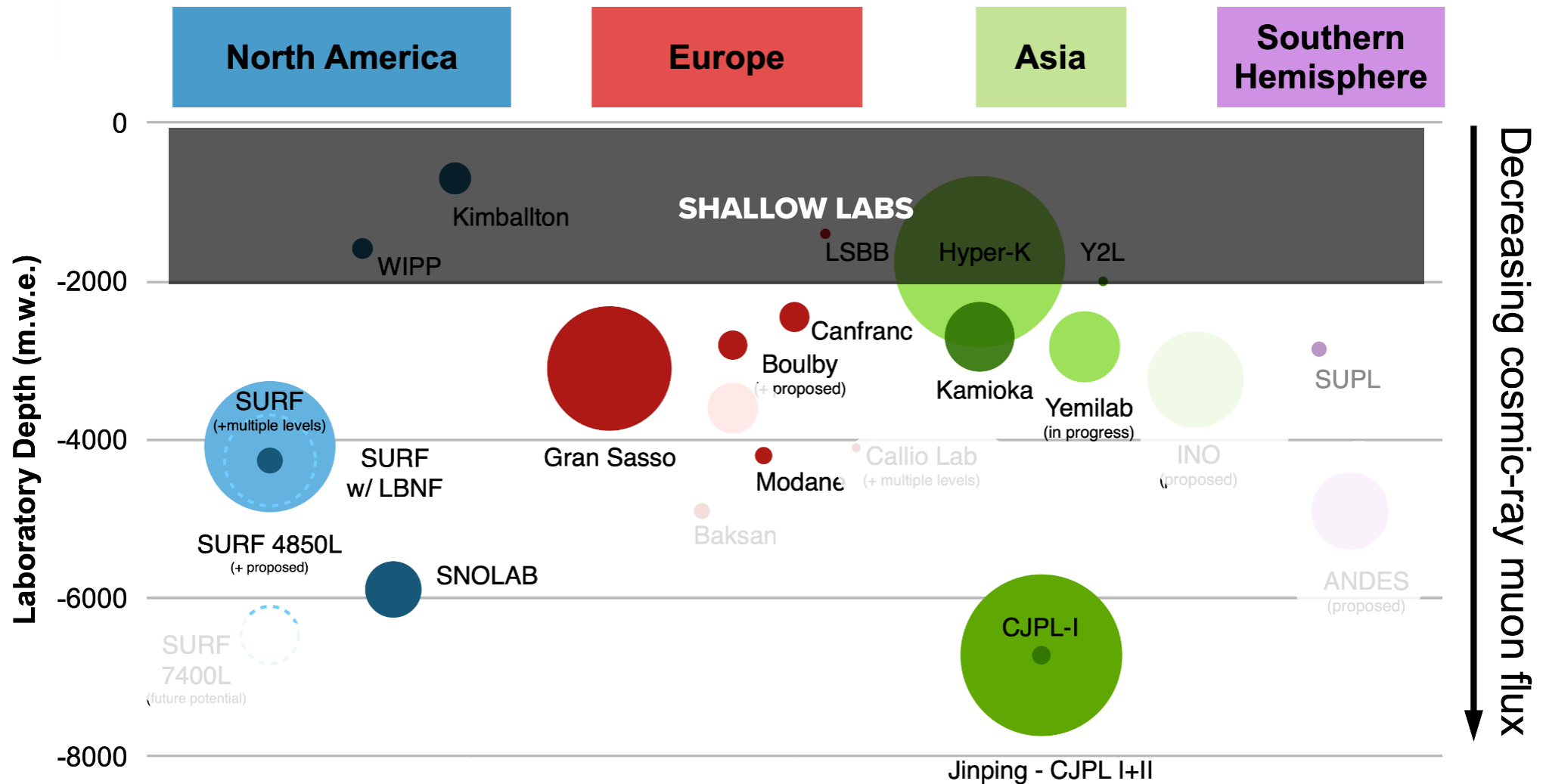
THE GLOBAL LANDSCAPE



Note: Circles represent volume of science space

Caveat: This picture overstates how many labs we have

THE GLOBAL LANDSCAPE



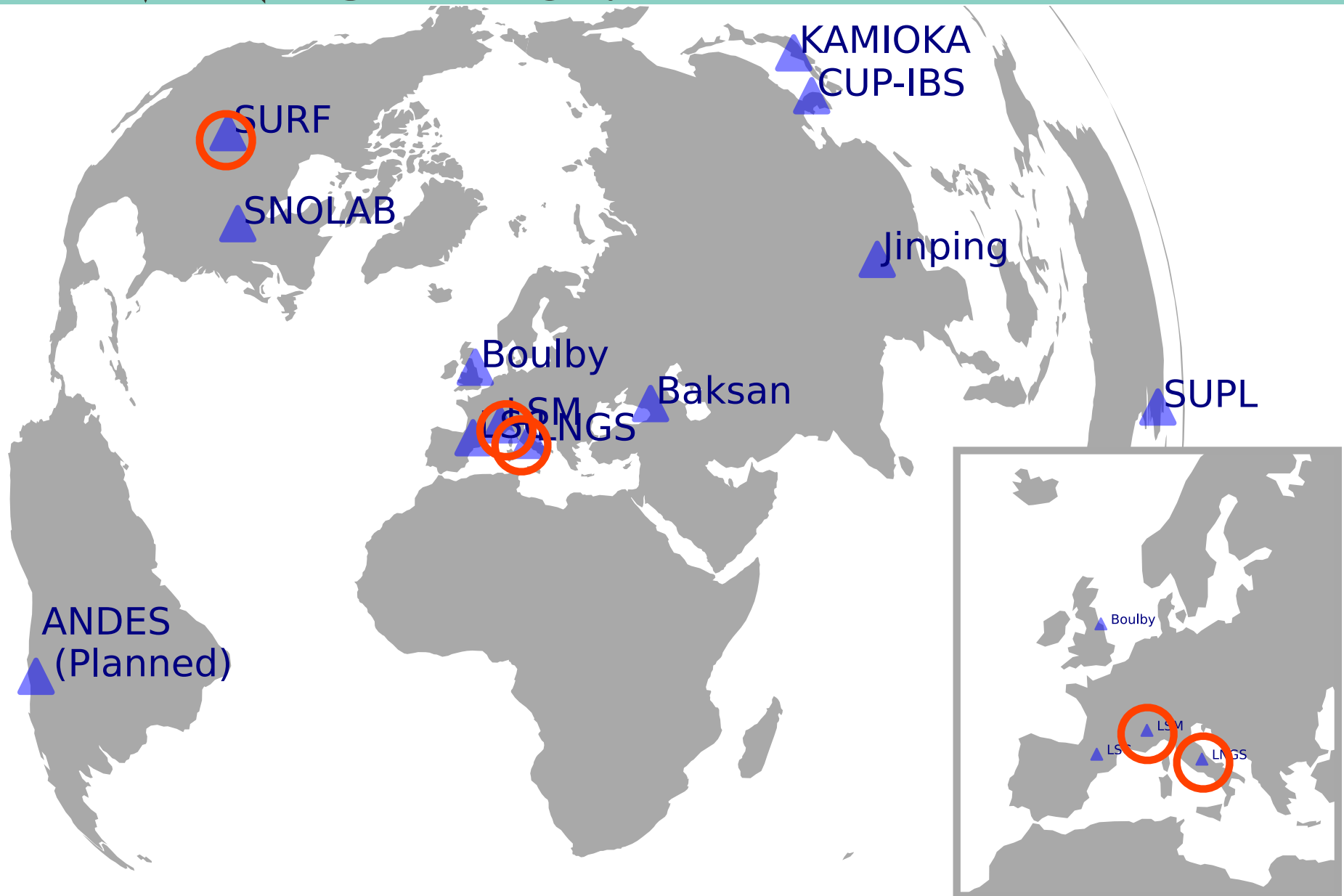
Note: Circles represent volume of science space

Closer to current state of the field

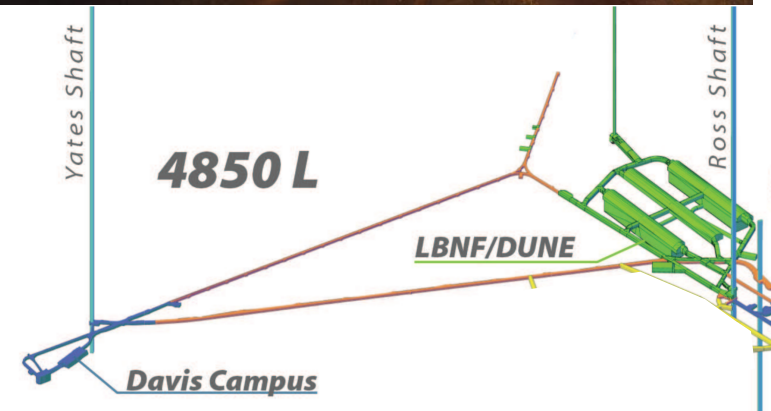
UZH, FOR EXAMPLE, WORKS WITH MANY OF THESE!



Universität
Zürich^{UZH}



SANFORD UNDERGROUND RESEARCH FACILITY



- Deepest US lab located in Lead, South Dakota, USA
- 1.6 km deep (4800 m.w.e.), $R_n \approx 150\text{--}350 \text{ Bq/m}^3$

SANFORD UNDERGROUND RESEARCH FACILITY



- Focus on Neutrino & DM physics

- Experiments: DUNE, LZ, Majorana, CASPAR

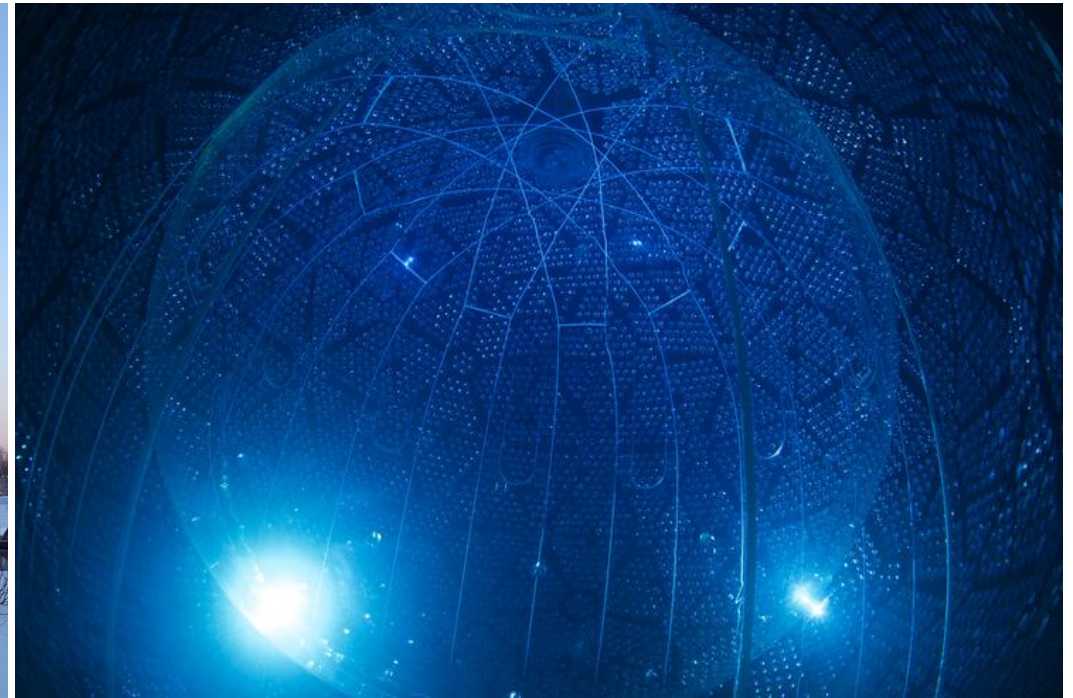
- DUNE: Excavation complete, cryostat install to start & science end of decade

- Caspar: Study stellar processes via underground low-energy accelerator

- Underground shops and majorana copper production

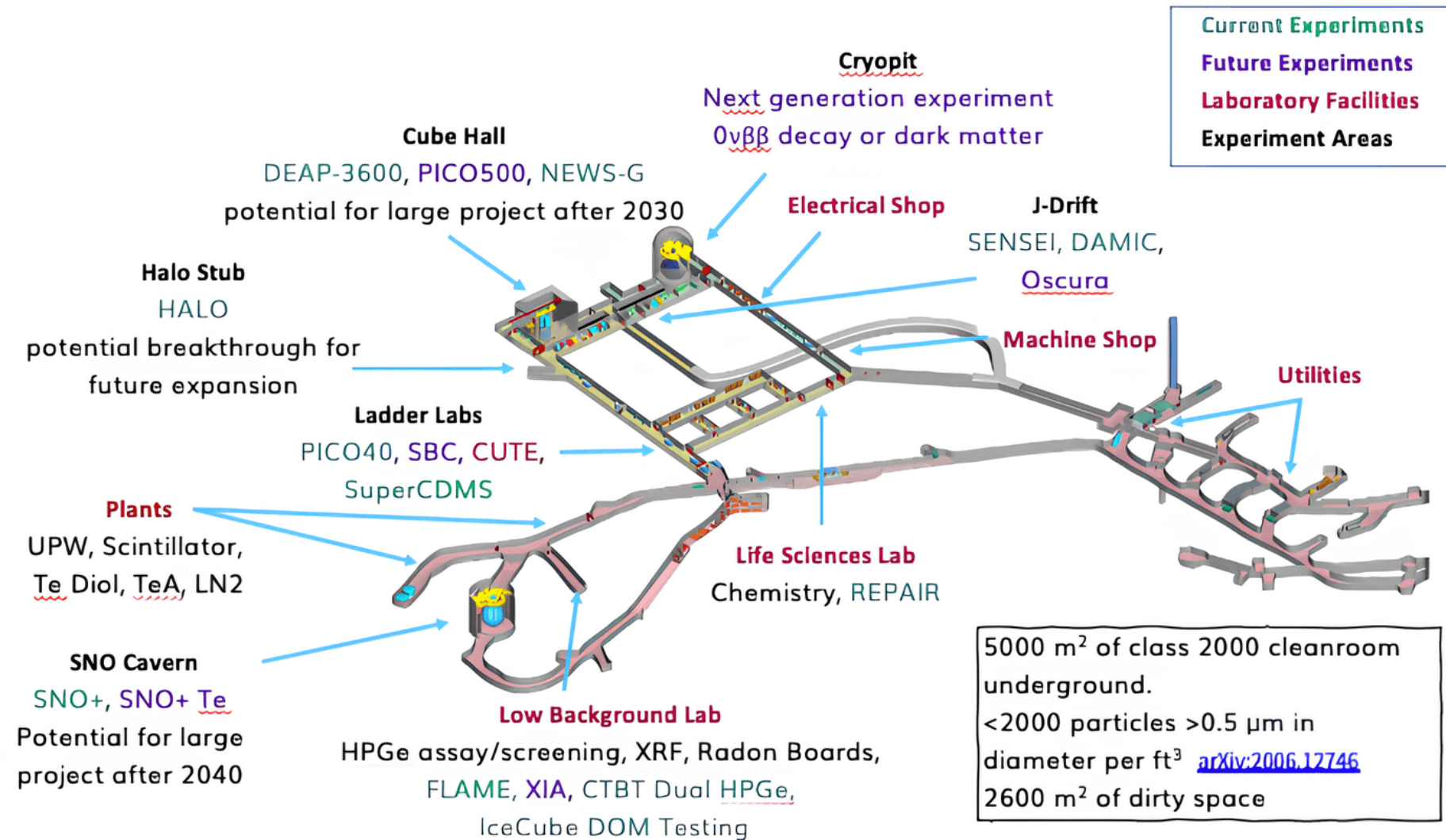
- Others: Radio assay setup (BHSU), geological and biological research

SNOLAB



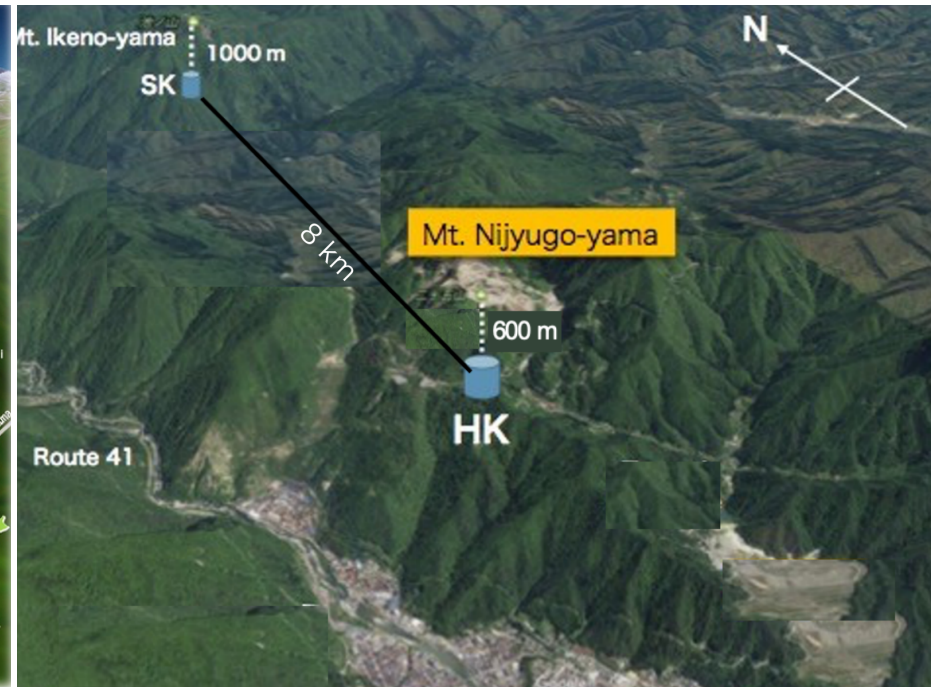
- SNOLab is located at in Sudbury Northern Ontario, Canada
- Depth: 2070 m (6010 m.w.e), $R_n \approx 130 \text{ Bq/m}^3$
- Particularly known for SNO (nomen est omen)
- Operating ore mine

SNOLAB



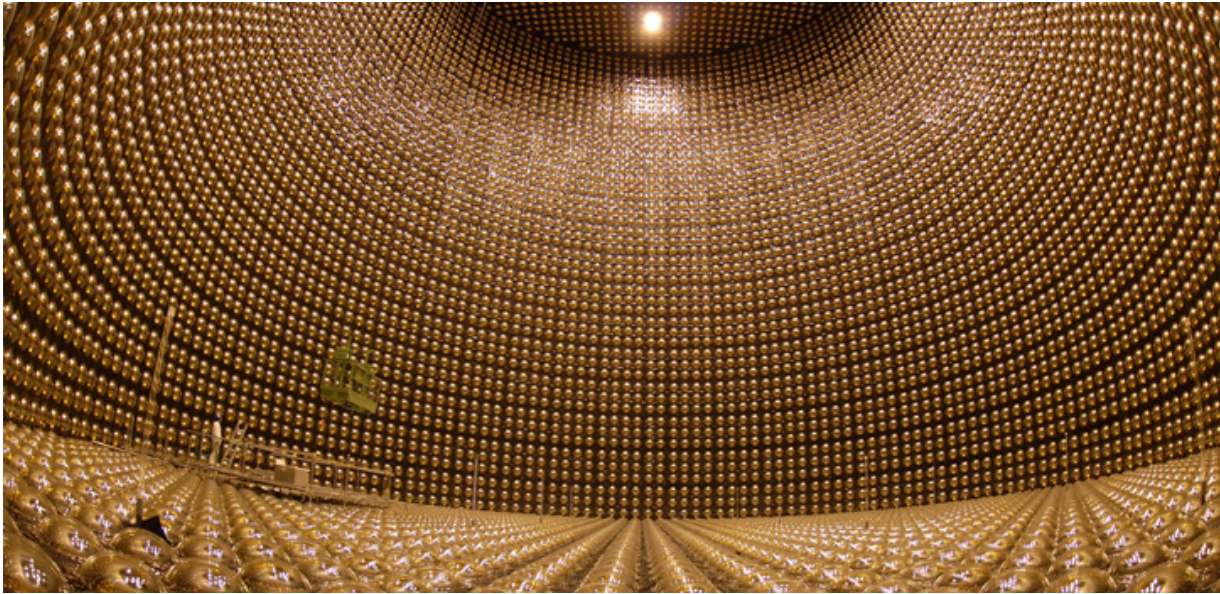
- Key part of Canadian Major Research Facilities (MRF) framework
- Extension and facility upgrades considered

KAMIOKA

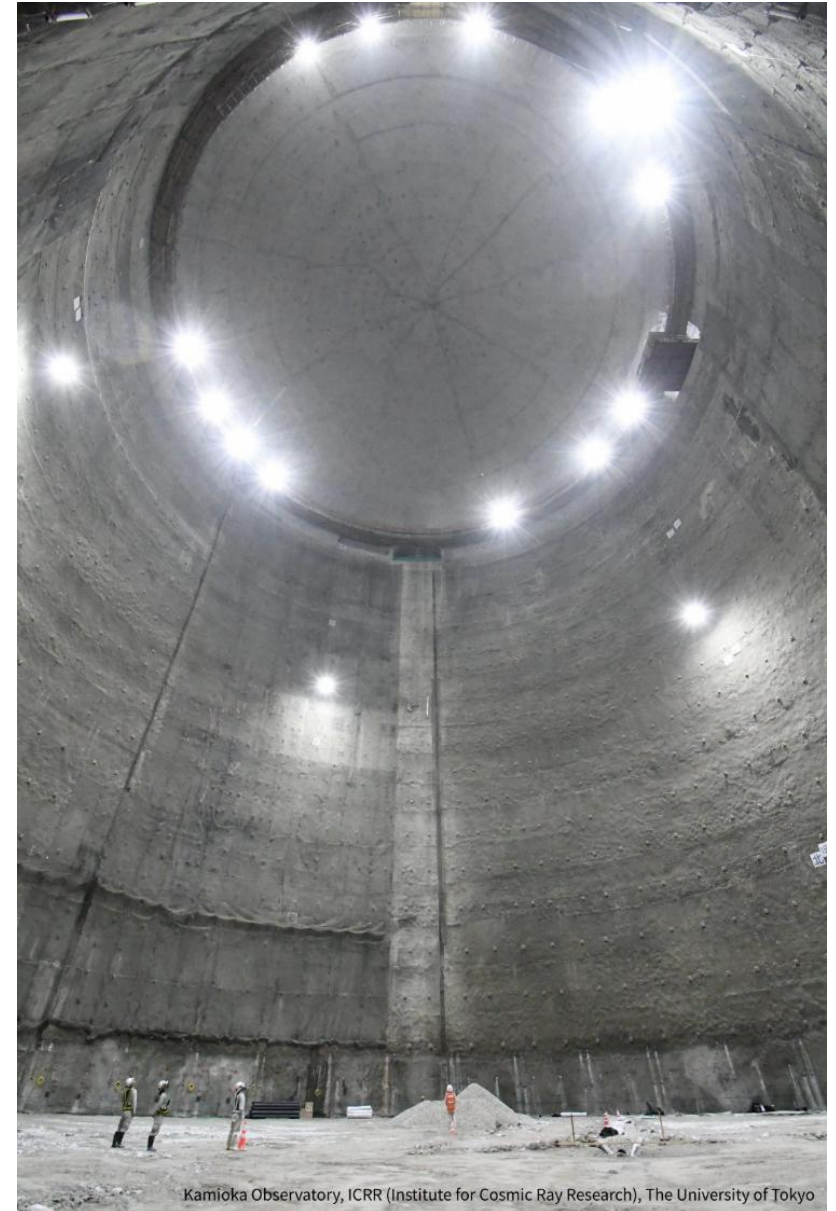


- Hida in Gifu Prefecture, Japan, close to Toyoma
- Depth: 1000 m (2,700 m.w.e.) in Mozumi - 600 m Tochibora (10km South)
- $R_n \approx 100\text{-}1000 \text{ Bq/m}^3$

KAMIOKA

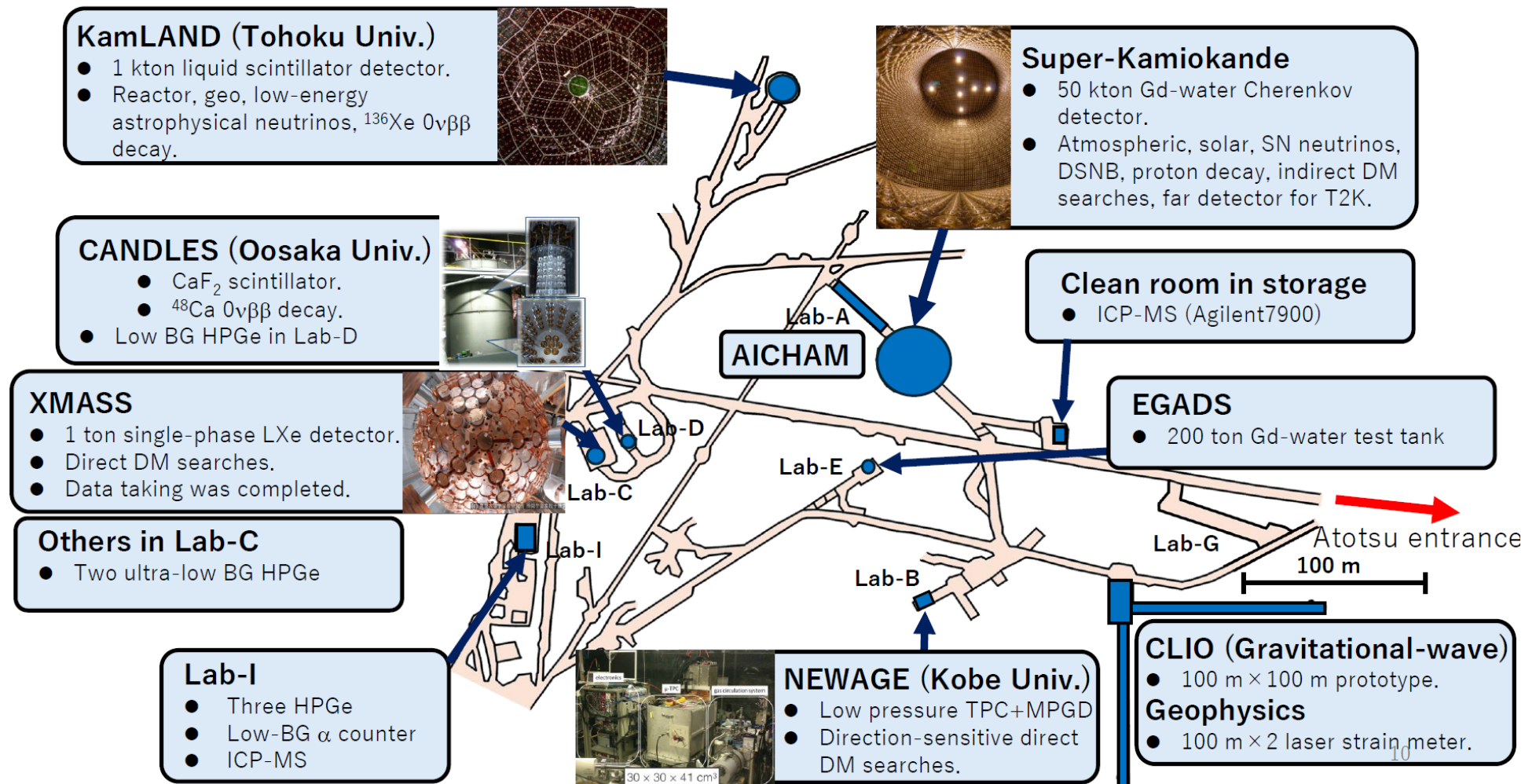


- Best known for T2K and Hyper-K:
 - 13k, 20k PMTs respectively
 - 50k vs. 250k tonnes of water
- Excavation of the huge cavern for Hyper-Kamiokande completed



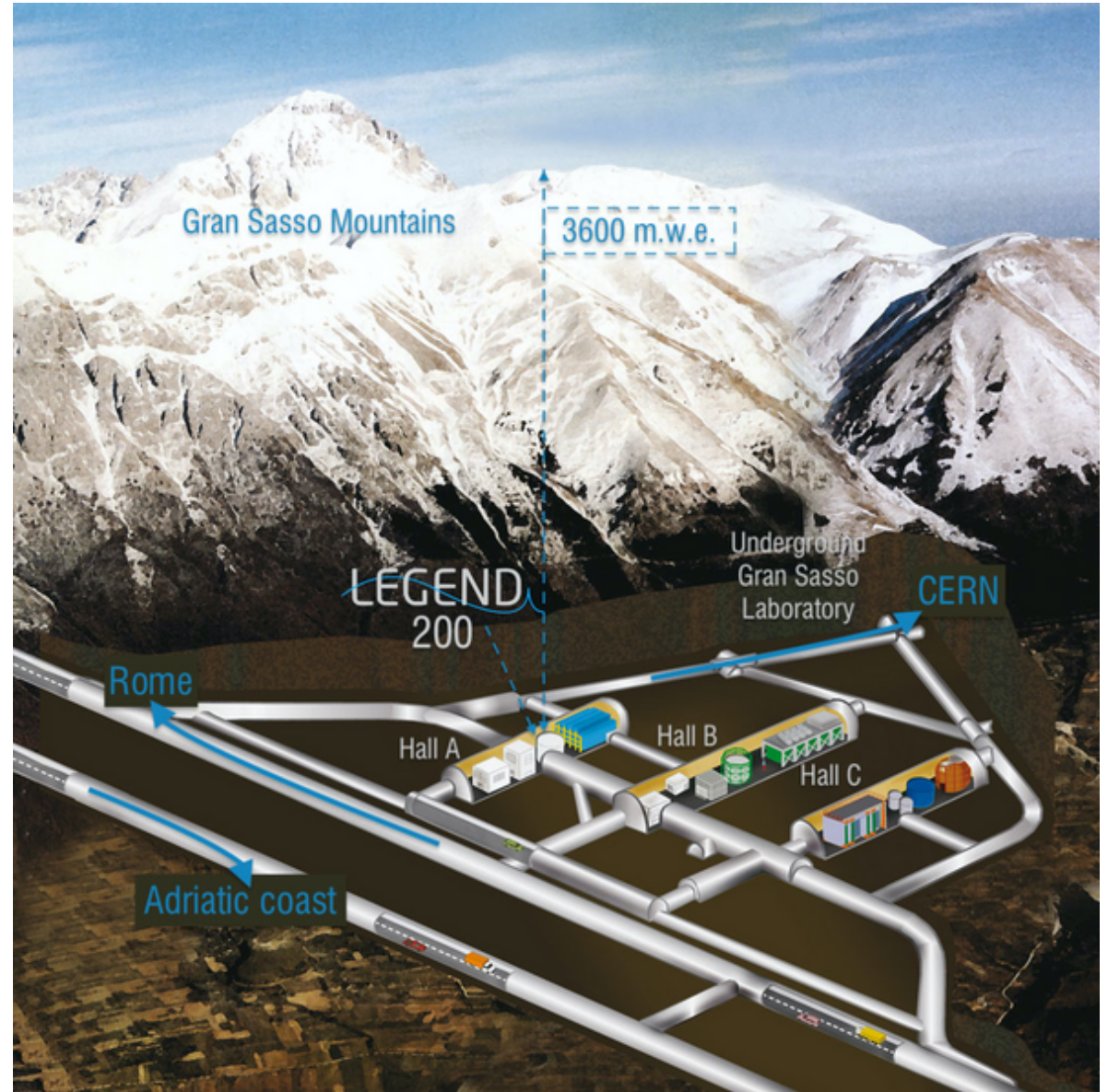
Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

KAMIOKA



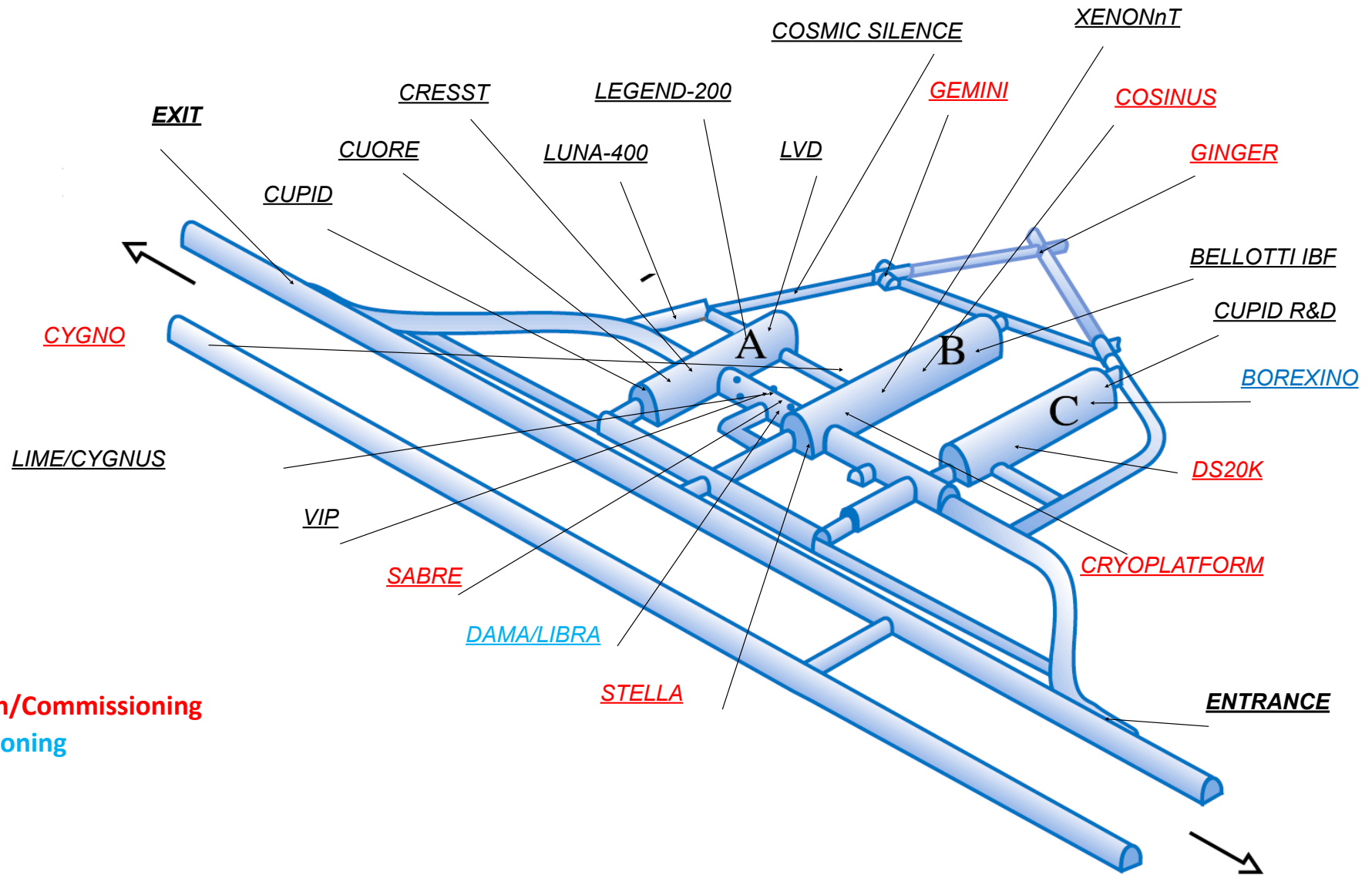
- Very large facility with some of the largest detectors in the world + GW

LNGS



- Gran Sasso National Laboratory (LNGS)
- Biggest European lab, ~2h from Rome
- 3800 m.w.e. of rock, $R_n \approx 100 \text{ Bq/m}^3$
- Three very large experimental halls

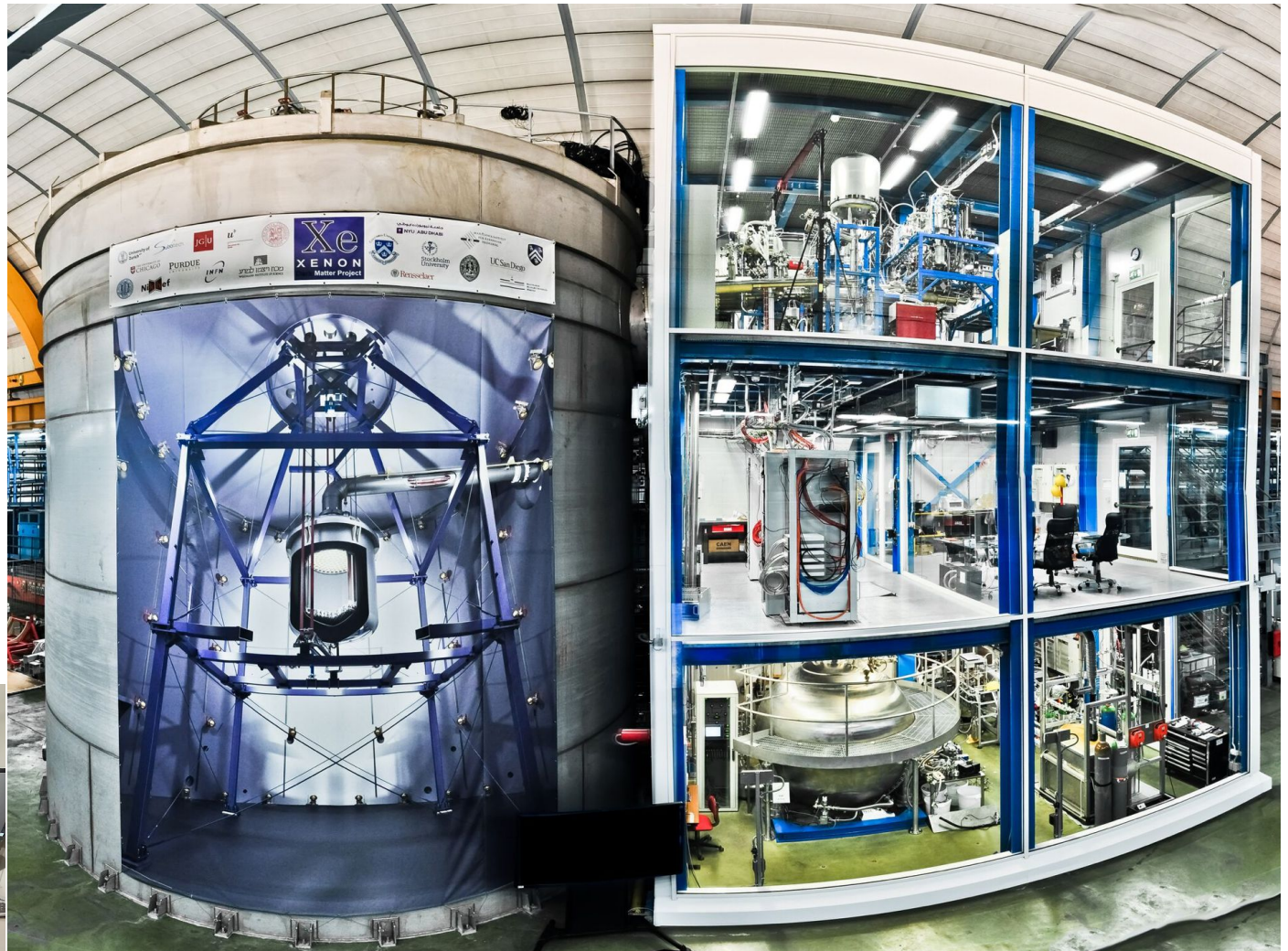
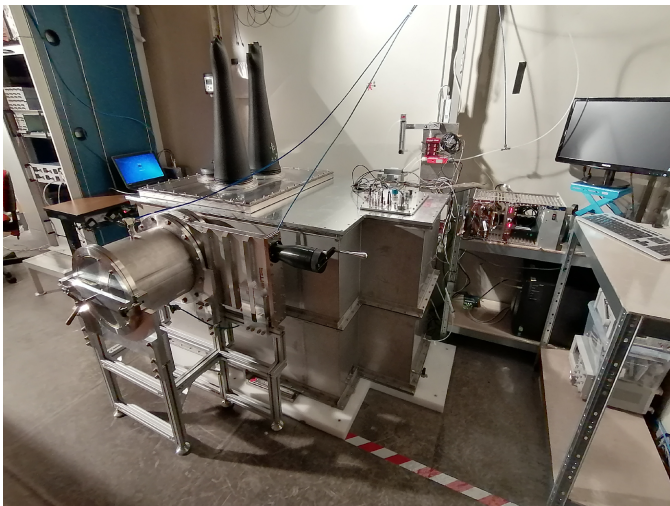
LNGS



Running
Construction/Commissioning
Decommissioning

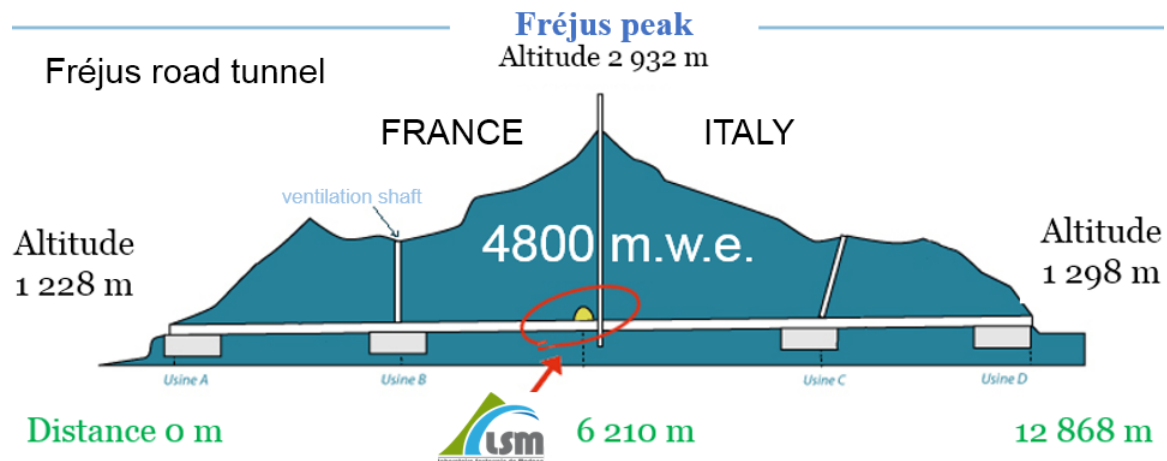
LNGS

- Lots of activities for present and future experiments
- Best known probably for: XENONnT, Borexino, DarkSide
- UZH operates Gator at LGNS, collaborate (a bit) on cryoplatfrom



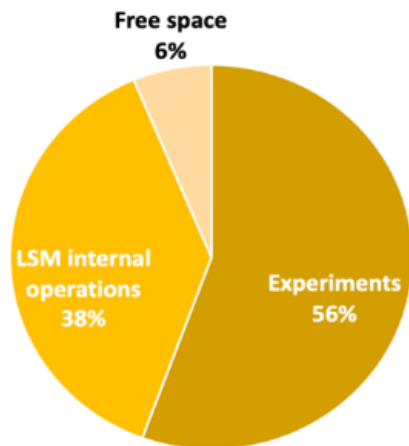
MODANE

- Located in Frejus tunnel between Italy & France (close to Geneva)
- Deepest European Lab
- 4800 m.w.e, $R_n \approx 10-15 \text{ Bq/m}^3$
- Rich history in DM & Neutrino (Edelweiss & SuperNemo)
- Extensive counting facilities



MODANE

- Science prog adapted to lab size:
 - Low-mass DM Experiments (TESSERACT)
 - $0\nu\beta\beta$ technologies
 - Background counting
- Space tight:



- Studies for a new mezzanine level



MODANE

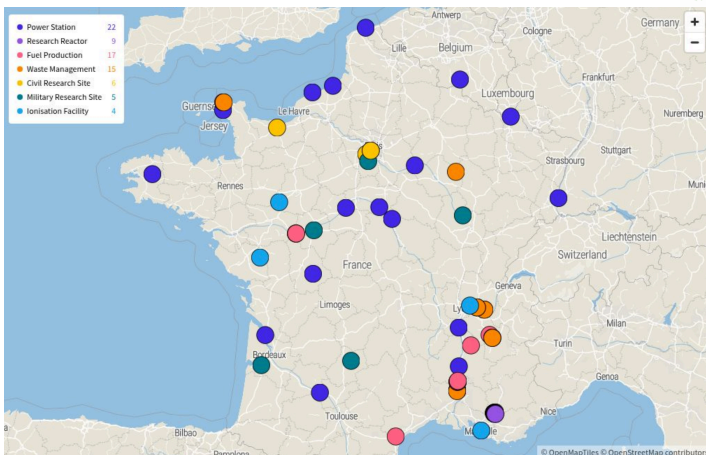
I do not know why France likes to put particle physics experiments at its borders:

CERN (Switzerland)

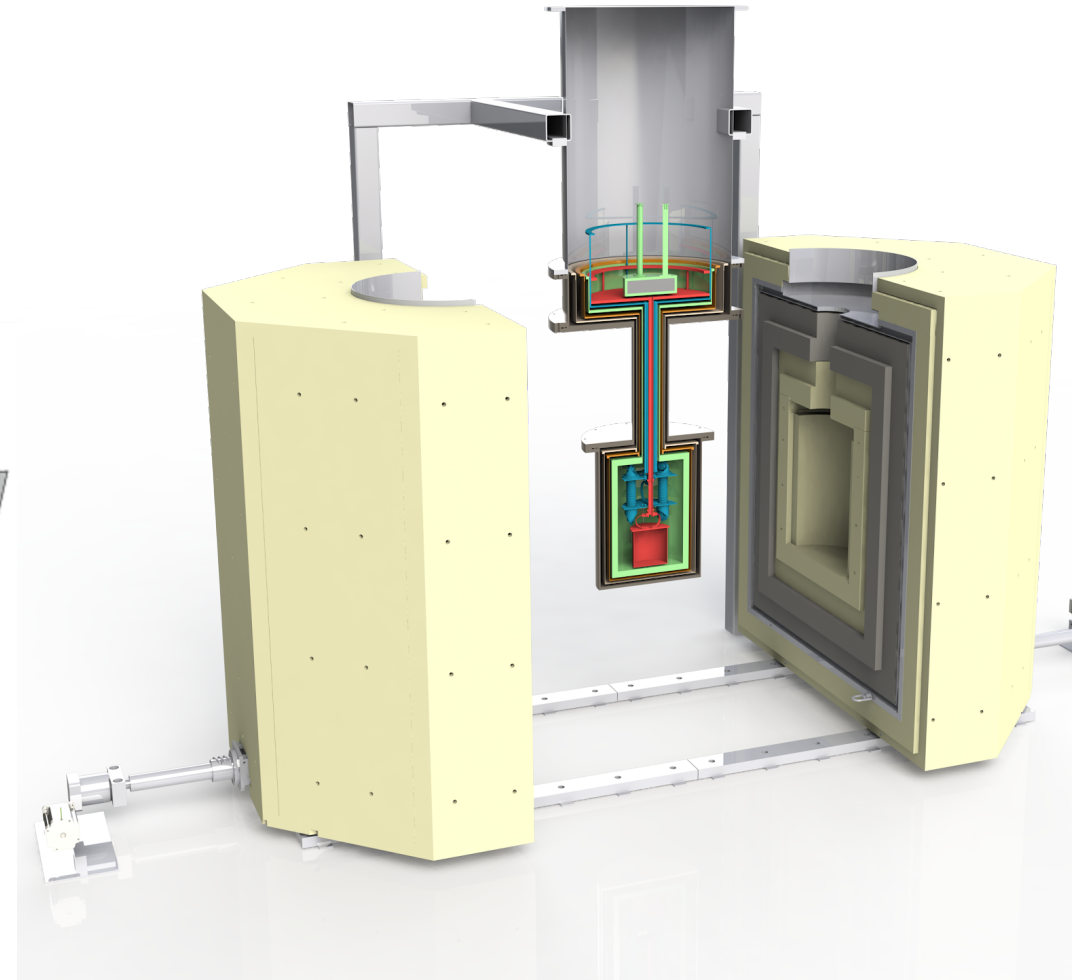
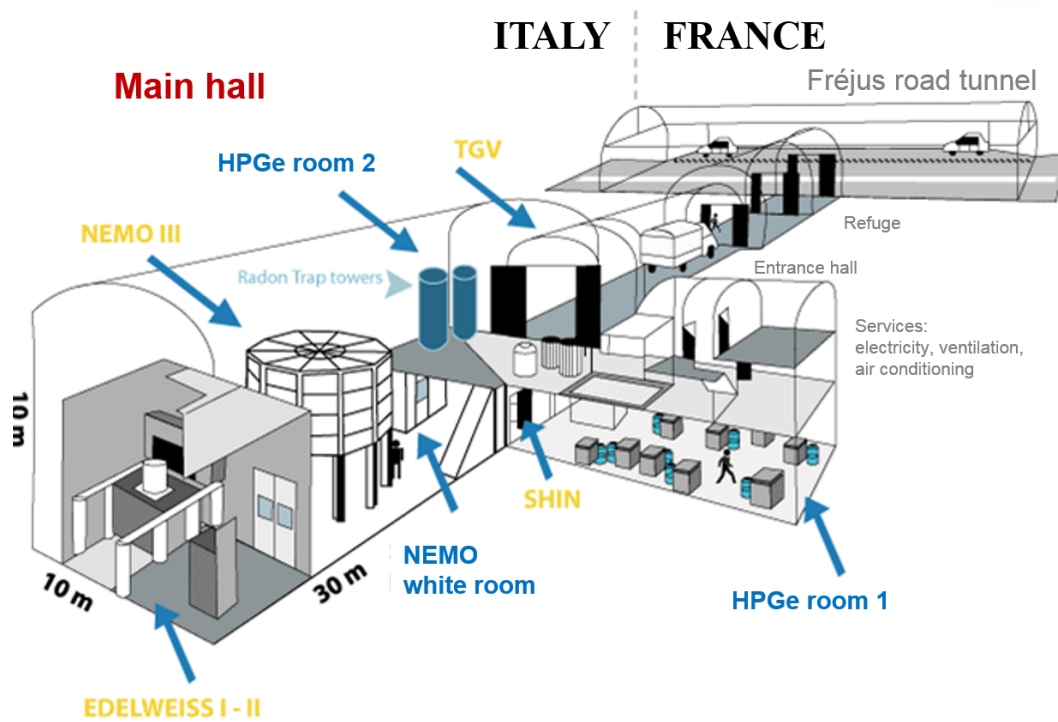
Canfranc (Spain)

Modane (Italy)

Belgium, Luxembourg and Germany gets nuclear reactors

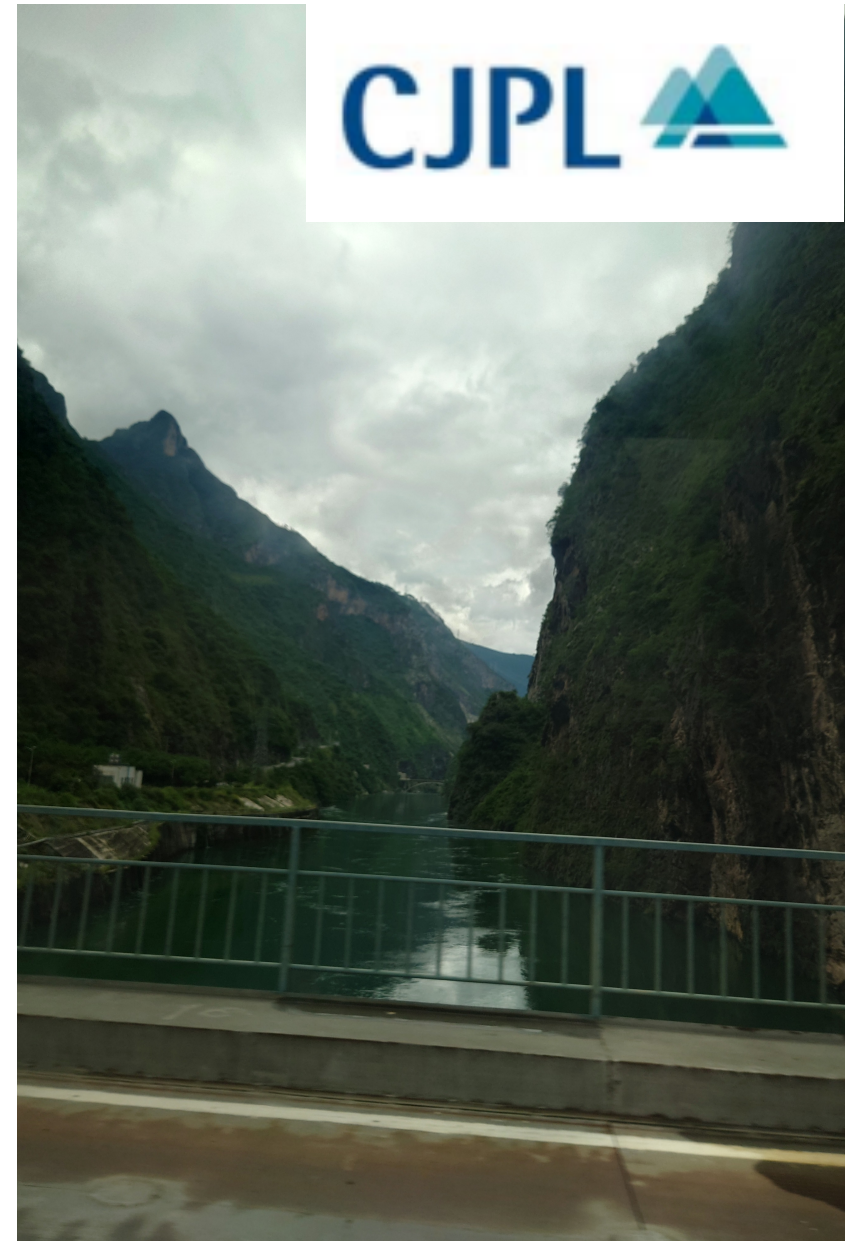


MODANE

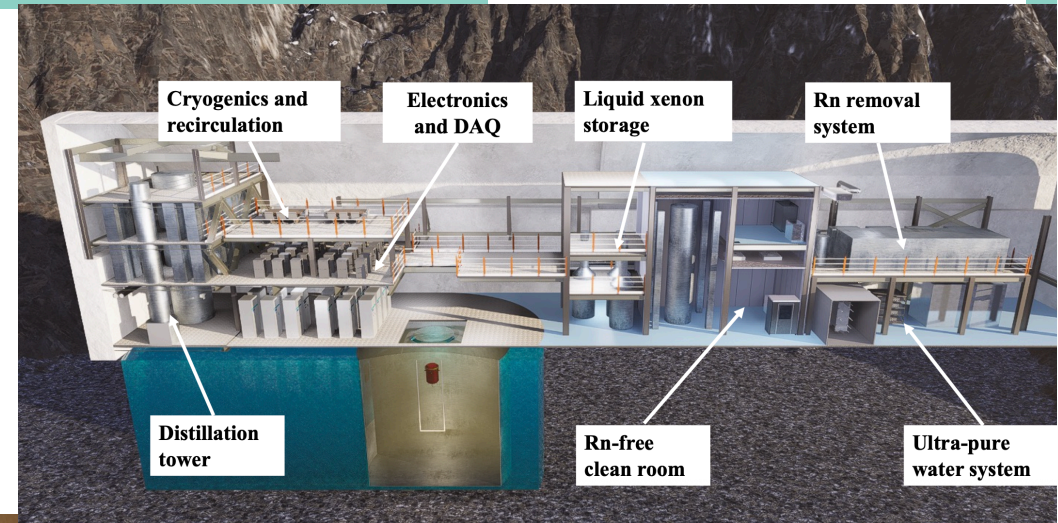


JINPING

- As part of the Yalong river hydropower complex in Sichuan, tunnels were dug through a river meander to redirect water, including access tunnels
- Deep, 2400 m of rock = 6720 meter water-equivalent
- CJPL is an expansion of these access tunnels, with four huge experimental halls 4x12x130 m



- Jinping houses PandaX, nee 4T, now starting construction on 20 tonne
- Also includes CDEX— a large germanium dark matter experiment
 - Underground Ge crystal manufacturing
- Large germanium screening facilities
- Quantum computing
- Biophysics



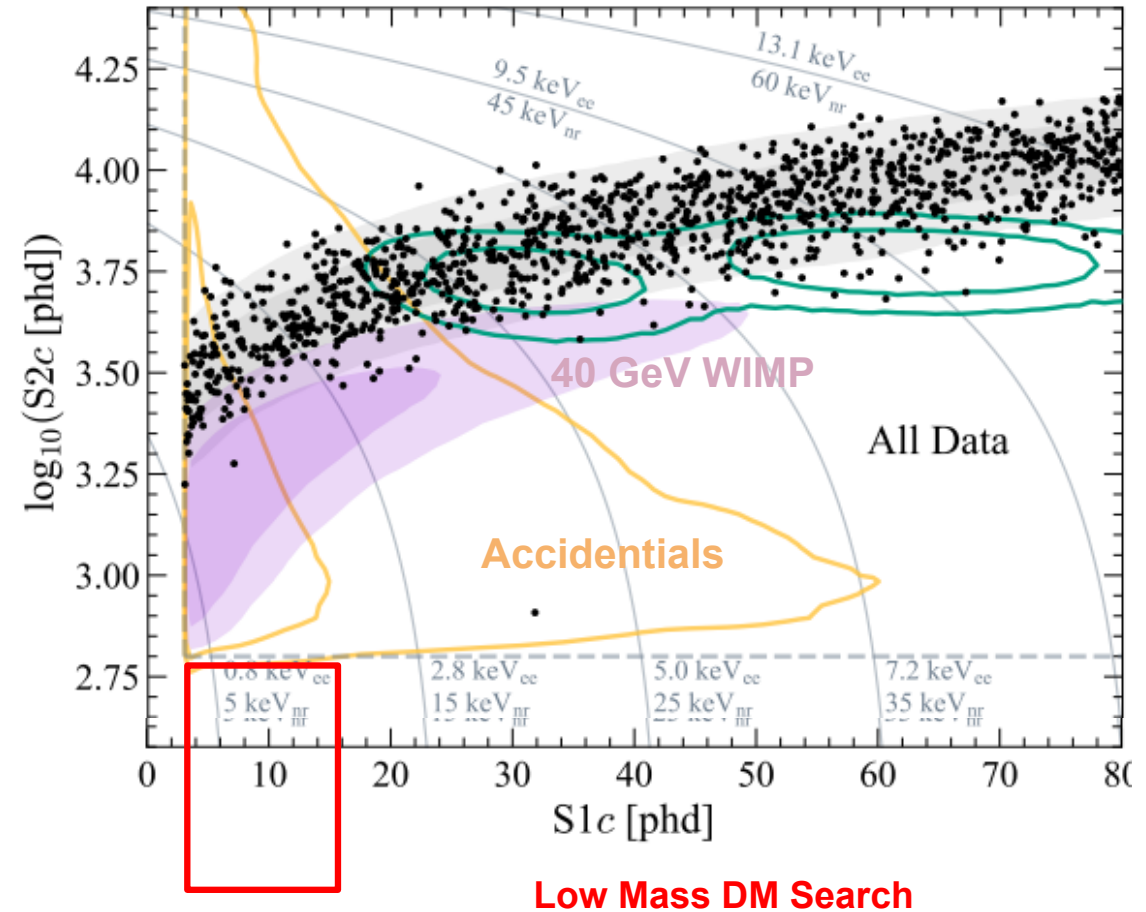
WORKING IN LABS

- **Limited number of labs, most rather occupied**
- **Not only having a lab matters, but infrastructure, accessibility, access, safety matters as well**
- **Examples:**
 - **Is the lab dedicated to science or is it an operational mine?**
 - **Often even available space is constrained by underground access, personpower & safety**
 - **Vertical access and remote locations create huge operation overhead**
- **Increasing need for underground R&D for future large scale experiments!**

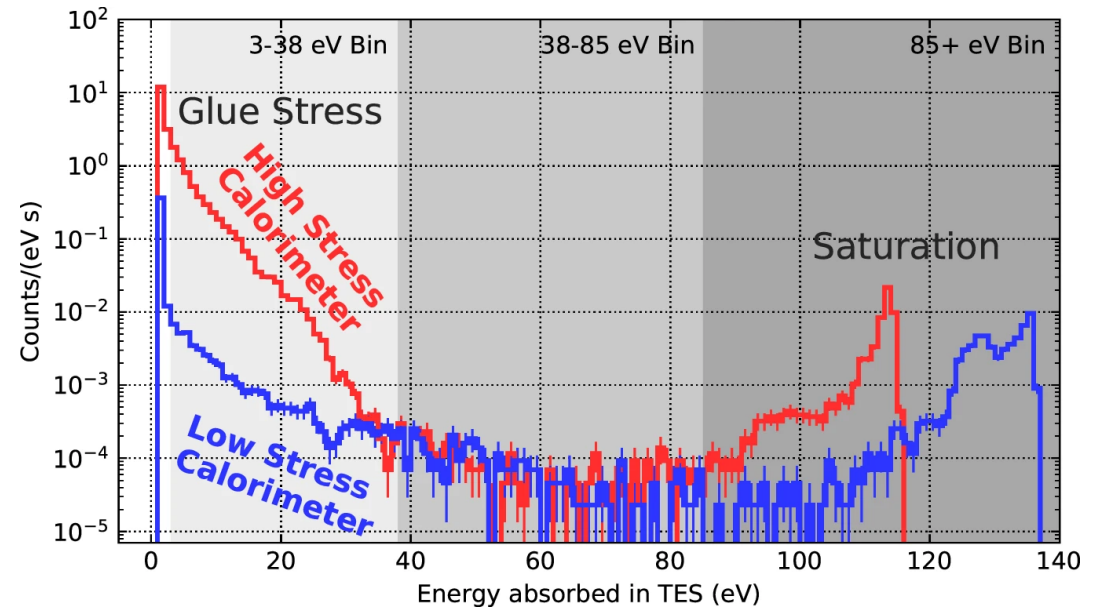
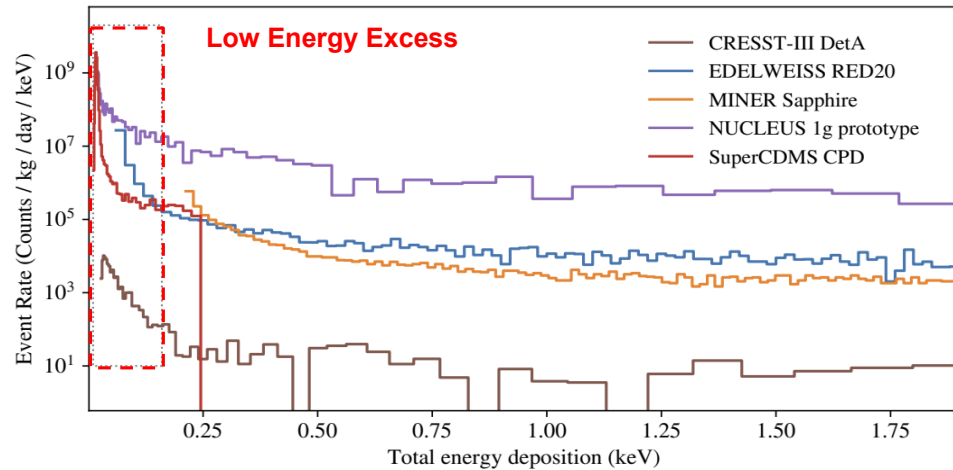


SCIENCE CASE FOR UNDERGROUND LABS

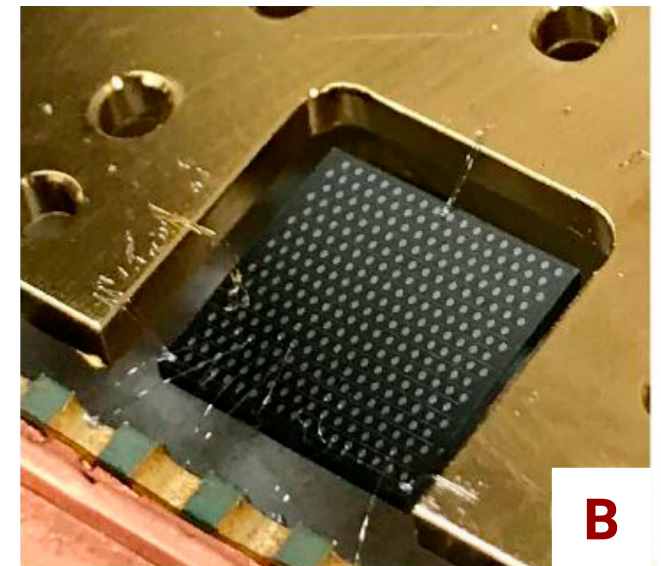
- Low energy signals are very challenging:
Single quantum signals
- Accidentals: dominant background
- S1s and S2s mostly from a large variety of instrumental effects, e.g.
 - PMT dark counts
 - Charge loss near walls
 - Grid emissions
 - Photon/electron ‘trains’ after large energy deposits
- Can only be understood and improved upon underground!— not just the actually science search but the R&D needed to develop and understand detectors



SCIENCE CASE FOR UNDERGROUND LABS

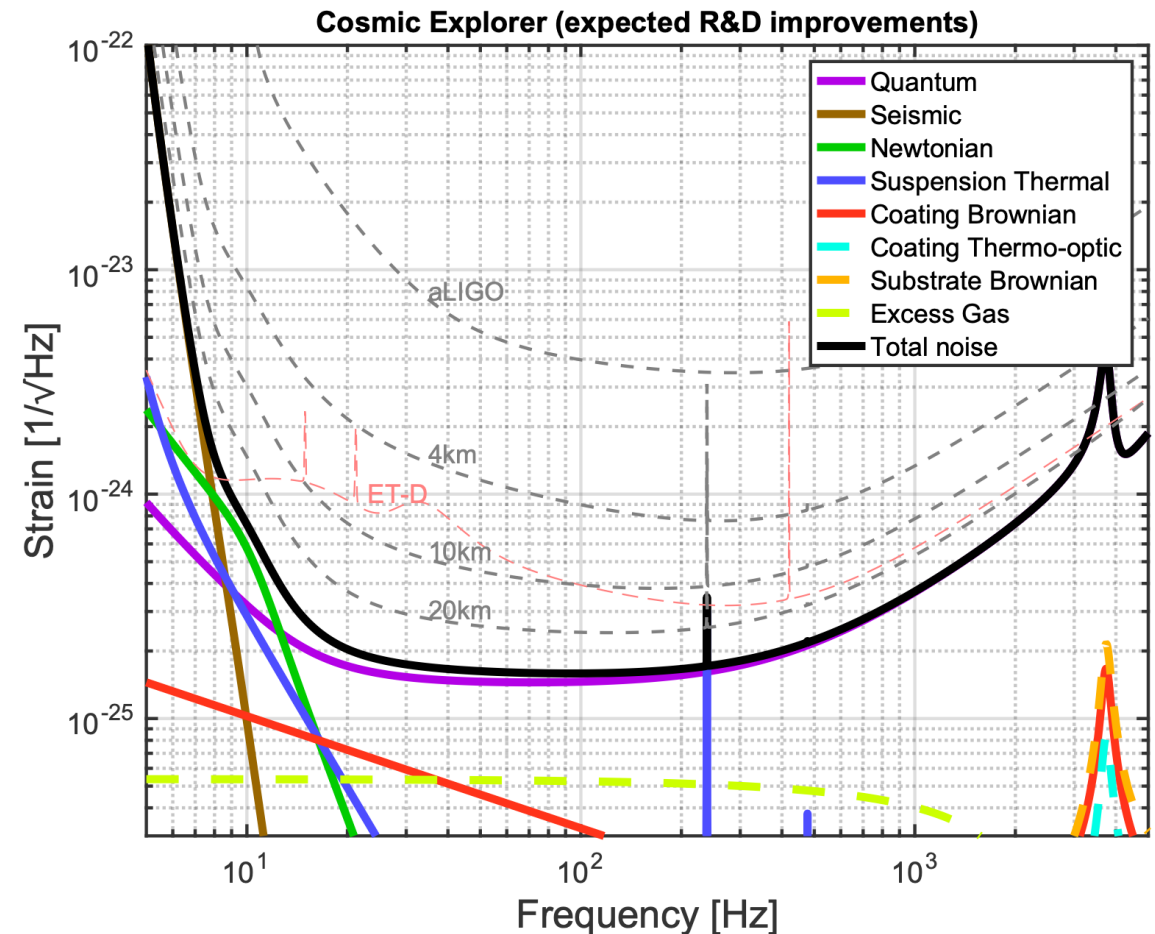
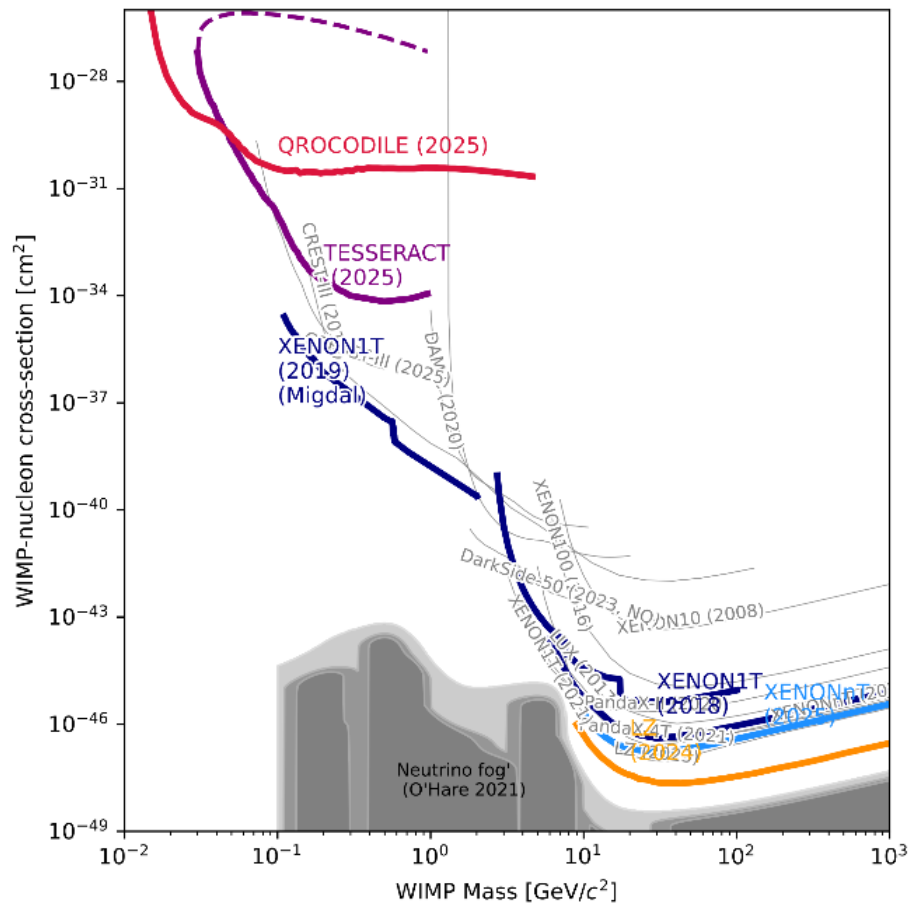


- Low energy excess backgrounds (LEE) at O(eV) in many experiments, varying by material and detector
- Origin is likely vibrations, but also probably some other components



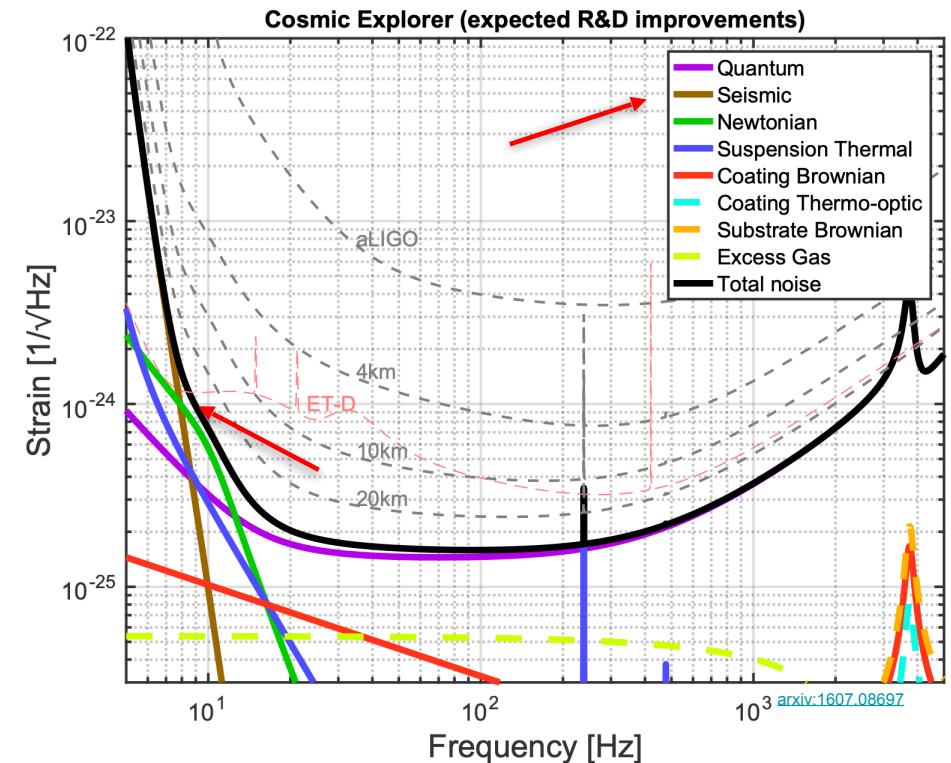
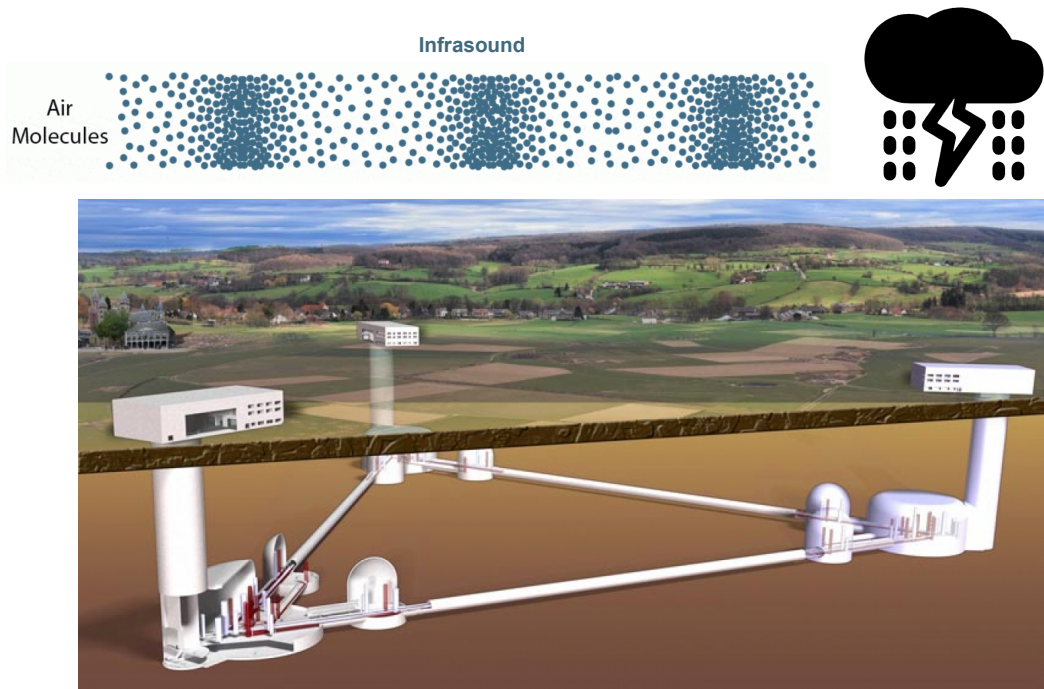
B

SCIENCE CASE FOR UNDERGROUND LABS



- There's some analogy here between two different fields exploring the precision frontier
- Require most quiet environment to start understanding novel processes ('table top experiments') and to prepare for large experiments

GRAVITY GRADIENT DETECTOR



- Gravitational coupling is an unshielded environmental noise
- Underground has less activity and thus reduces gravity gradient noise (GGN)
- GGN is a major noise source for laser interferometry at low frequencies
 - Will be limiting noise source for next generation GW detectors.

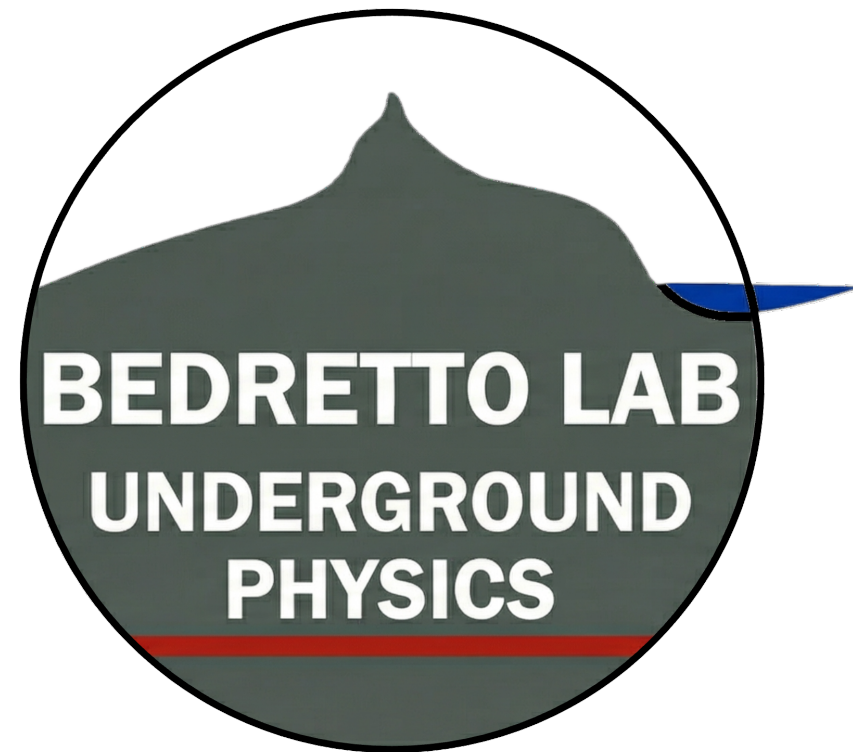
**ASK MARCELLE ABOUT
THIS NEXT WEEK!**

BEDRETTO— STARTING A NEW LAB



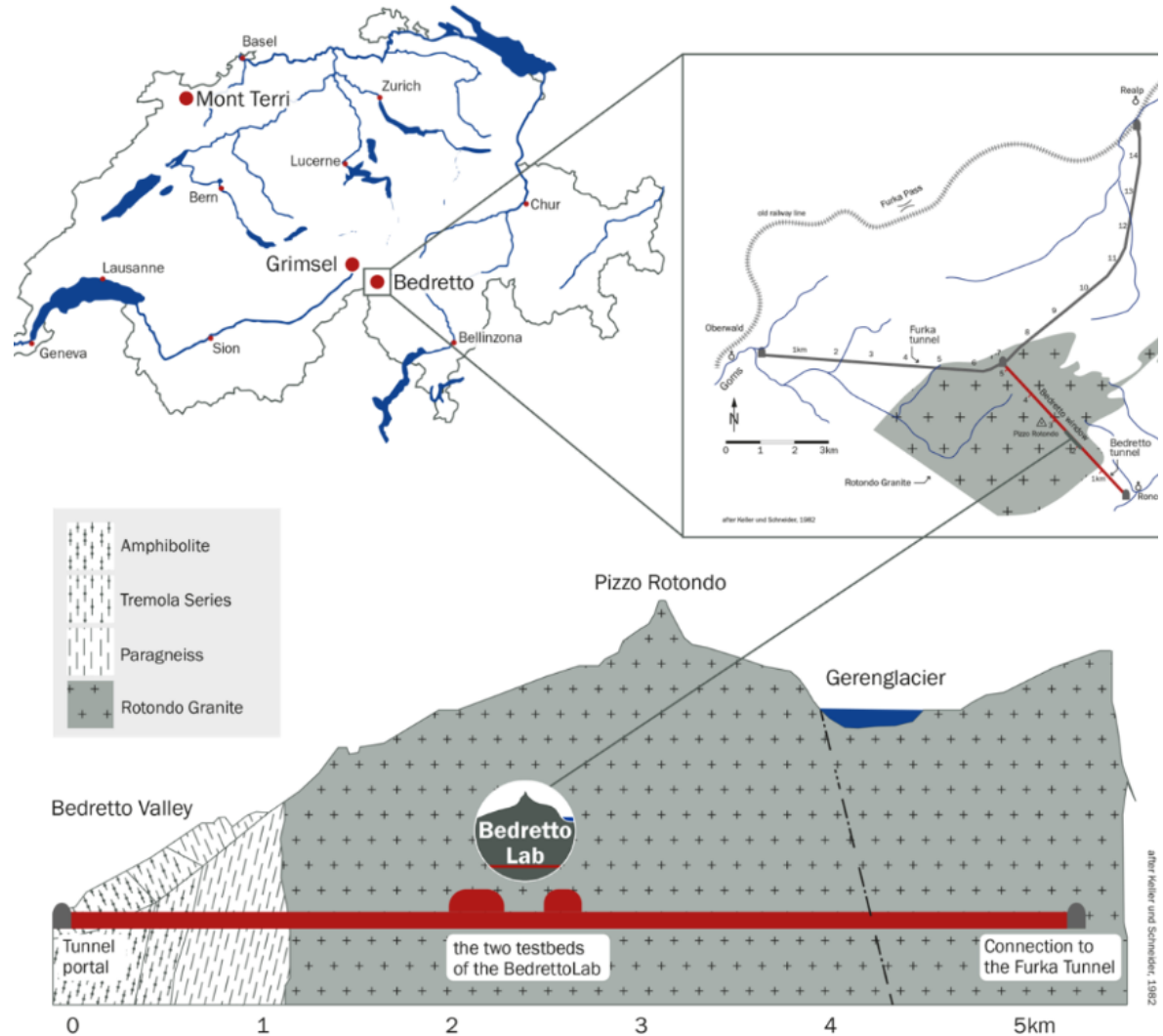
BEDRETTO LAB

- **Bedretto Underground Laboratory for Fundamental Physics Lab, or Bedretto Lab Physics (BLP), is a planned research infrastructure in Switzerland.**
- **It will be one the deepest labs in the world, most-vibration free & custom built, reachable by public transport right here!**
- **BLP's scientific program includes dark matter searches, neutrino physics, and R&D for future gravitational-wave detectors and quantum sensing**
- **Jointly proposed by:**
 - **UHZ: Penning, Baudis, Soares-Snatos**
 - **UniGe: Sanchez, Schramm**
 - **UniBe: Weber, Tuflani**
 - **ETHZ: Crivelli, Wiemer**



BEDRETTO LAB

- 5.2 km long, connecting the Furka train tunnel to the Bedretto valley 1'000 - 1'600 m overburden
- Three large caverns, 6 m wide and 50-100 m long
- Seismically very quiet
- Remote area but excellent accessibility
- Two tunnel exits → safety!
- Very good cooperation with the Matterhorn-Gotthard-Bahn



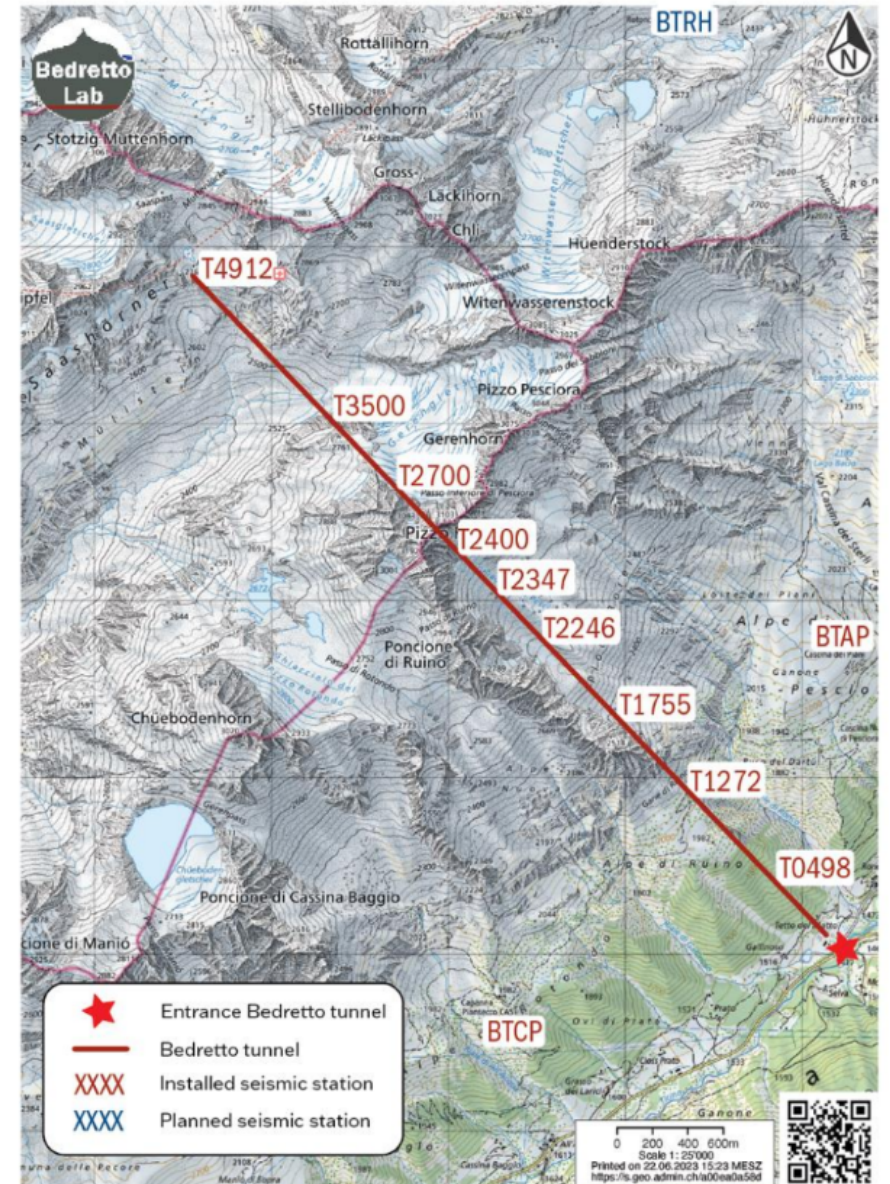
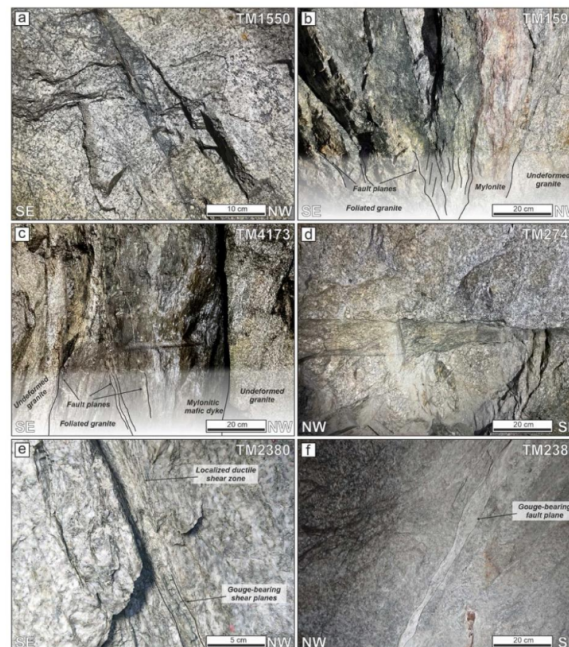
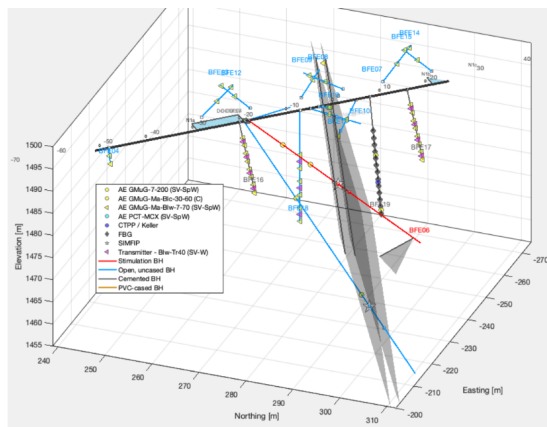
BEDRETTO LAB

- **1973:** Built as a side tunnel of the Furka base tunnel, as a possible train connection between Ticino and Valais
- **1983:** Abandoned after completion of the Furka railroad, partly blocked by rockfall
- **2000:** First mapping and research
- **2012:** Partial reconditioning for Furka ventilation, enabling access to the full tunnel
- **2018:** The tunnel is selected by ETH to host the BedrettoLab, scaling up experiments from Grimsel,
- **May 2019:** Inauguration of the BedrettoLab
- **2020:** Experiments in Geothermal energies started
- **2024:** Experiments in Earthquake Physics started
- **2025:** Experiments in Astroparticle Physics started



BEDRETTO LAB

- Lots of existing activities:
- Interdisciplinary Rock characterization
- Earthquake measurements/research
- FEAR - Fault Activation & Earthquake Rupture
- Seismic real time monitoring
- Deep Life Monitoring



BEDRETTO LAB



BEDRETTO LAB



BEDRETTO LAB



BEDRETTO LAB



- Comparably fast and easy excavations

BACKGROUND MEASUREMENTS



- Performed a comprehensive set of background measurements

BACKGROUND MEASUREMENTS

- We measured **all relevant backgrounds**:
 - Muons, gamma, radon, EMI, vibrations
- Summarized in a **paper** that we recently submitted
 - <https://arxiv.org/abs/2512.14815>
- The **existing seismic instrumentation** and understanding is actually supporting our measurements
 - Seismic vetoes, add Rn monitoring etc

arXiv:2512.14815v2 [astro-ph.IM] 18 Dec 2025

Characterisation of the Bedretto Underground Site for Fundamental Physics Experiments

Björn Penning^{a,1}, Nicolas Angelides¹, Laura Baudis¹, Harvey Birch¹, Abigail Flowers¹, Florian Jörg^{b,1}, Alexander Kavner^{c,1}, Marcelle Soares-Santos¹, Aravind Remesan Sreekala¹, Johannes Wüthrich¹, Guandi Zhao^{1,3}, Chiara Capelli¹, John Clinton⁶, Jose Cuenca García¹, Paolo Crivelli³, Domenico Giardini², Evangelos-Leonidas Gkougkousis¹, Yacine Haddad⁵, Marian Hertrich², Rebecca Hochreutener², Luisa Höttsch¹, Philippe Jetzer¹, Ben Kilminster¹, Boris Korzh⁴, Frédéric Massin⁶, Knut Dundas Morá¹, Margherita Noia¹, Francesco Piastra¹, Christian Regenfus³, Federico Sanchez⁴, Steven Schramm⁴, Francesco Riva⁴, Serhan Tufanli⁵, Michele Weber⁵, Stefan Wiemer², Mathilde Wimez²

¹Physik-Institut, University of Zürich, Winterthurerstrasse 190, Zürich, 8057, Switzerland

²Bedretto Underground Laboratory, ETH Zürich, Sonneggstrasse 5, Zürich, 8092, Switzerland

³Département Physik, ETH Zürich, Otto-Stern-Weg 1, Zürich, 8093, Switzerland

⁴Département de Physique Nucléaire et Corpusculaire, University of Geneva, 24, quai Ernest-Ansermet, Geneva, 1205, Switzerland

⁵Physikalisches Institut, University of Bern, Sidlerstr. 5, Bern, 3012, Switzerland

⁶Swiss Seismological Service (SED), ETH Zürich, Sonneggstrasse 5, Zürich, 8092, Switzerland

the date of receipt and acceptance should be inserted later

Abstract Underground laboratories provide the ultra-low background and low-vibration environments essential for rare-event searches, gravitational-wave detection, and quantum-sensing technologies. We report a comprehensive environmental characterisation of the Bedretto tunnel in Ticino, Switzerland, a site offering horizontal access, excellent infrastructure, and the potential to be Europe's second-deepest and quietest underground laboratory. At the prospective physics site, located beneath an overburden exceeding 1400 m, we measure the cosmic-muon, γ -ray, and neutron fluxes, as well as the radon concentration, magnetic-field spectrum, and seismic backgrounds. The muon flux is suppressed by six orders of magnitude relative to the surface, consistent with an effective depth of about 4000 metre water equivalent, gamma-ray and neutron measurements reflect the local geology and guide shielding requirements for future particle and nuclear physics experiments. Magnetic and seismic noise levels are found to be exceptionally low, meeting or exceeding the criteria for next-generation atom-interferometric gravitational-wave detectors. These results establish the site as a

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^ce-mail: alexander.kavner@physik.uzh.ch

highly competitive, accessible deep-underground location for fundamental-physics experiments.

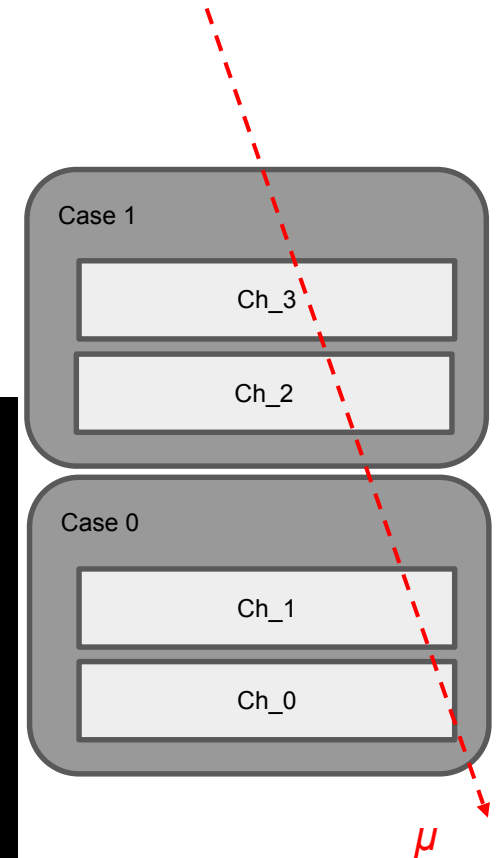
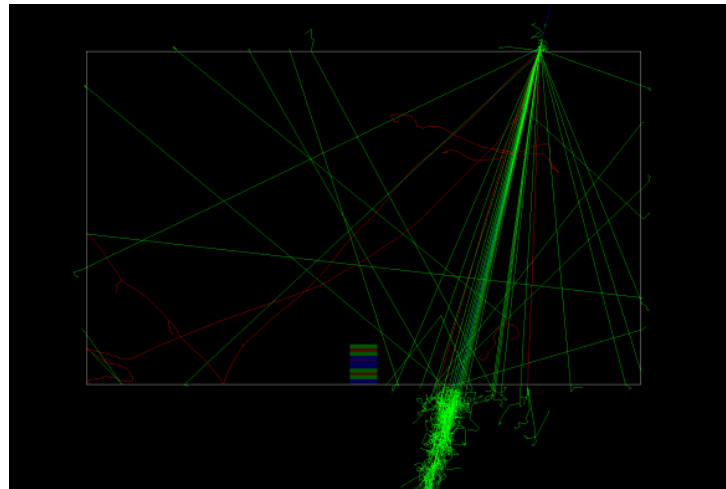
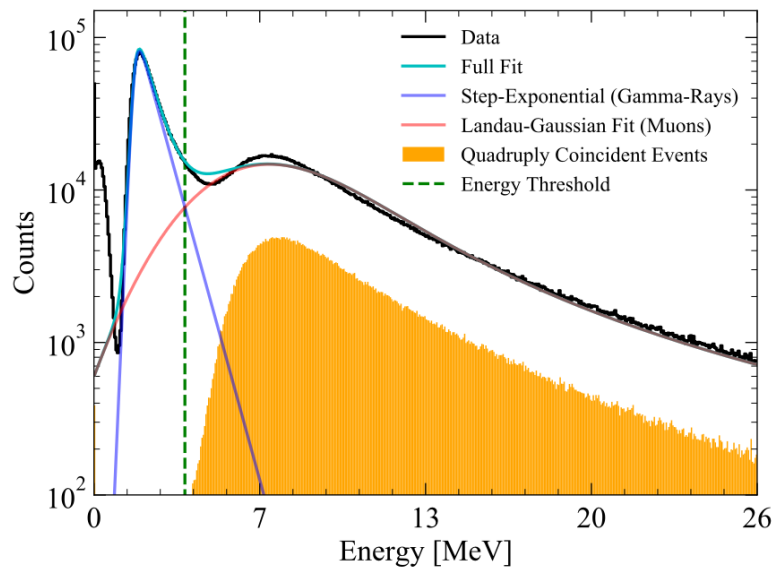
Keywords underground laboratory, gravitational waves, dark matter, rare event searches, radiopurity, radio assay, atom interferometry, neutrinoless double beta decay

1 Introduction

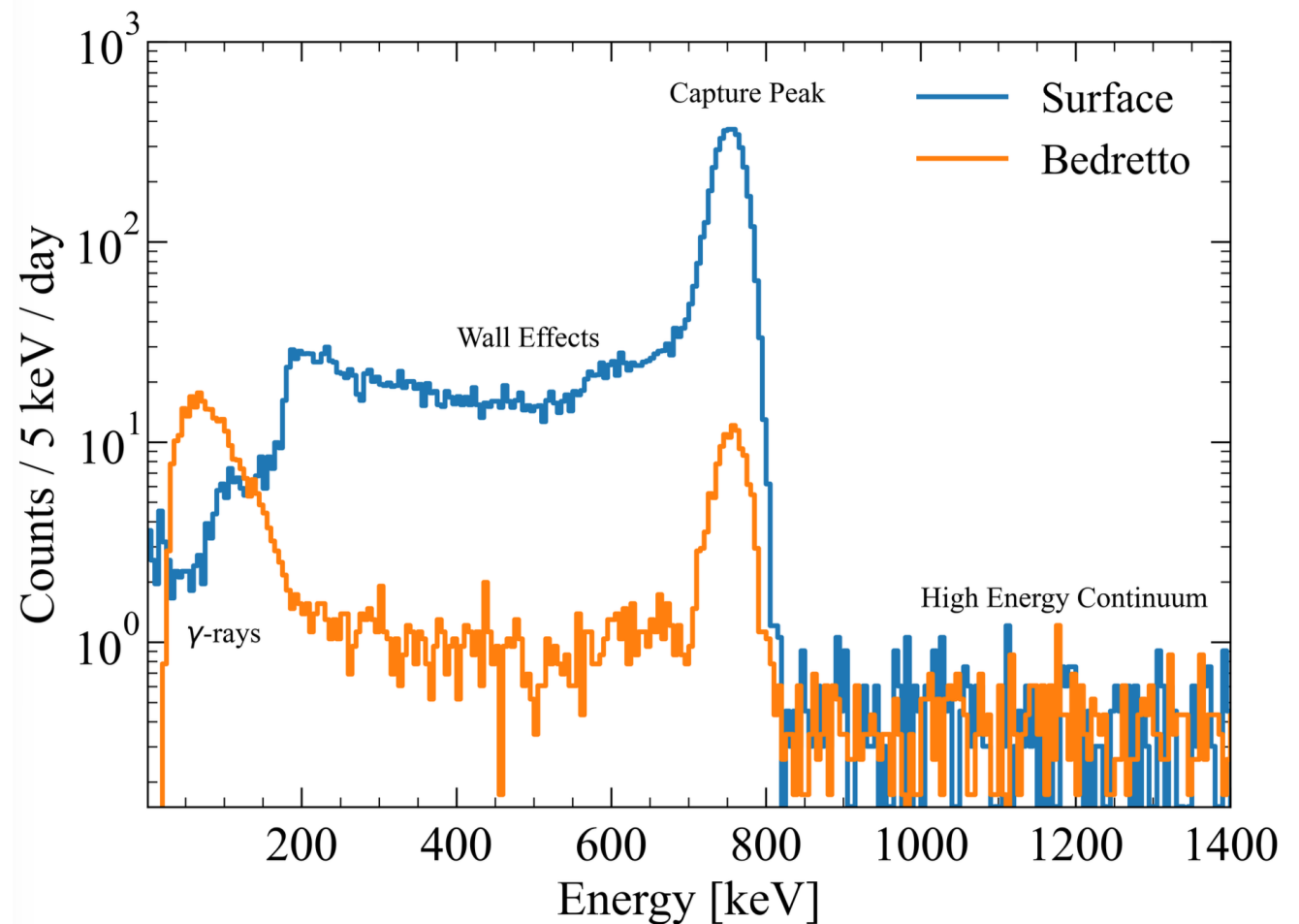
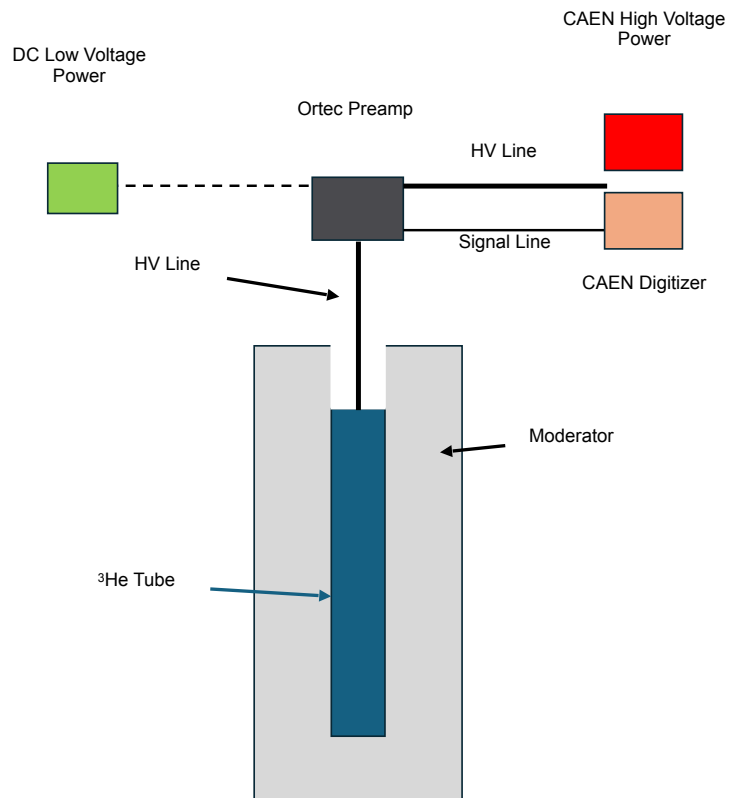
Underground laboratories provide uniquely background-free environments and are indispensable tools to understand fundamental physics processes. The massive rock overburden shields effectively even from the highest energetic cosmic rays, they are seismically very quiet since most vibrations travel at the surface and are attenuated quickly at depth, and Newtonian noise is reduced by the very large mass of rock surrounding the laboratory. Examples of underground experiments include rare-event searches such as the search for dark matter and neutrinoless double beta decay, rare-decay nuclear physics measurements, low-background material assay, environmental monitoring, and optimal sensitivity and stability of quantum sensors. Furthermore, the stable, low-background, and low-vibration environment offered by underground locations is highly beneficial for gravitational wave detection. Several major deep underground

BACKGROUND MEASUREMENTS

- Performed measurements of **muon flux** at the TM3500 location
- Measurement of $2.54 \pm 0.97 \cdot 10^{-8} \text{ mu/sec/cm}^2$ agrees well with simulations



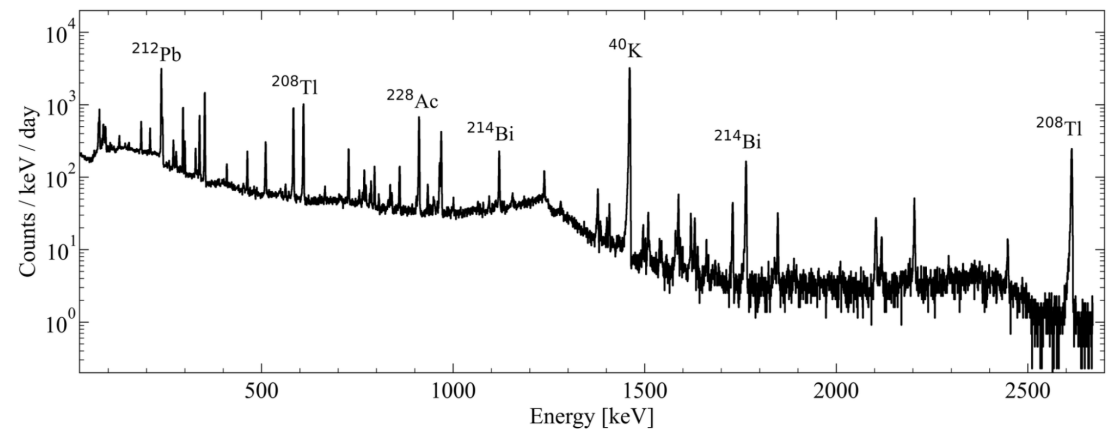
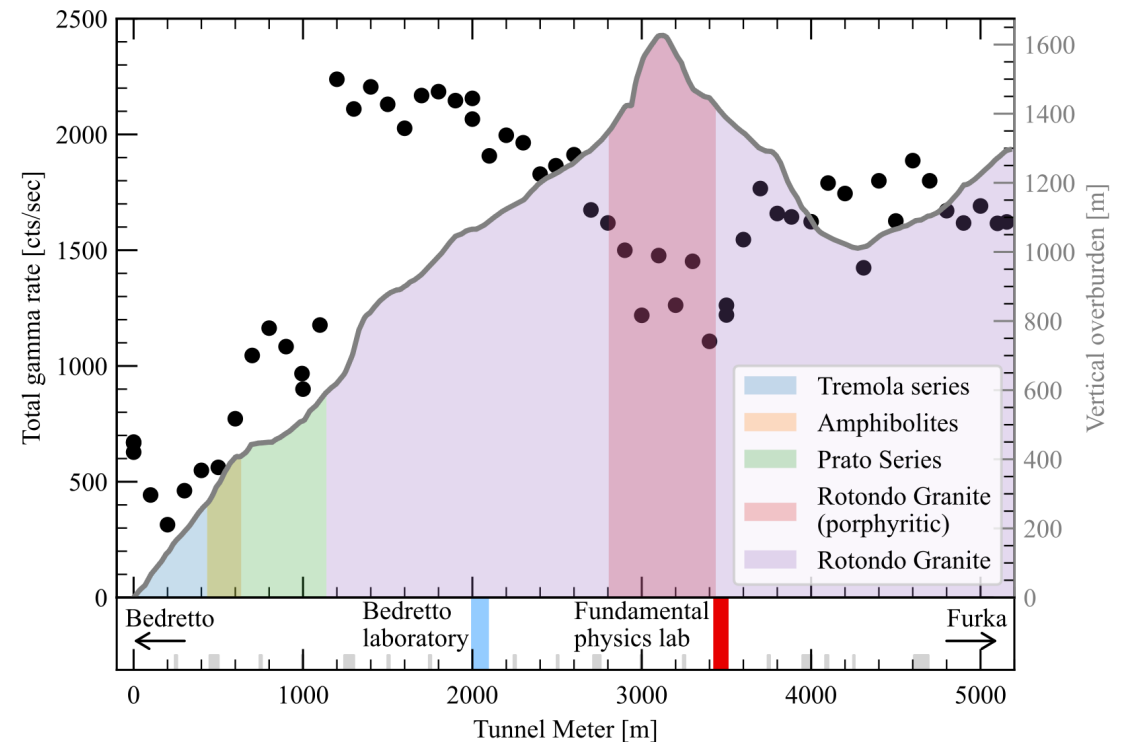
BACKGROUND MEASUREMENTS



- Fast and slow neutron flux at TM3500 of $5.6 \times 10^{-5} \pm 0.3 \text{ n/cm}^2/\text{s}$
- Measured w and w/o moderator and comparing to simulations

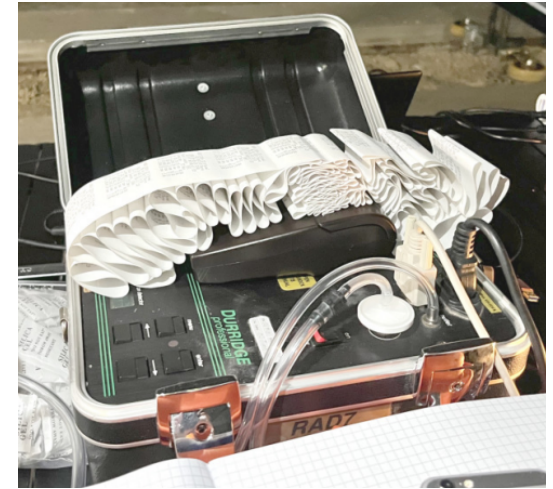
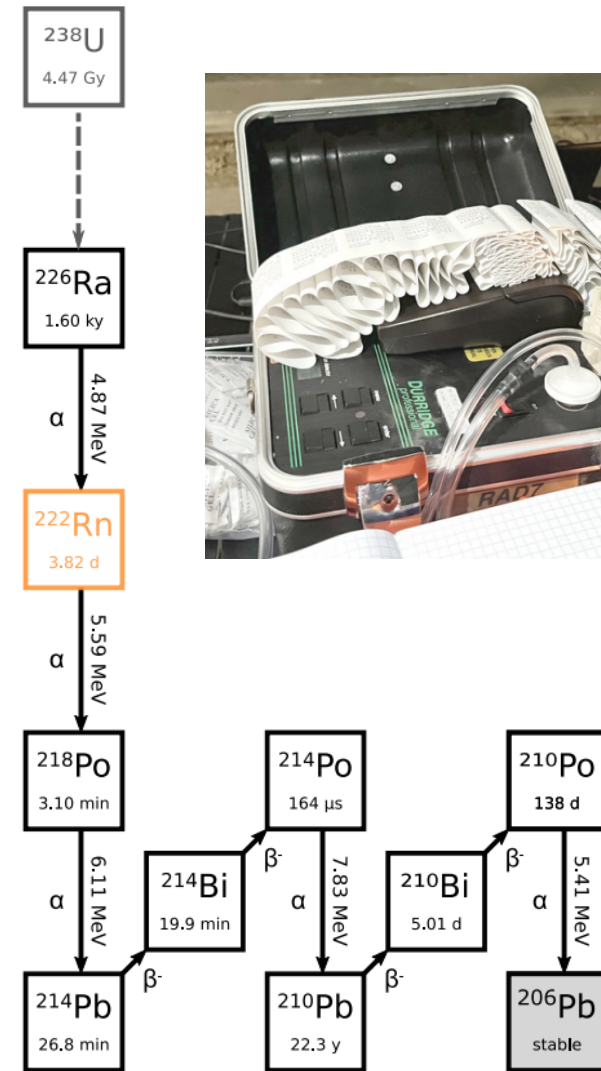
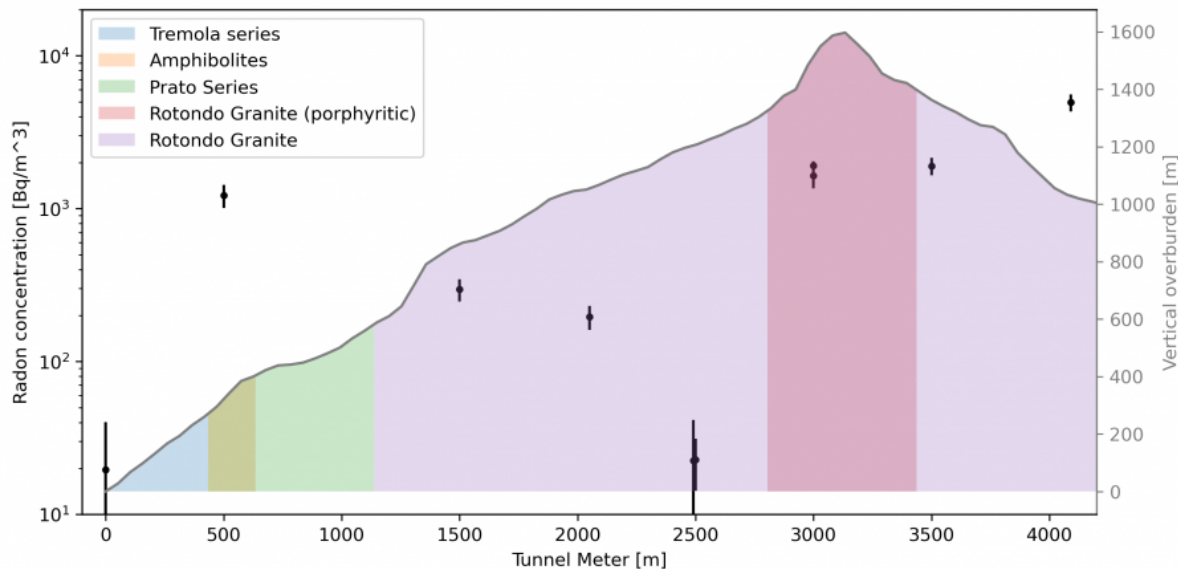
BACKGROUND MEASUREMENTS

- Measured gamma activity along Bedretto tunnel, at TM3500 and for rock using different detectors
- Intended lab location is actually very serendipitous



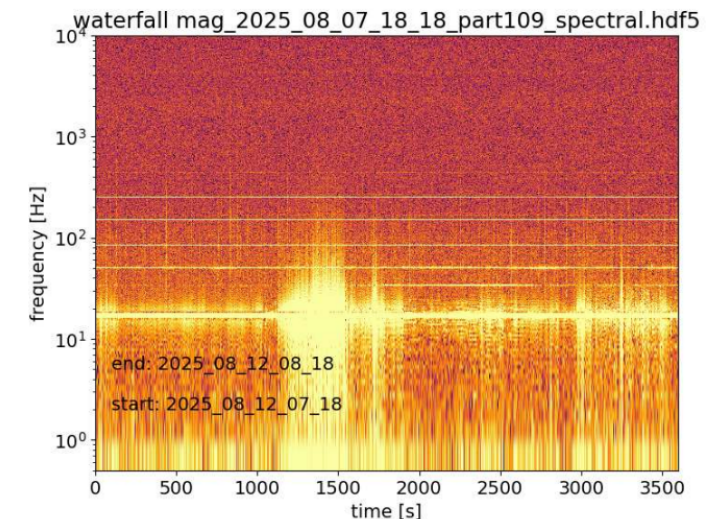
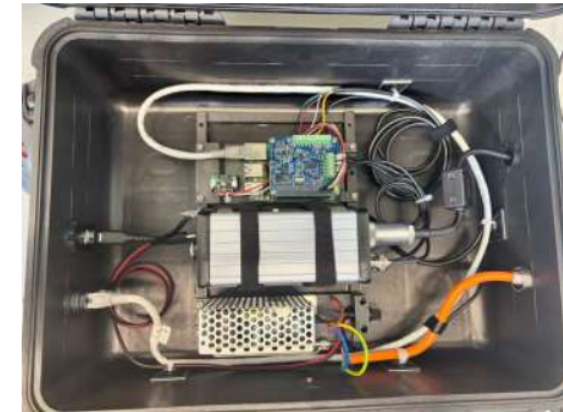
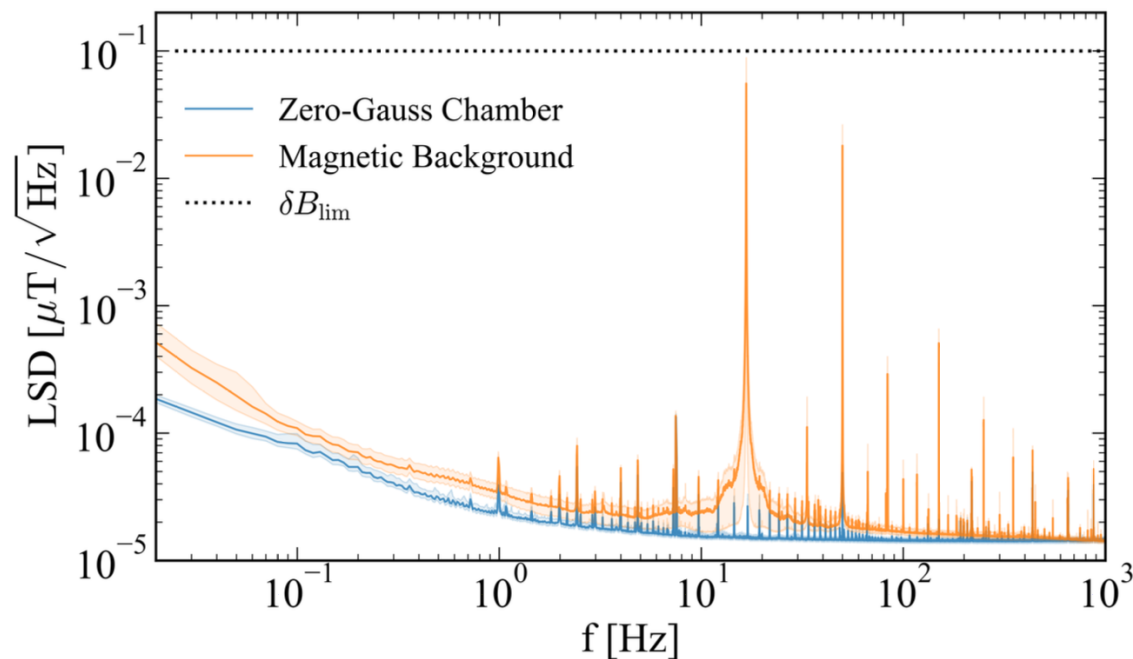
BACKGROUND MEASUREMENTS

- Radon Measurement align tunnel, blasting & outside
- Radon high, interesting dynamics during blasting
- Outside air is very clean, can be simply used to purge our labs
- Study of seasonal variation of radon concentration is ongoing



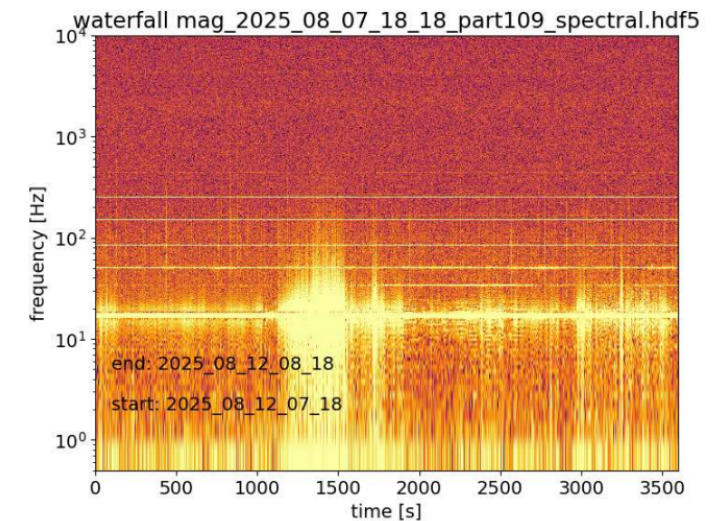
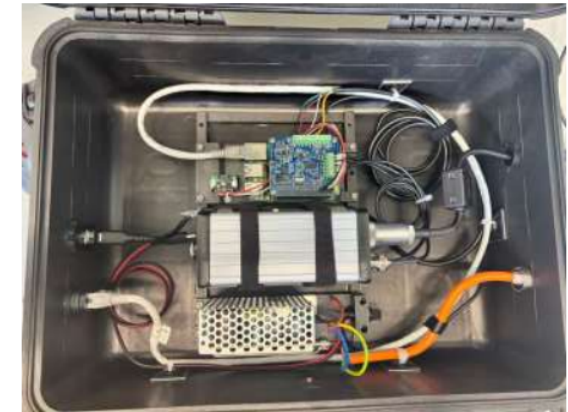
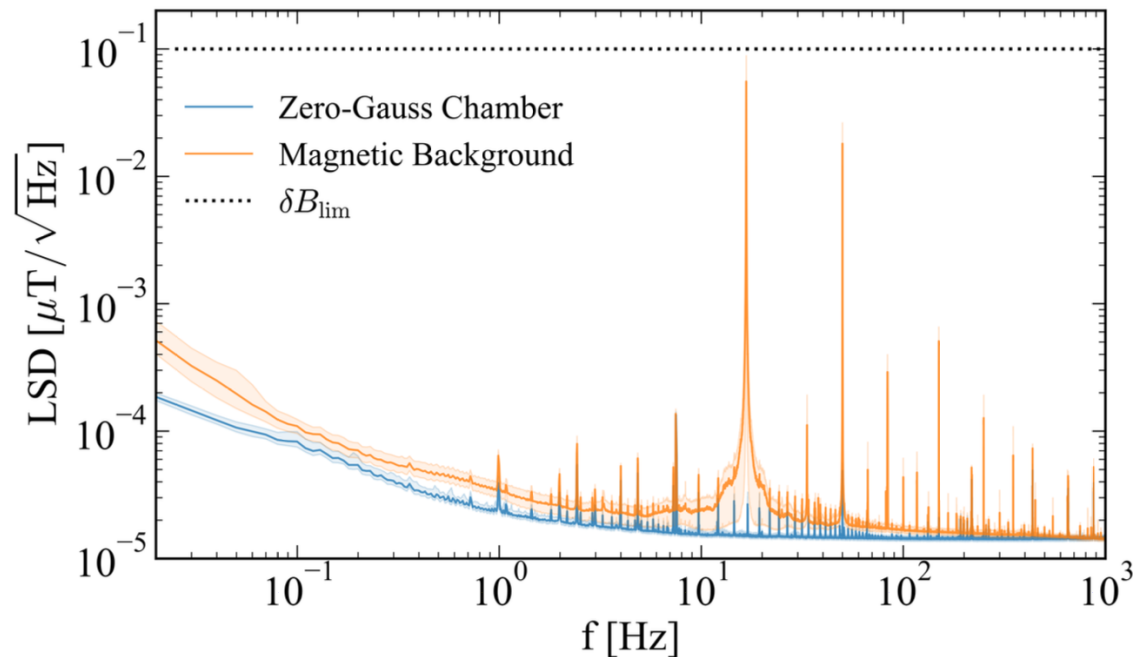
BACKGROUND MEASUREMENTS

- Measured magnetic power spectra with clear peaks identifiable
- Can identify components from human interactions, train power line and AC power line in Bedretto
- Day/night difference & 16.7 Hz peaks/waterfall plot correspond to [REDACTED]

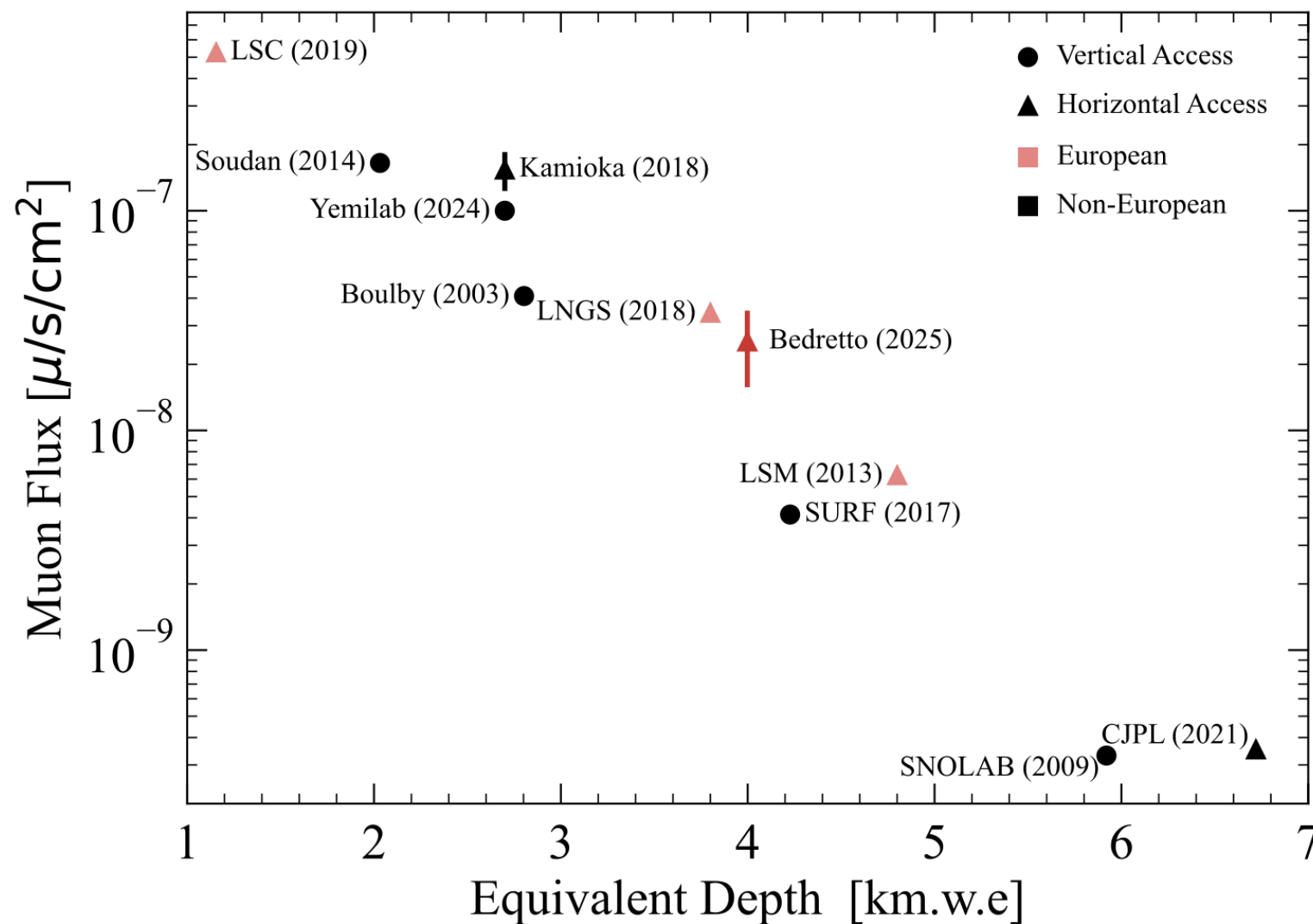


BACKGROUND MEASUREMENTS

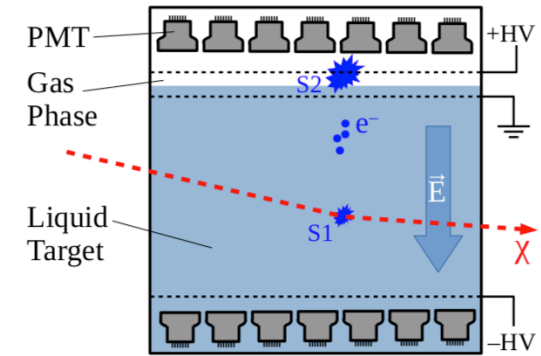
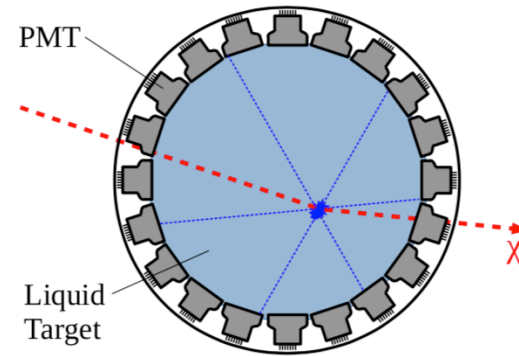
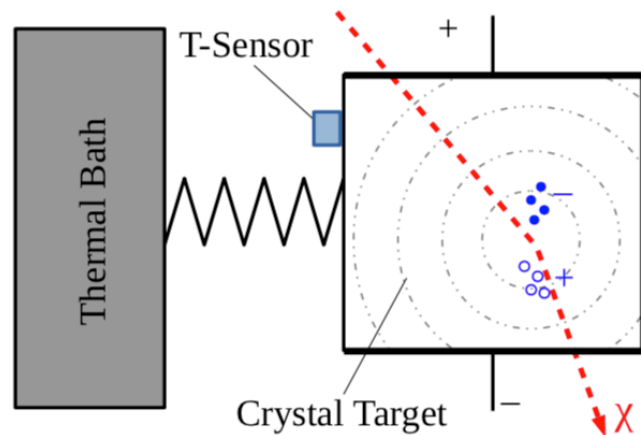
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- Can identify components from human interactions, train power line and AC power line in Bedretto
- Day/night difference & 16.7 Hz peaks/waterfall plot correspond to train schedule



- **BedrettoLab will be one of the deepest and most quiet fundamental physics underground labs**

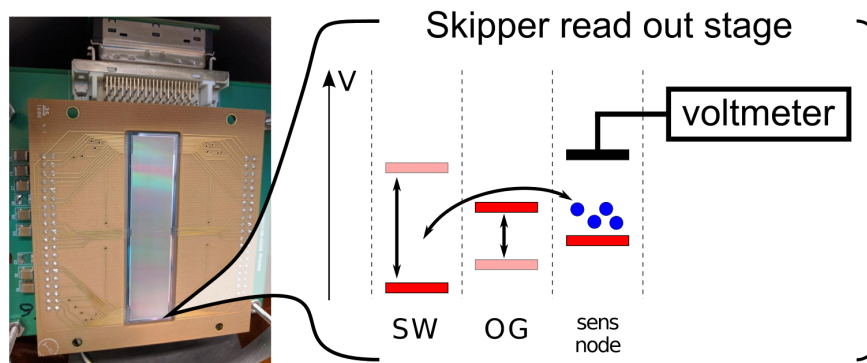


MANY DETECTOR TECHNOLOGIES ARE MOTIVATED BY A DESIRE TO COMPLEMENT XENON DETECTORS

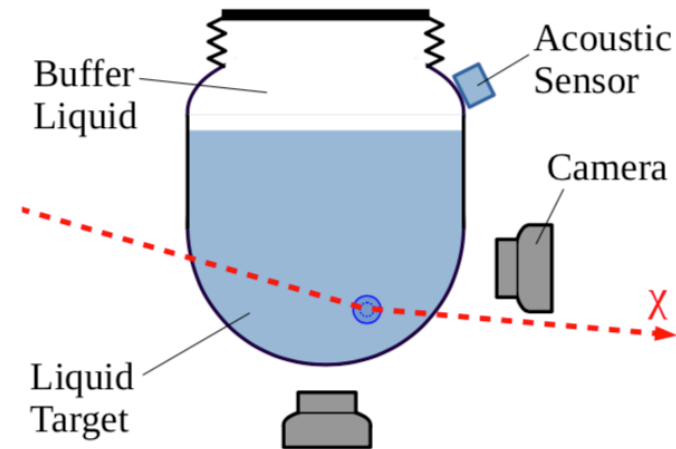


LIQUID NOBLE GAS 1- AND 2-PHASE TPCS

CRYOGENIC DETECTOR: HEAT & IONISATION



CCD READ OUT REPEATEDLY PER-PIXEL

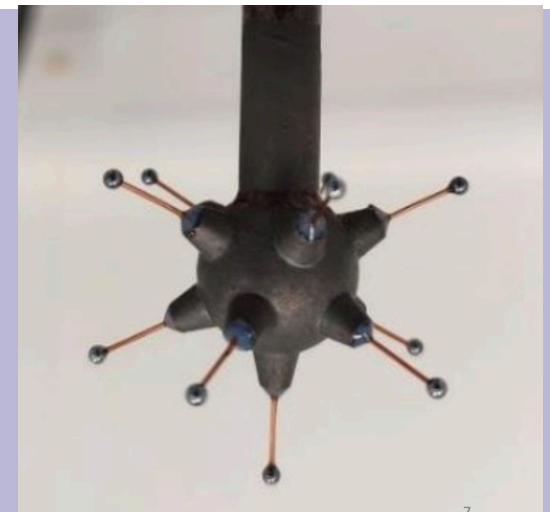
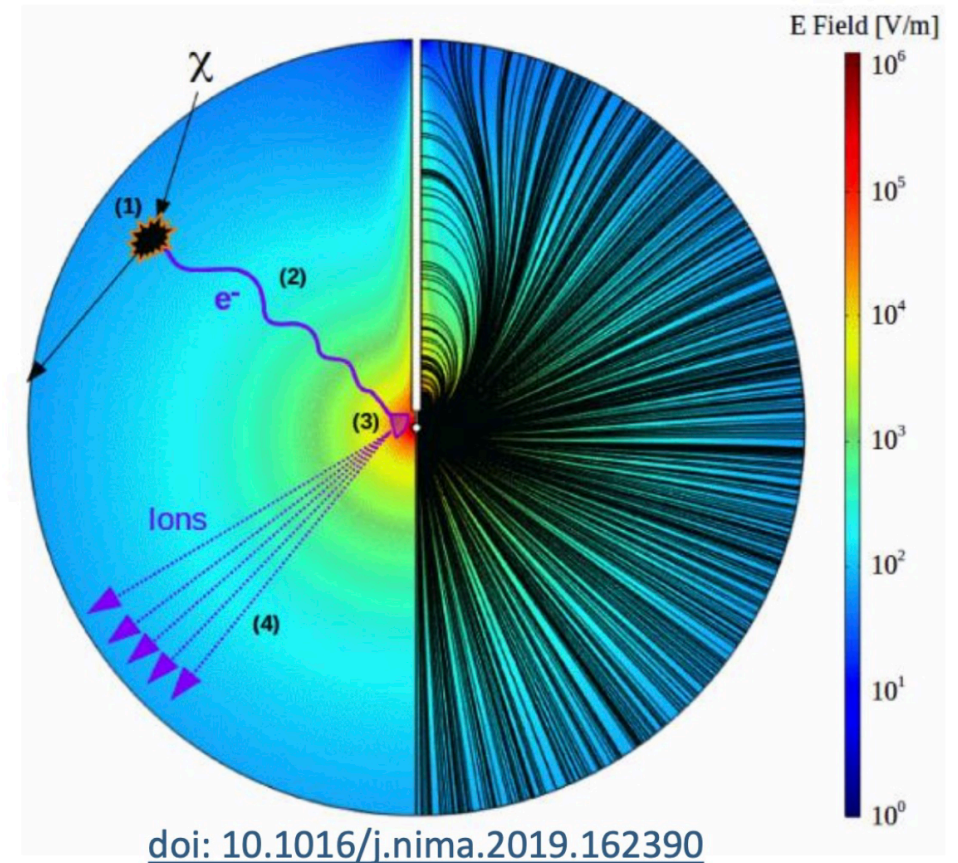


BUBBLE CHAMBER

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>

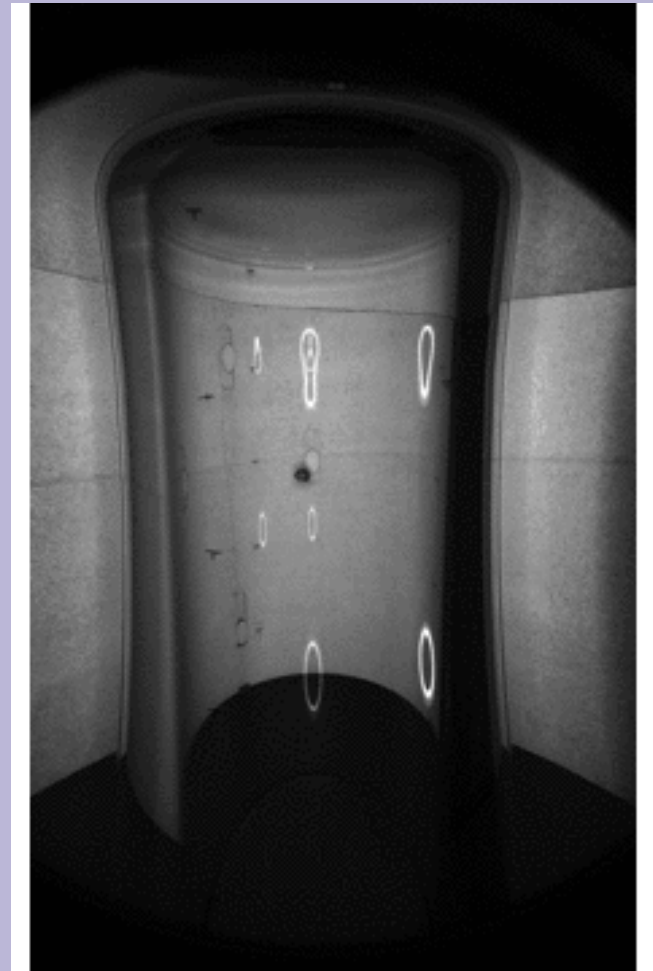
SINGLE-PHASE

- NEWS-G uses a spherical volume filled with a target gas (H, He, Ne) and a very strong electric field to read out events
- The very strong field near the central sensor/electrode causes a strong amplification of the signal
- Being able to search for electron-only events makes them, in principle, better optimised for ionization-only studies than the two-phase TPCs
- Good limits on spin-dependent interactions



BUBBLE CHAMBERS

- 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
- ~ 3keV energy thresholds in science mode, lower thresholds of $1.2 \pm 0.08\text{keV}$ can be achieved if you accept some ER leakage



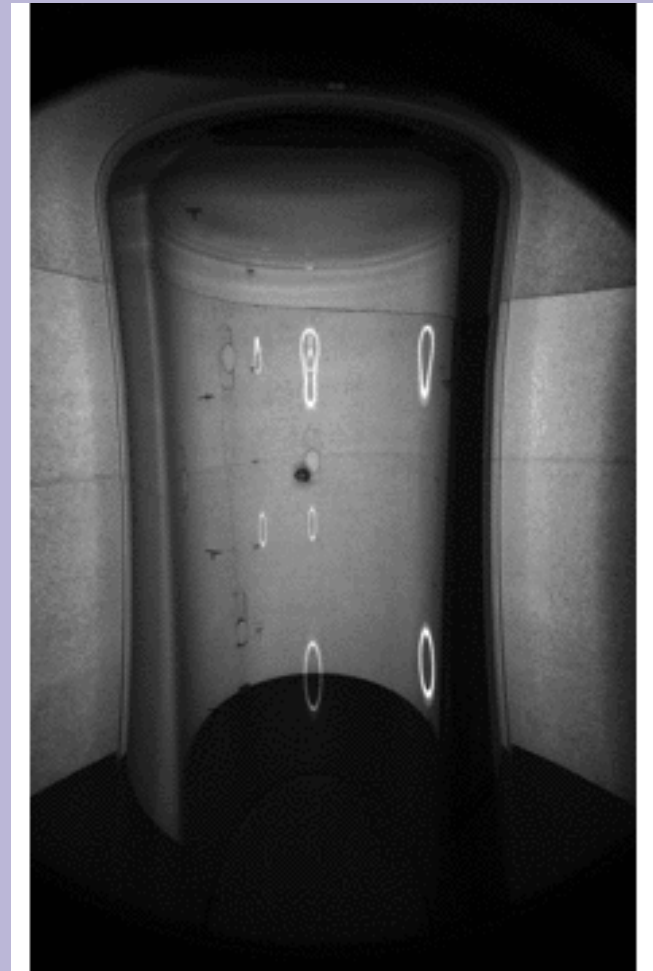
Single-bubble event captured during PICO-40L commissioning courtesy of the PICO experiment

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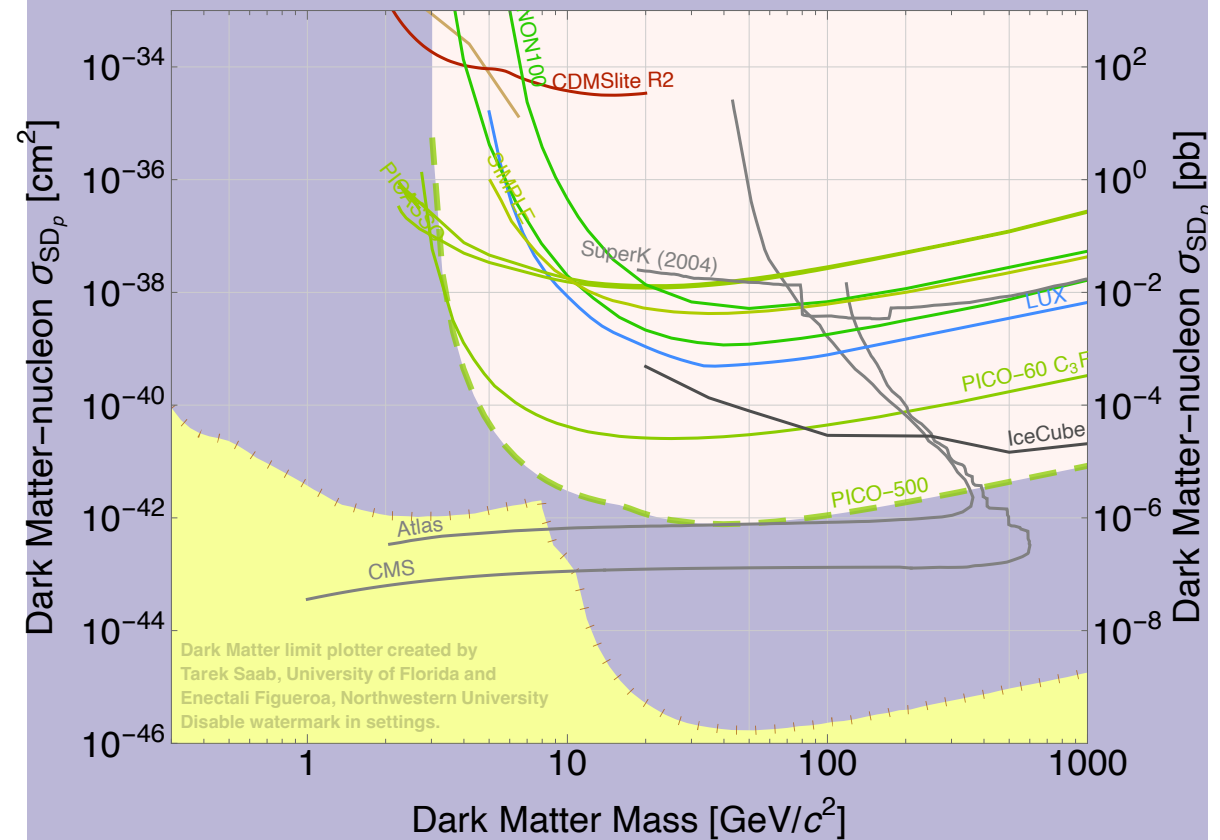
C. Amole et al. Dark Matter Search Results from the Complete Exposure of the PICO- 60 C_3F_8 Bubble Chamber. *Phys. Rev. D*, 100(2):022001, 2019. doi: 10.1103/PhysRevD.100.022001.

BUBBLE CHAMBERS

- 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

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.

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

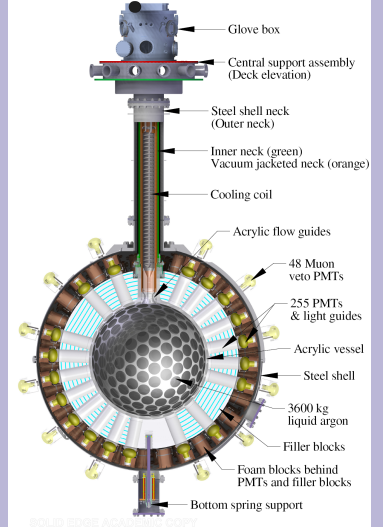


- Caution: Combining collider and direct detection bounds like this involves some model dependence.

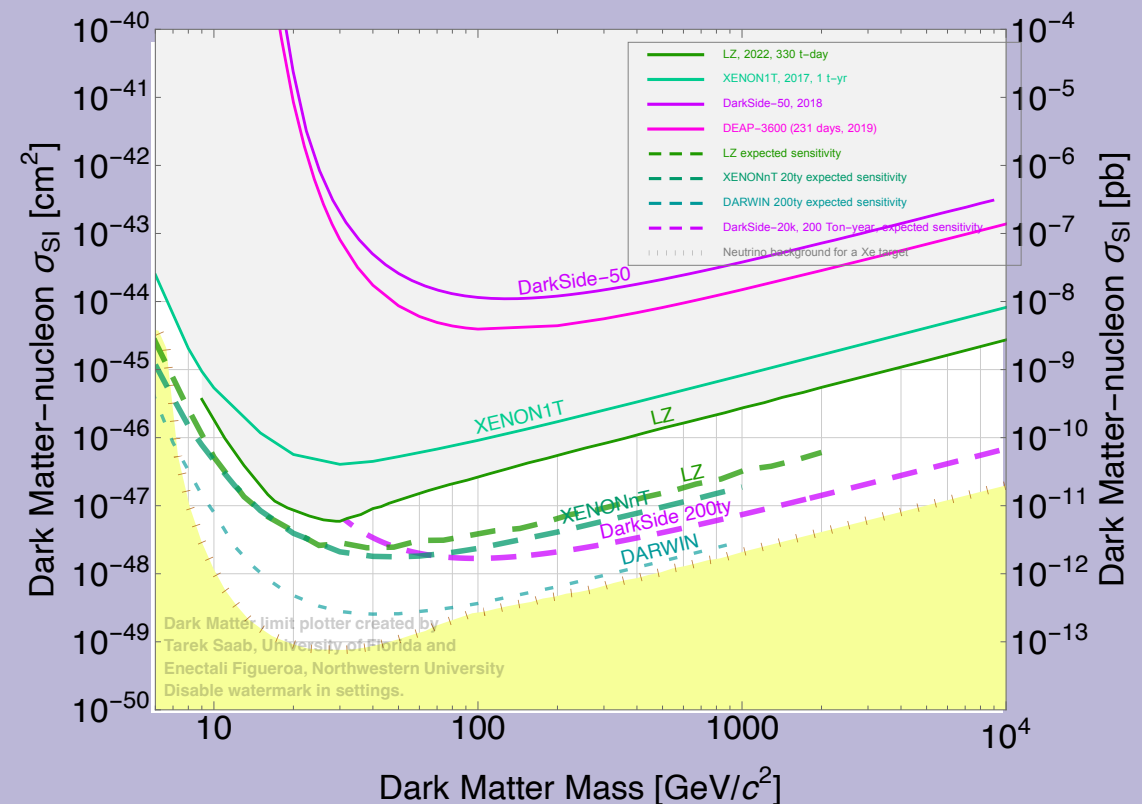


ARGON DETECTORS

- Argon shares many of the positive properties of xenon, but is lighter
- Lower scintillation wavelength, $\lambda = 128\text{nm}$
- Scintillation time structure allows the detector to resolve electronic recoils and electronic recoils from pulse shape alone
- Darkside-20K aims to achieve a nearly background-free ($\mu_{\text{bkg}} \ll 1$) 100 tonne-year exposure
- 20 tonne fiducial volume (surface background observed with Darkside-50)
- Underground argon will reduce the ^{39}Ar background, but projections still assume an ER-limited threshold of 30 keV

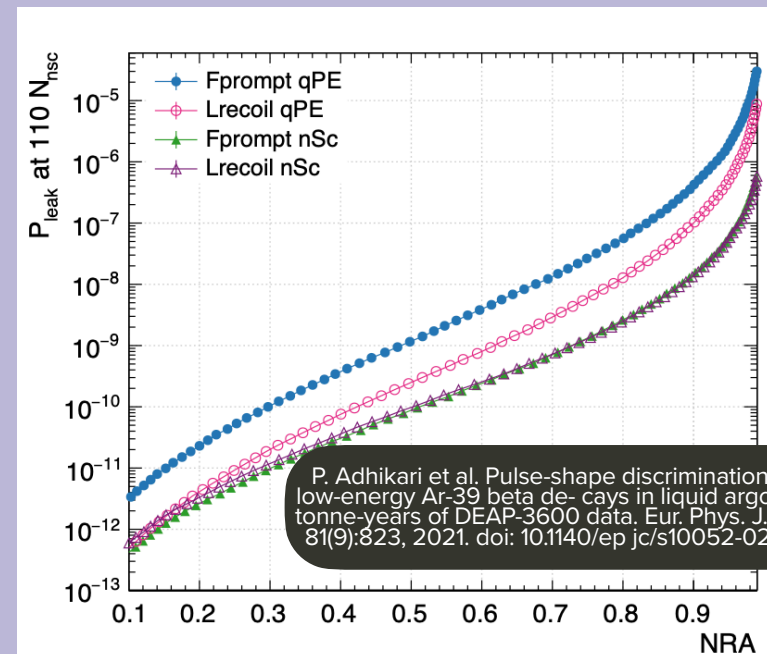
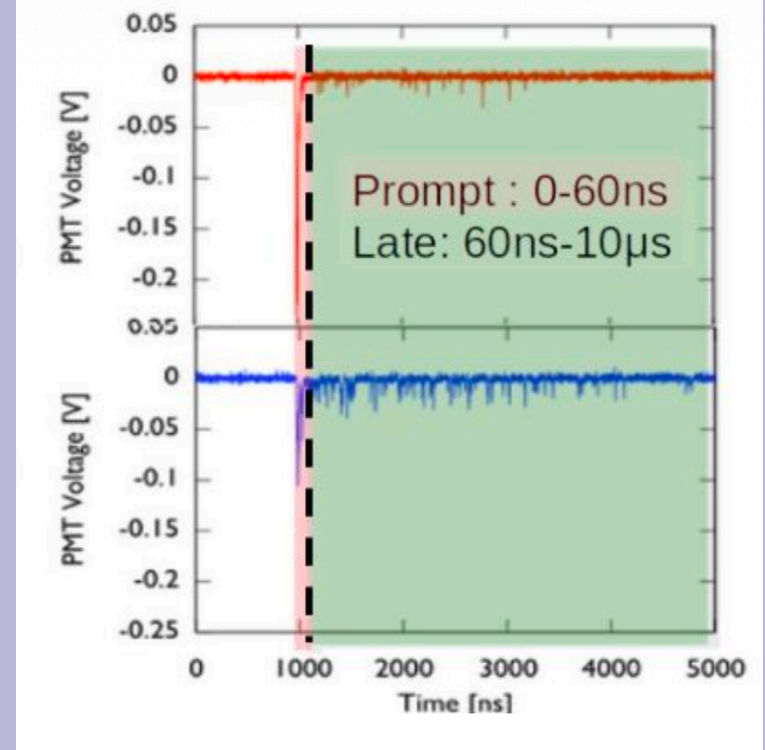


Schematic courtesy of DEAP-3600



PULSE SHAPE DISCRIMINATION

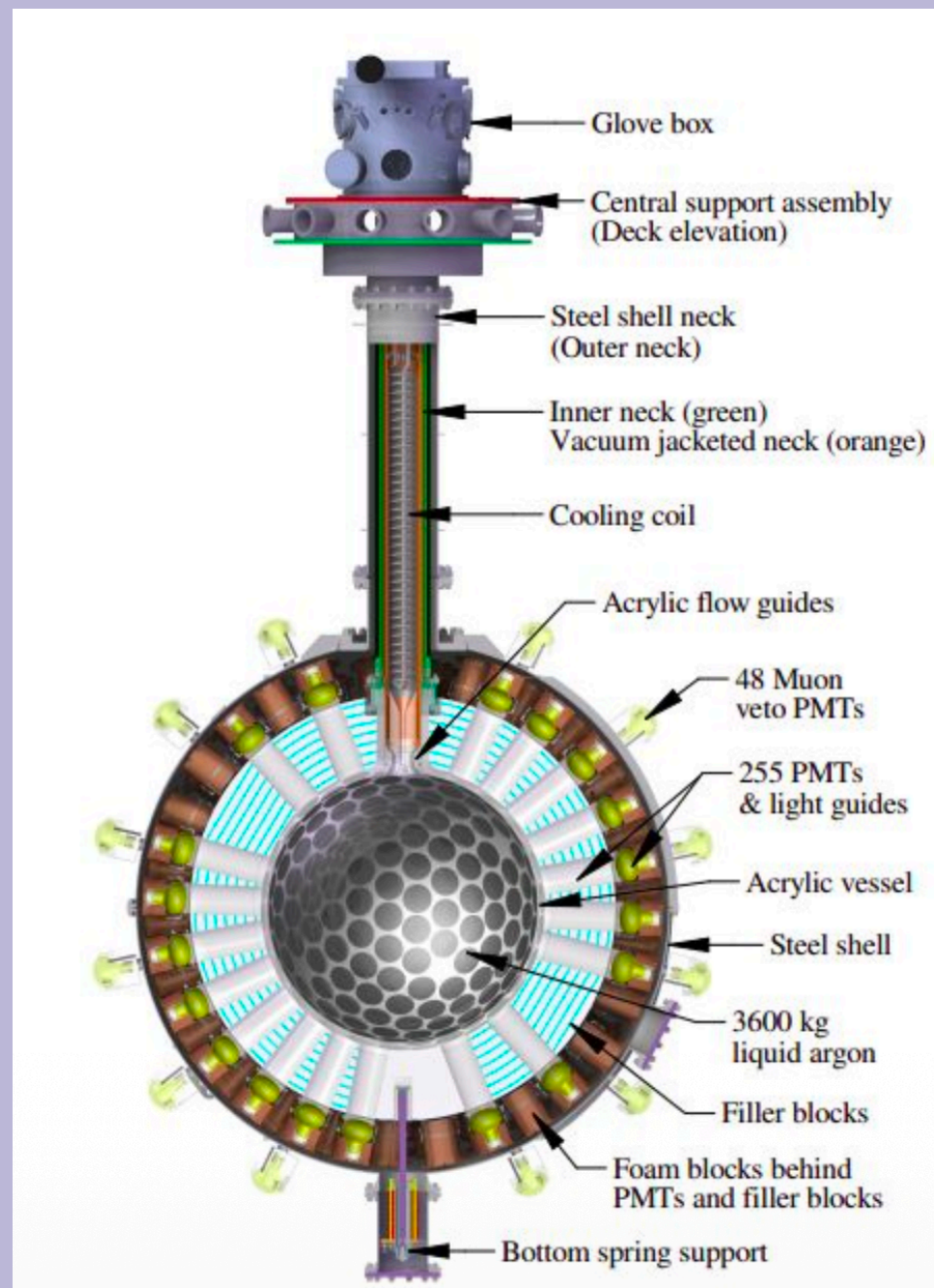
- Unlike in xenon, where the two excimer states decay too fast to be distinguished, Ar has two well-separated excimers:
 - The singlet state, preferentially excited by nuclear recoils decay in 8 ns
 - The triplet state, preferentially excited by electronic recoils, take 1400 ns
- This allows exquisite ER-NR discrimination; 50% of NRs have 10^{-10} of the ERs
- However, this only works with S1s large enough to see the pulse shape



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.

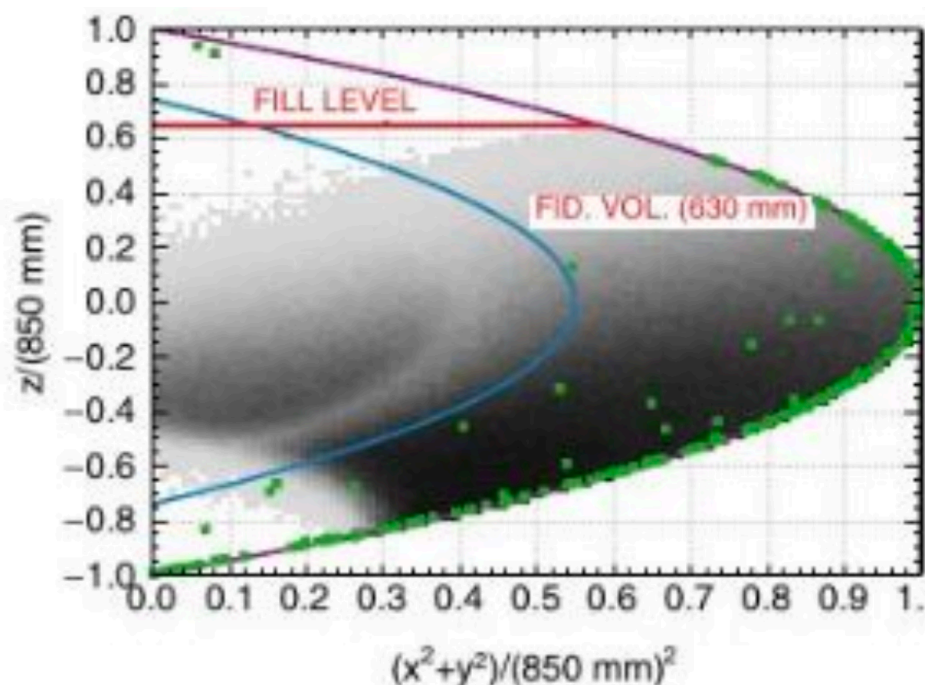
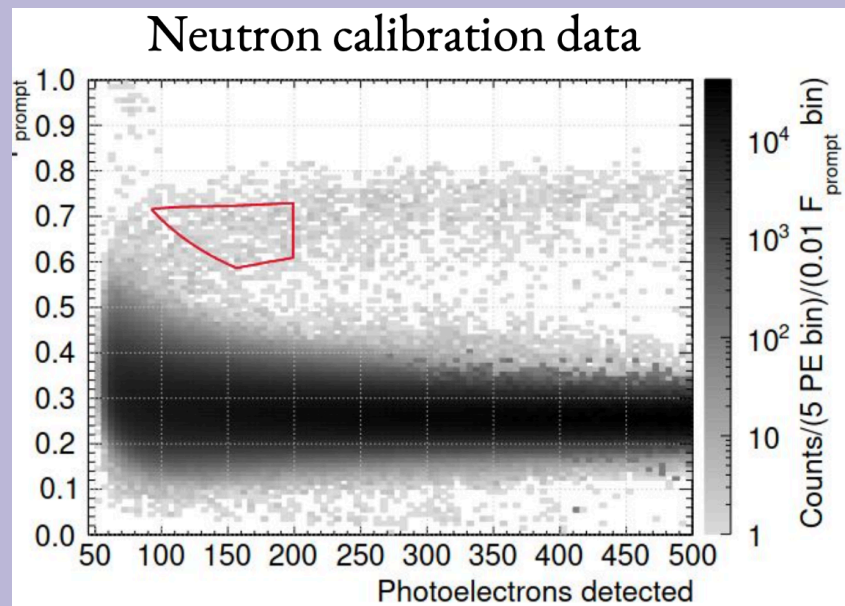
DEAP-3600

- Located at SNOLAB, with 255 PMTs surrounding the 3.3t argon target
- And shielded by a muon veto water tank
- 75% area covered in photosensors,
- 32 % quantum efficiency PMTs
- Scintillation light is mismatched to PMTs— wavelength shifters used to make it observable
- No field— all energy goes into scintillation



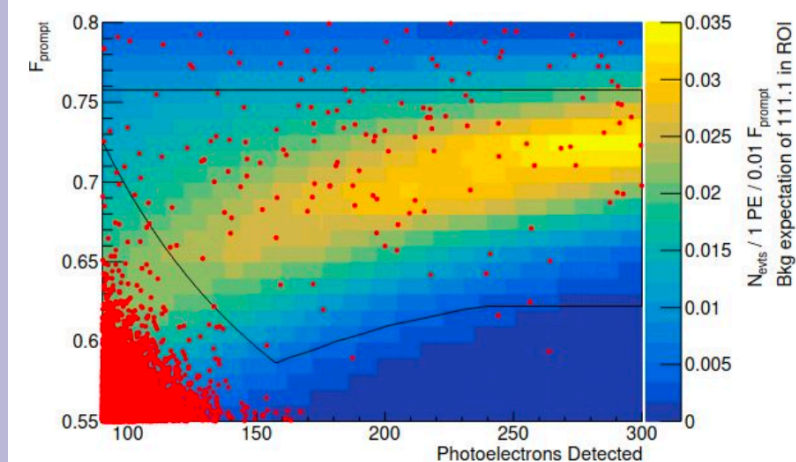
DEAP-3600

- The analysis space is fraction of light early/late
- and fiducialisation is possible—resolution of ca. 5 cm
- However, DEAP has had challenges with alpha-particles which make more light, which leak in from the “neck” of the detector
- Machine learning methods was able to tag many alphas
- Now, surfaces in the neck are coated with wavelength shifting material to make the events more distinctive
- Many alphas from dust in the detector!

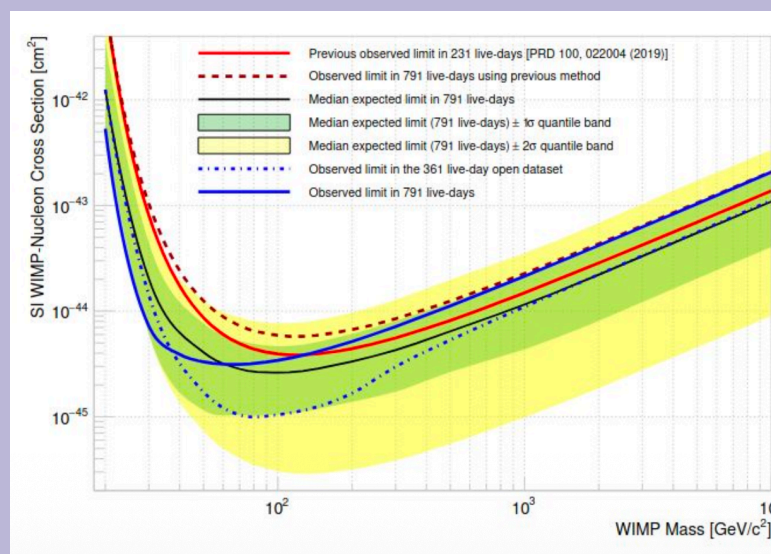


DEAP-3600

- The alphas dominate the background budget of DEAPs current run
- Hardware upgrades for filtration will reduce this significantly
- but the current limits are already the strongest from Ar
- Still ca. two orders of magnitude less restrictive than xenon

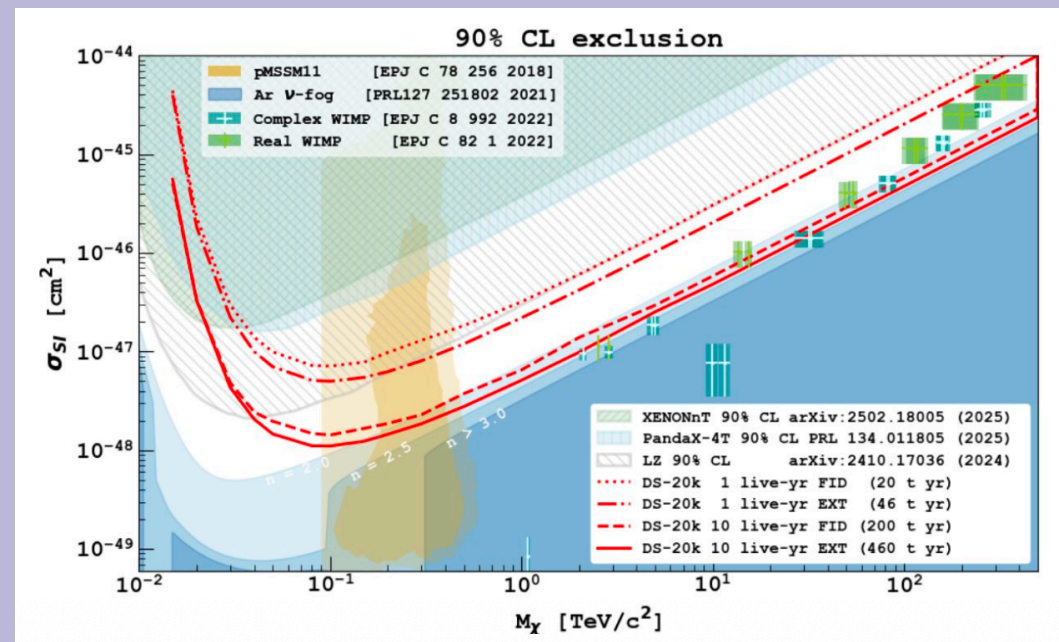
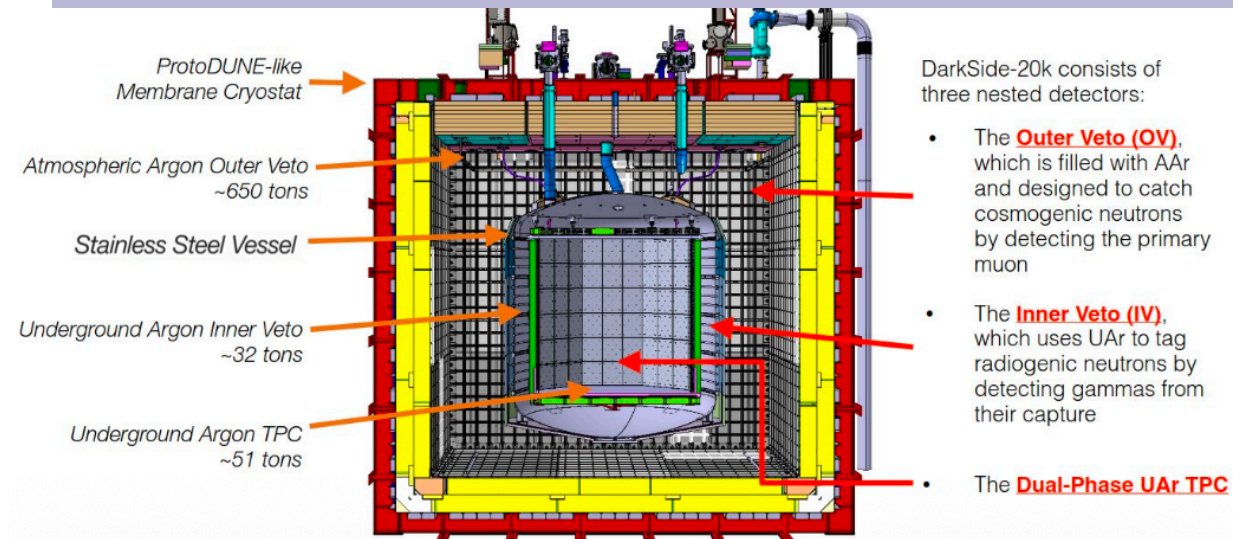


Source	Prior	Best-fit (bkg-only)	Best-fit (sig+bkg)
Radiogenic n	$1.2^{+1.0}_{-1.0}$	$1.2^{+0.9}_{-0.9}$	$1.2^{+0.9}_{-0.9}$
Surface α	$7.4^{+15.2}_{-15.4}$	$0.0^{+3.1}_{-3.1}$	$0.0^{+1.8}_{-1.8}$
Shadowed α	$15.2^{+12.3}_{-10.3}$	$18.3^{+8.9}_{-7.4}$	$16.5^{+8.2}_{-6.9}$
Dust α	$44.2^{+39.9}_{-40.4}$	$91.6^{+10.6}_{-11.9}$	$64.1^{+15.9}_{-16.2}$
Total Bkg	$68.0^{+49.9}_{-45.2}$	$111.1^{+16.3}_{-15.2}$	$81.7^{+20.3}_{-18.0}$
$M_\chi = 1 \text{ TeV}/c^2$	—	—	$32.0^{+23.9}_{-22.4}$



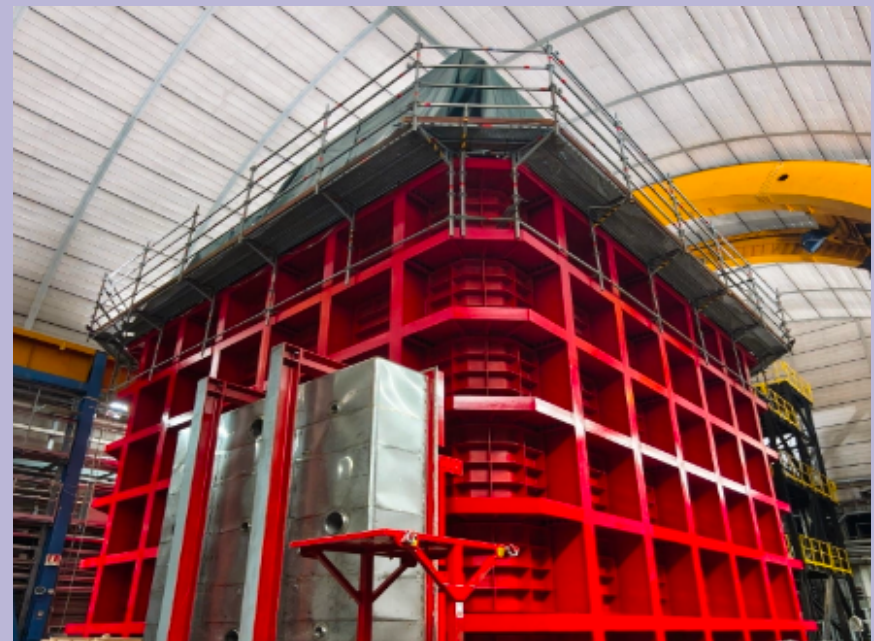
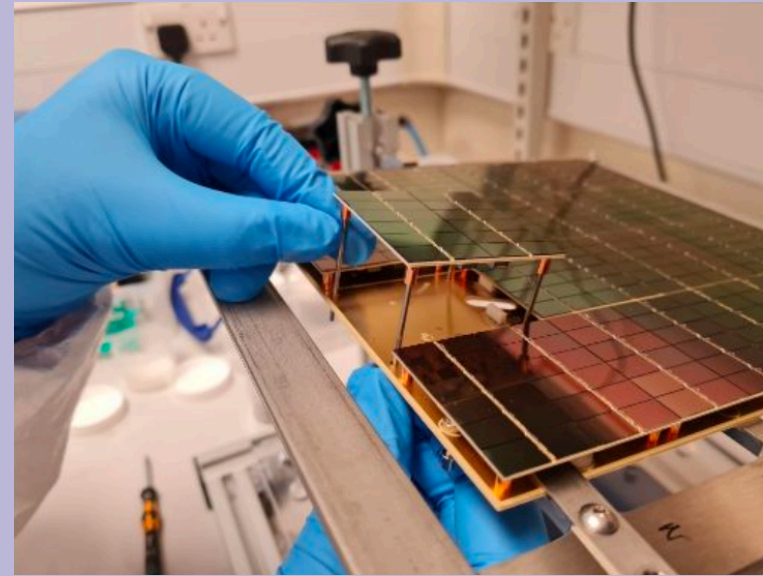
DARKSIDE

- Darkside aims to operate a massive (50 tonne!) two-phase TPC using argon
- So they'll have S1, S2 _and_ pulse shape
- Two main science cases:
 - Lower-mass WIMPs, using the fact that Ar is better kinematically matched
 - Heavy WIMP searches
- Argon is cheap(ish) — so even their outer veto will use 650 tonnes of the stuff!
- Simplifies cooling a bit— the entire muon veto + inner veto + TPC are kept at the same temperature



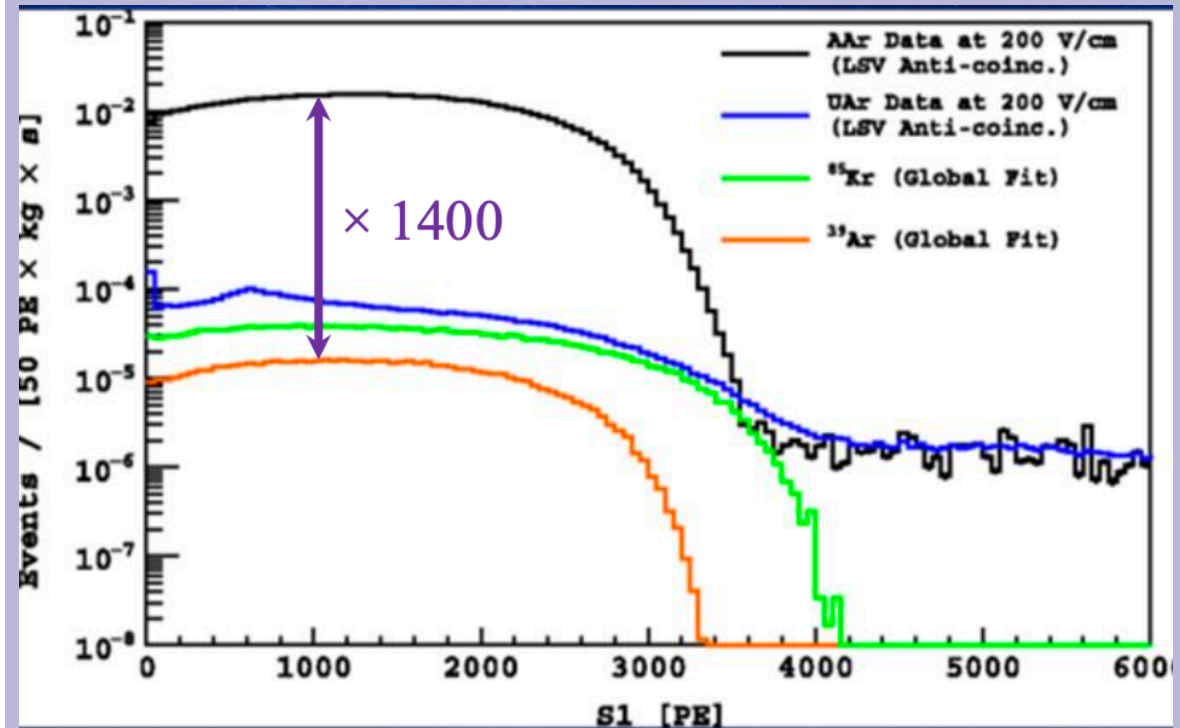
DARKSIDE

- R&D + construction is ongoing
- Darkside has developed SiPMs that are radiopure and quiet enough to be used!
 - 96% occupancy of the optical plane of 21m^2
- Cryostat installed at LNGS



^{39}Ar

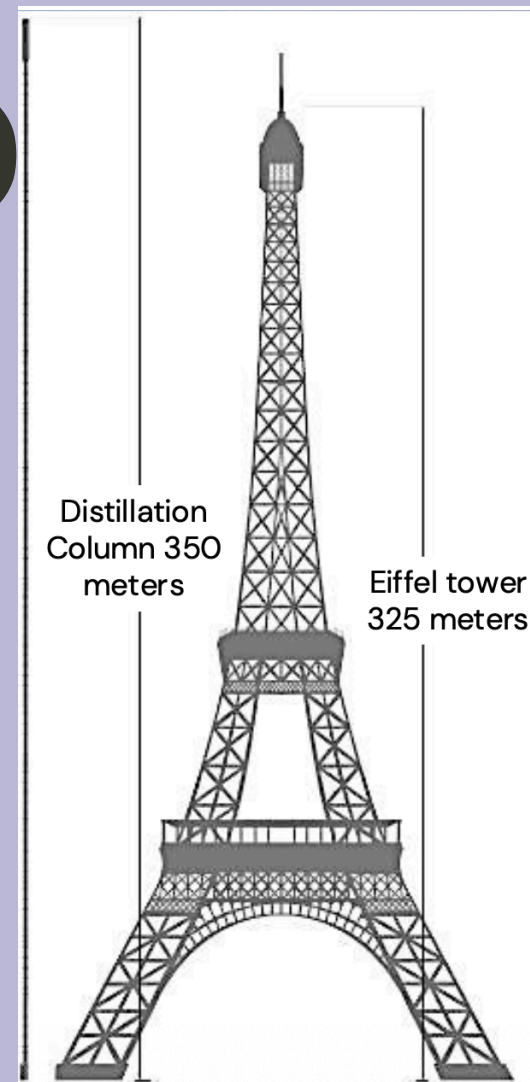
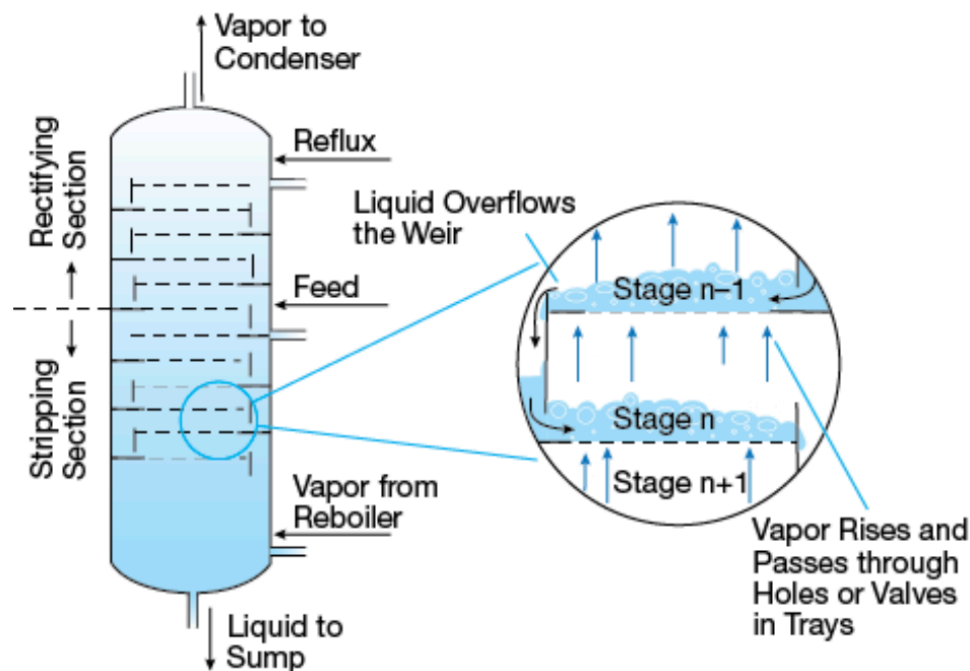
- Argon in the atmosphere has ca. 1Bq/kg of ^{39}Ar from cosmogenic activation ($\tau = 269\text{y}$)
- It can be removed on the analysis level from the science search, but
- If you have tonnes of it, you'll have kHz of background events!
 - Pileup and deadtime would make the experiment completely impossible
- Darkside will use Ar from underground sources to mitigate this
 - 1 Hz/tonne is more liveable



ARIA

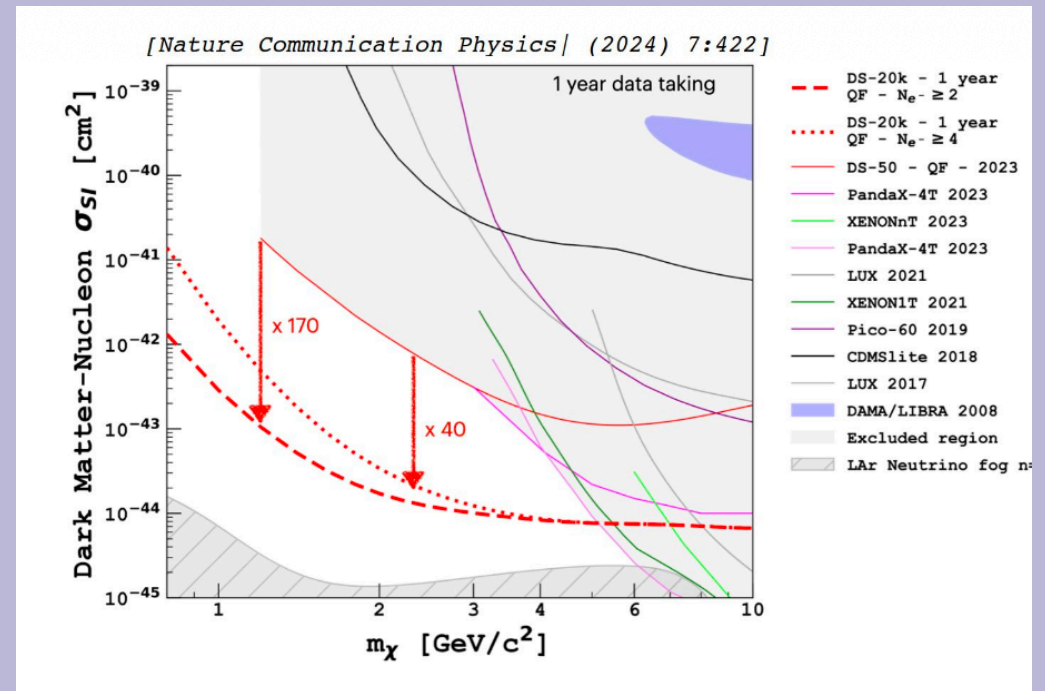
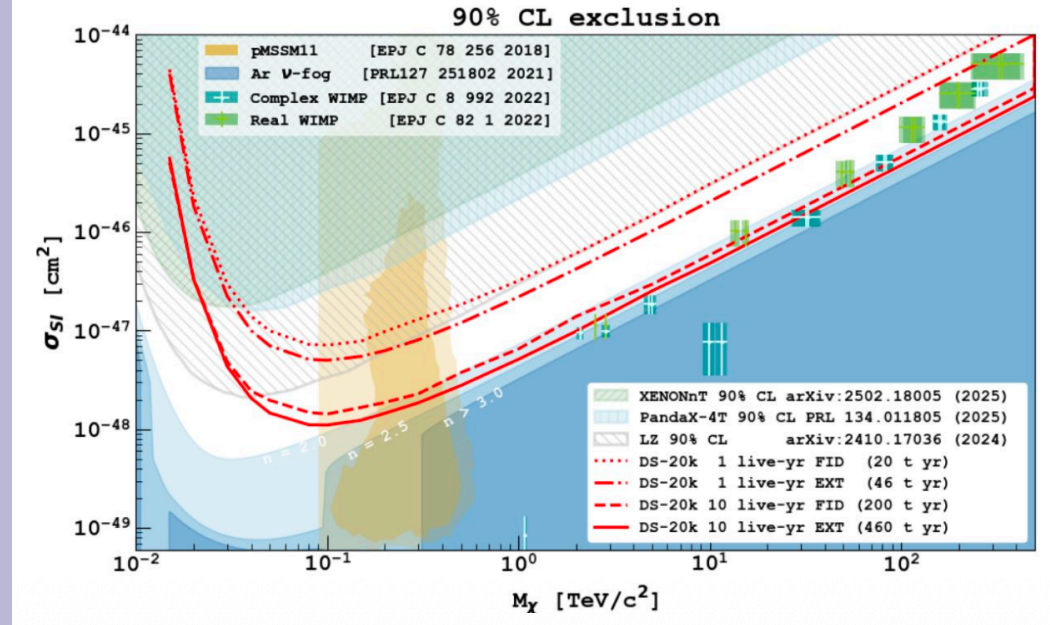
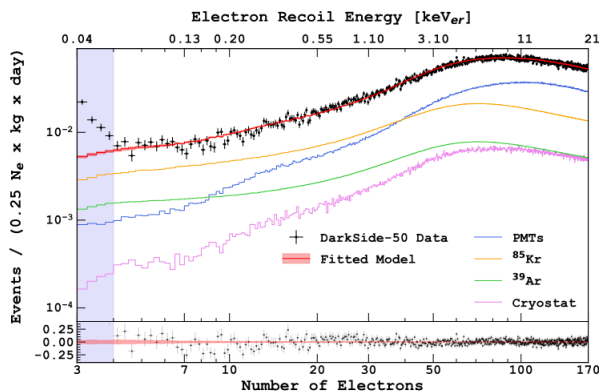
- To go even further, this Darkside will use a 350 meter tall distillation column, Aria to separate the isotopes
- 10-15 kg/day— extensive work to get to 50 tonnes!

Argon distillation with the Aria project for dark matter searches
Teena Vallivilayil John



DARKSIDE

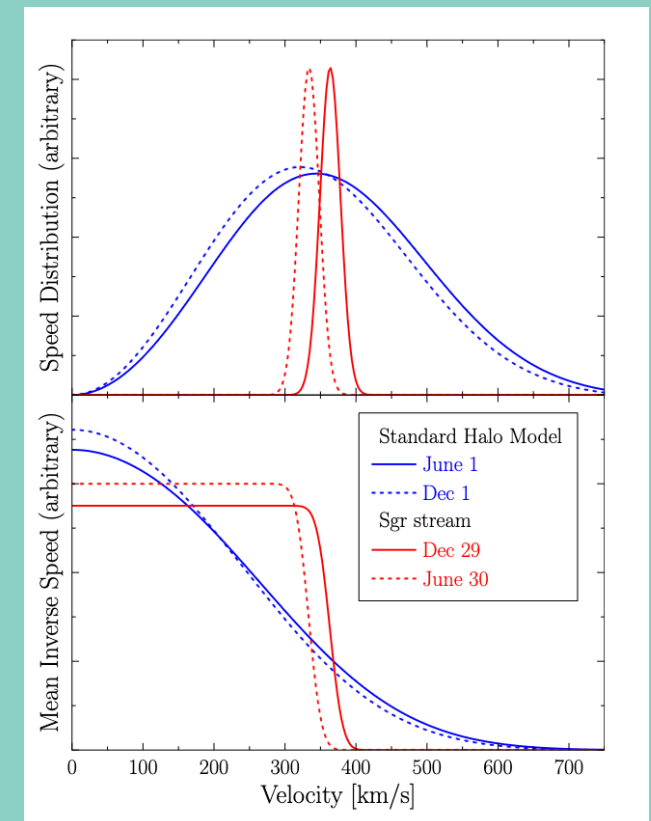
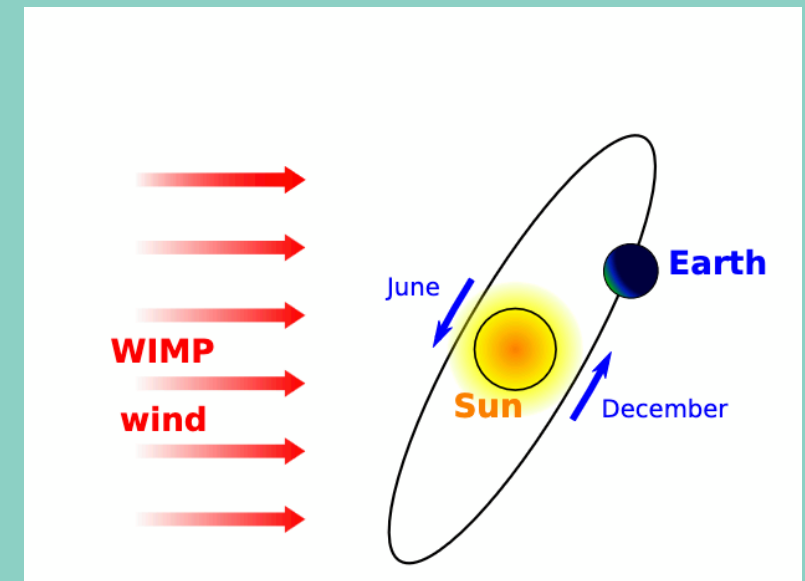
- With the underground and purified Ar, Darkside expects to reach a similar level of sensitivity as xenon experiments at higher masses (where pulse shape discrimination works)
- A second powerful science channel for Darkside is (and has been) the S2-only channel: give up looking for an S1, and you reach much lower energy thresholds
- Analysis uses the S2 shape to retain some background discrimination power, and significant effort can allow you to attempt to model some or all of the backgrounds



Search for low-mass dark matter WIMPs with 12 ton-day exposure of DarkSide-50 [2207.11966](https://arxiv.org/abs/2207.11966)

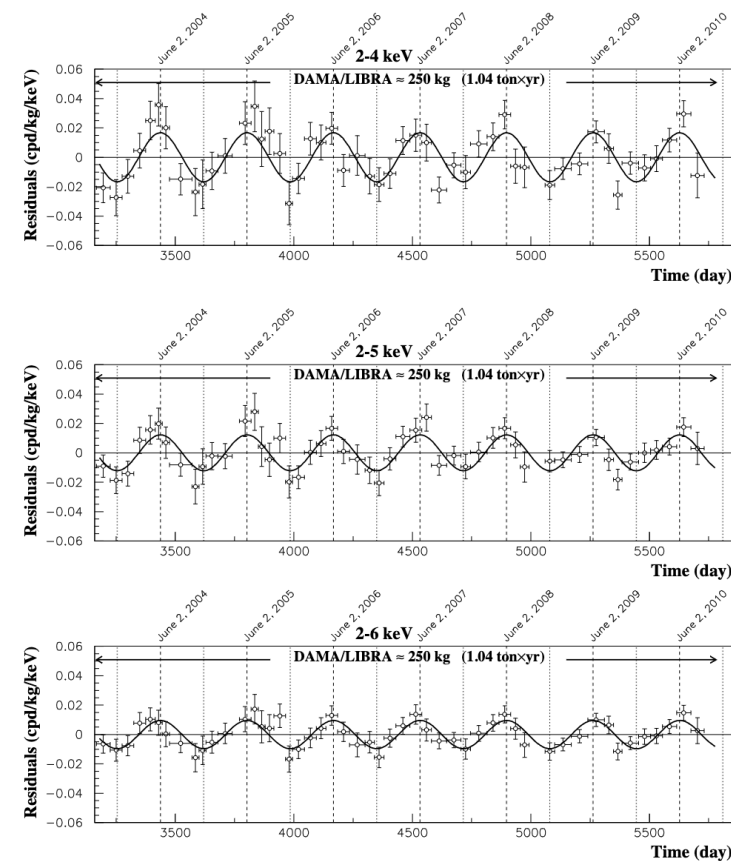
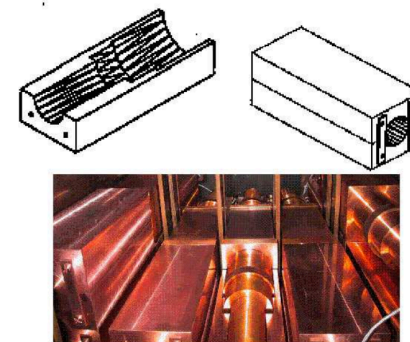
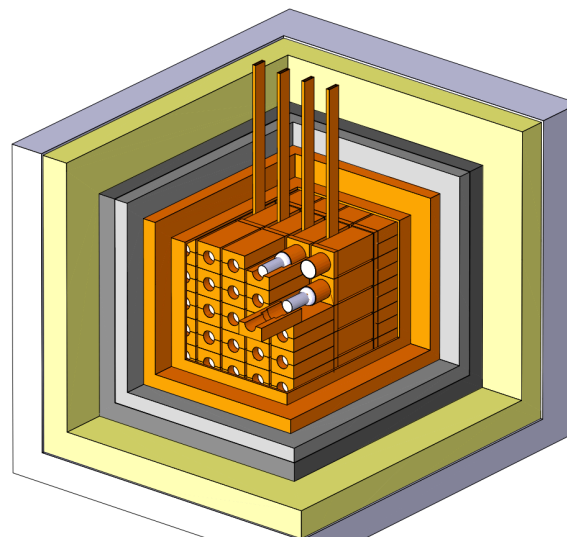
RECALL ANNUAL MODULATION

- On top of the average dark matter velocity distribution, the movement of the Earth yields a small additional energy boost when Earth is moving with the movement of the Sun, into the dark matter “wind” just around now (June)!
- Two effects: higher rate, and a higher average energy of the recoils. Depending on the energy threshold and the underlying dark matter velocity distribution, this is expected to give an amplitude of $\sim 1\%$
- While this signal will therefore only be visible in most cases when you have already seen many dark matter events, it is a crucial signature to be able to identify an excess in a direct detection experiment with dark matter.



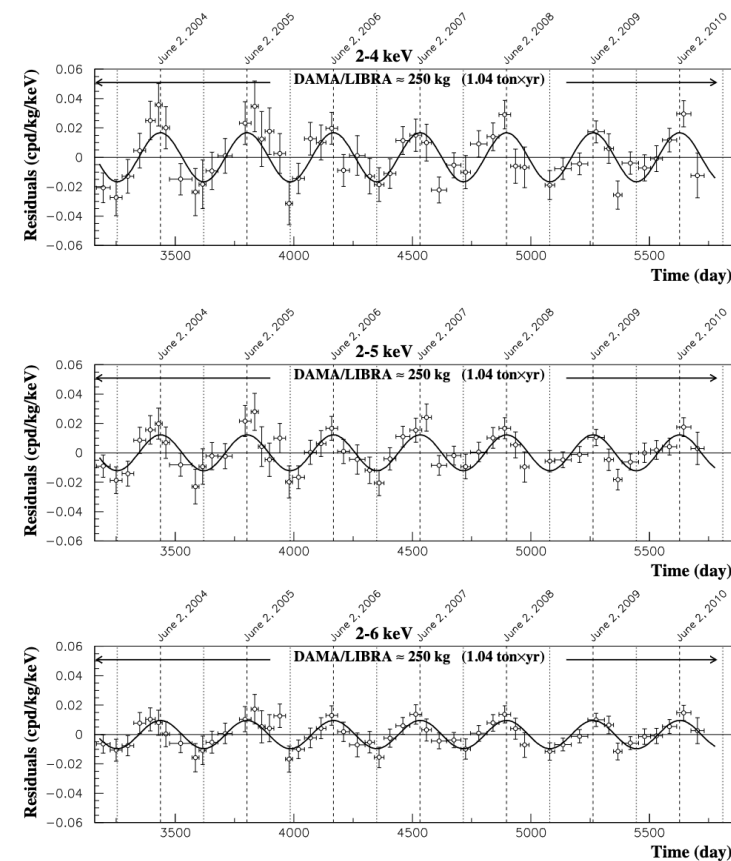
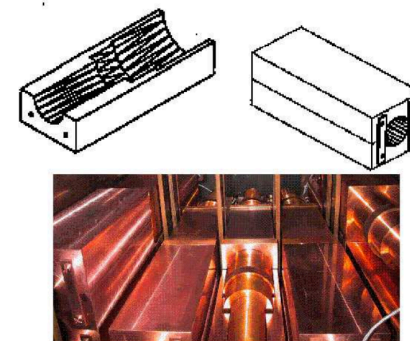
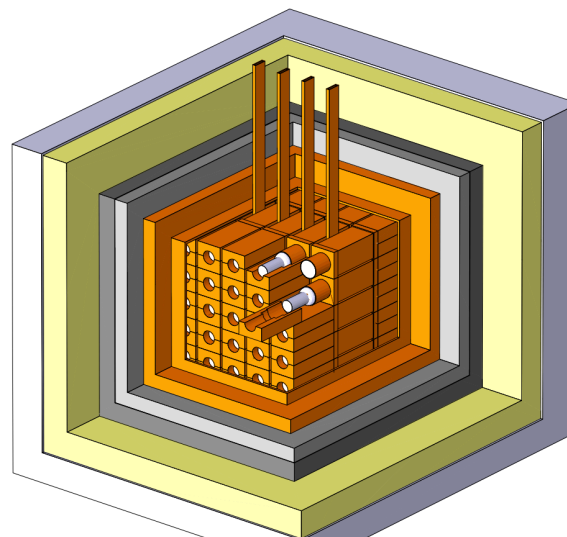
DAMA

- Sodium iodide is a strong scintillator and the DAMA detectors observe 5 – 7 photoelectrons/keV, with an analysis threshold around a few keV
- Running for 14+ year, DAMA/Libra collected an exposure of a tonne-year
- And observed an excess, very high statistical significance for a modulation as expected from dark matter
- However, no other experiment has seen a similar excess, which is very challenging to combine with the strong signal this implies



DAMA

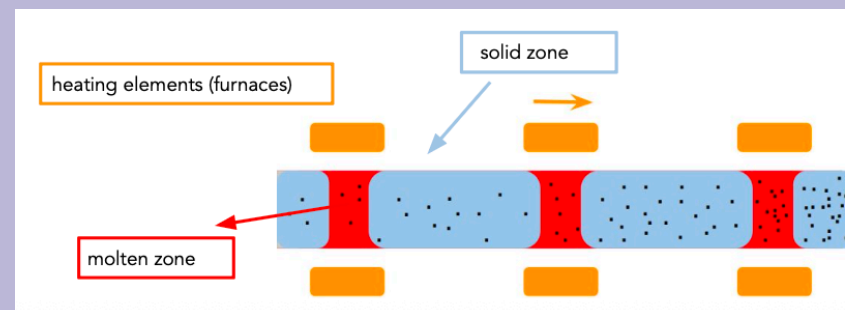
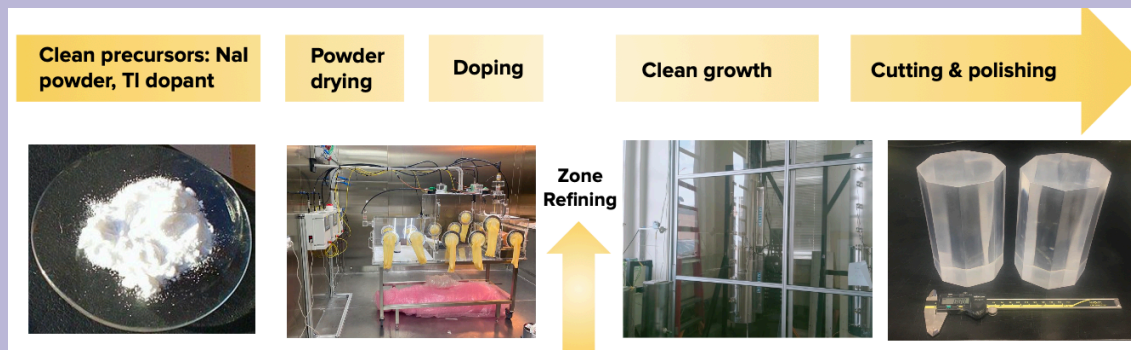
- Possible explanations have included:
 - Leaky PMTs
 - An analysis artifact of subtracting the baseline per-yearly-basis
 - or changes in the muon flux—DAMA does not have a muon veto
 - Seasonal



CHECKING DAMA

The SABRE North experiment:
status and prospects, Claudia Tomei, IDM2026

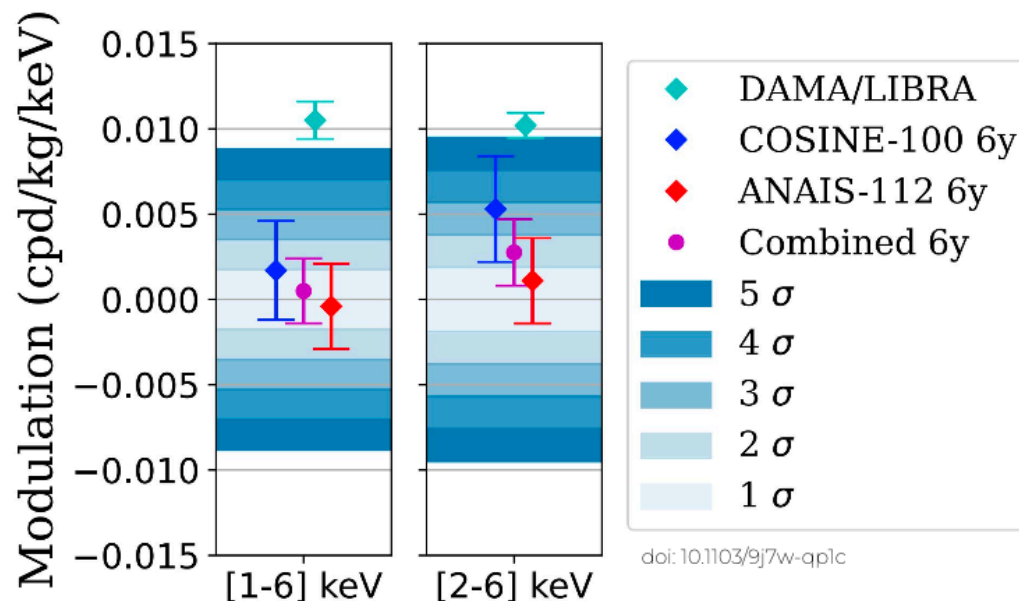
- Since DAMA results were announced, great efforts have been put into replicating or investigating DAMA
- the excess is incompatible with a wide range of other experiments (xenon-phobic dark matter was a thing)
- Extremely high-quality crystals are also hard to grow, making exact replication challenging



CHECKING DAMA

The SABRE North experiment:
status and prospects, Claudia Tomei, IDM2026
The COSINUS Experiment at LNGS
Commissioning and Start of the first Phase
Mariano Cababie

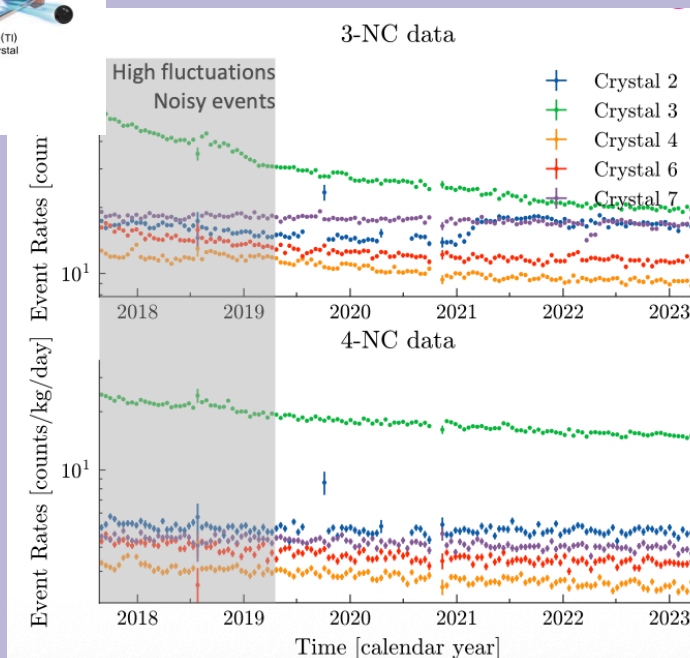
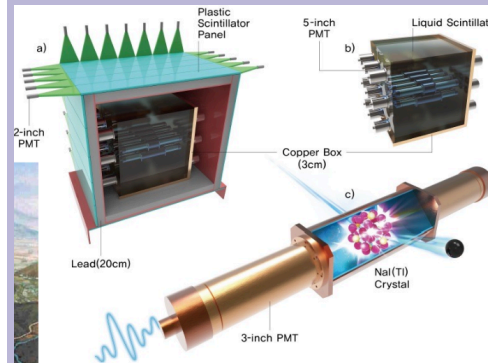
- A location on the southern hemisphere would be able to check seasonality— SABRE south is being built/commissioning?
- COSINUS aim to have photon+phonon discrimination capability
- But other experiments already have shown incompatiblish results:
 - COSINE + ANAIS
- ANAIS is upgrading to lower their energy threshold with TESs



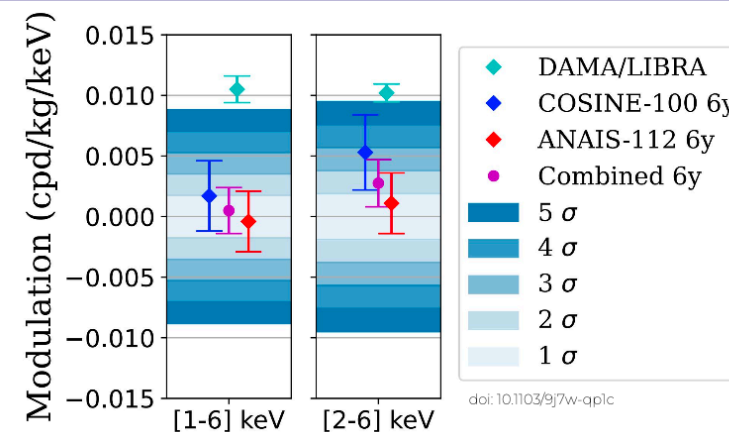
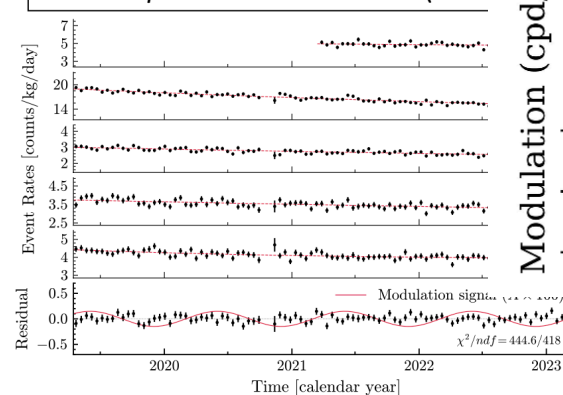
COSINE-100

Pioneering Sub-GeV Dark Matter
Limits with COSINE-100, Won Kyung Kim, IDM2026

- Similar detector as DAMA, in the Yangyang underground laboratory
- Equipped with scintillator vetos in addition to the sodium iodide crystals
- No significant excess



4-NC : Amplitude = 0.001 ± 0.001 (count)

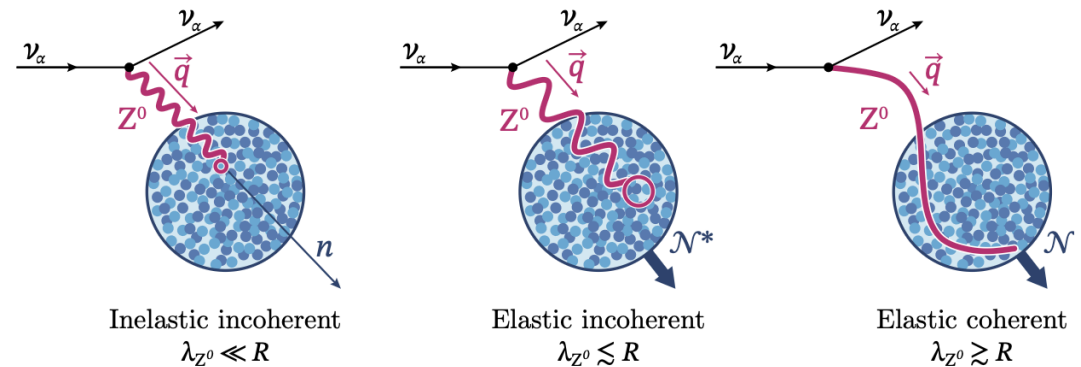
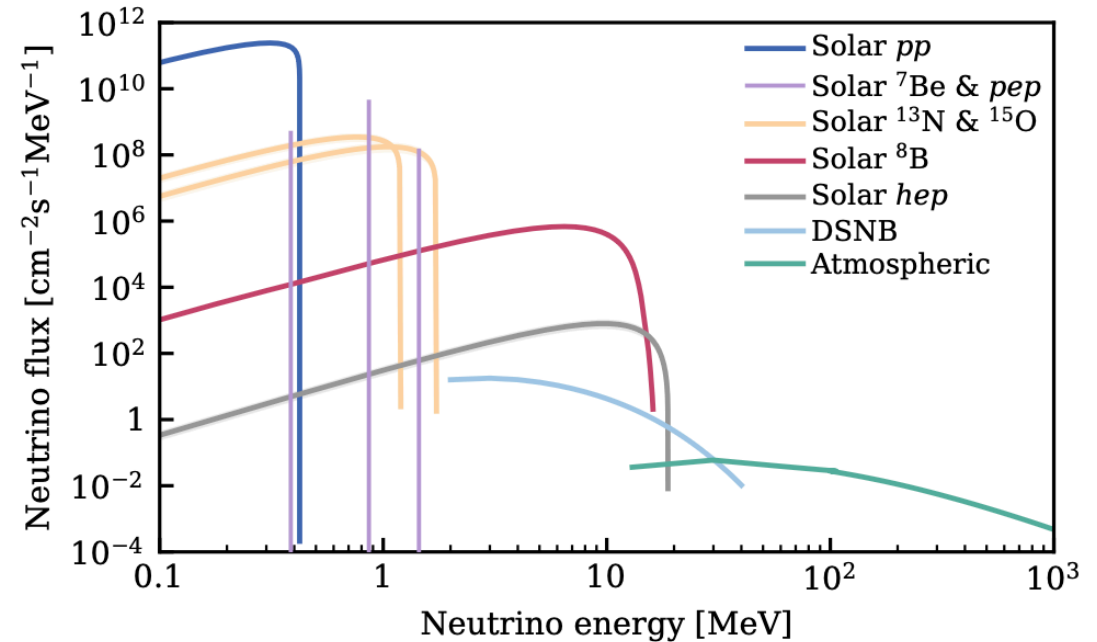


doi: 10.1103/9j7w-qplc

THE NEUTRINO FLOOR (FOG)

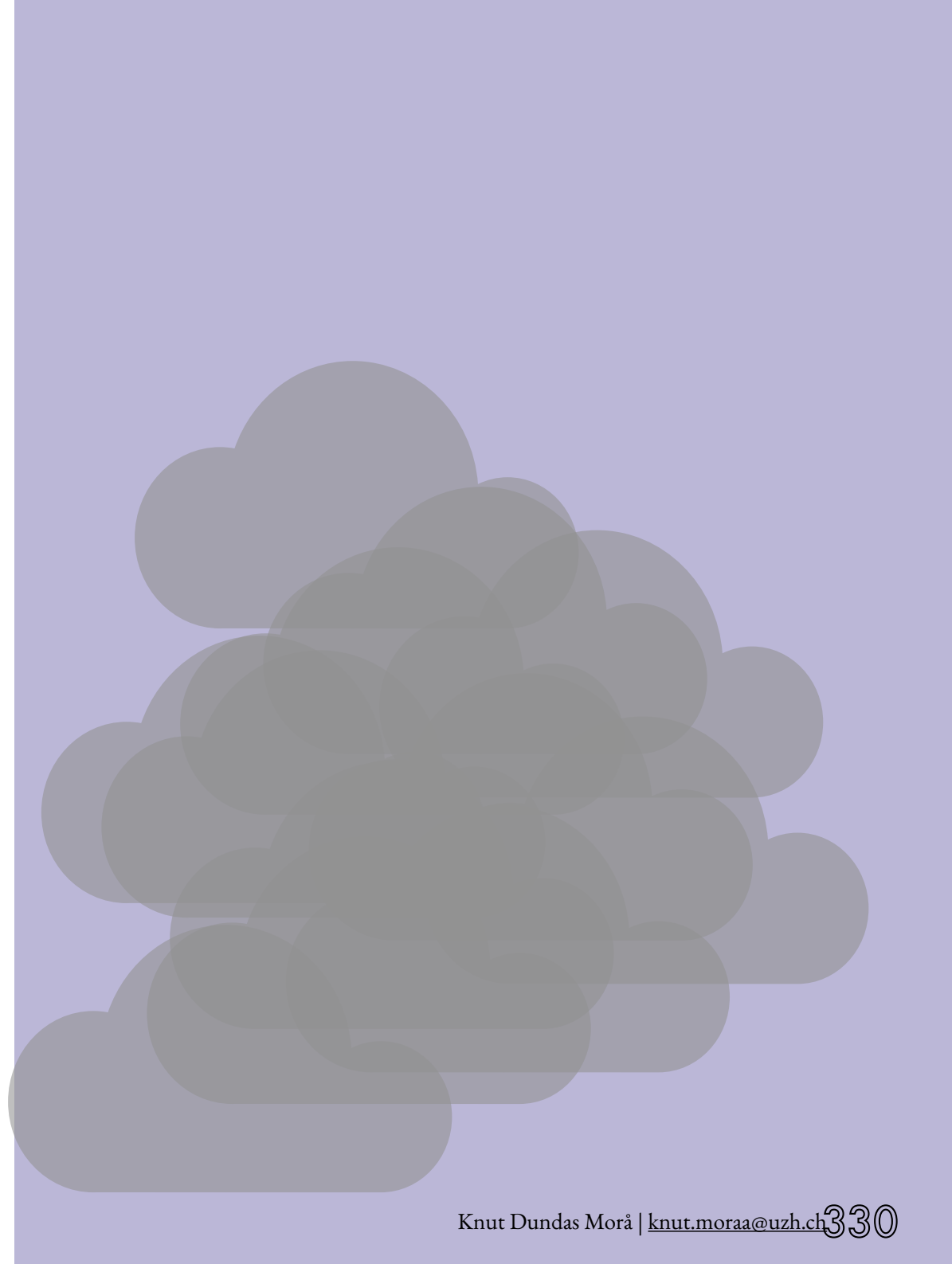
- Neutrinos are WIMPs minus that they're not a dark matter particle
- Neutrinos from a number of astrophysical sources have high enough energies that despite their miniscule masses, they can give keV-scale recoils in xenon
- Coherent scattering exactly similar to how WIMPs interact
- Cannot be shielded, and cause NRs exactly similar to what we expect from WIMPs
- If they have a different recoil spectrum, we can distinguish them,
- but some are almost impossible
- Depends on target material

Probing the Invisible, Robert Hamann PhD Thesis, Heidelberg 2025

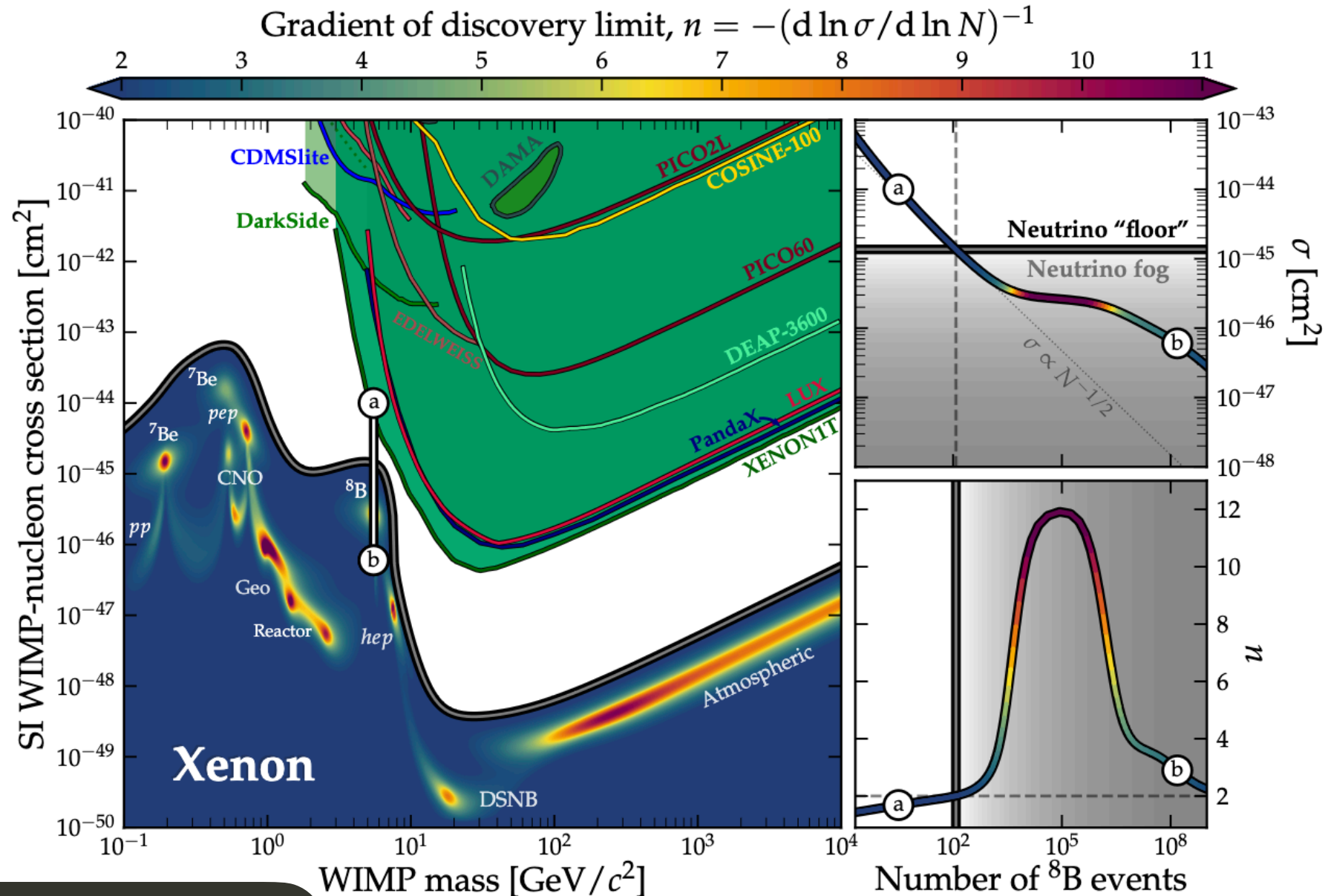


THE NEUTRINO FLOOR (FOG)

- Both the definition and the actual experience of the floor are foggy:
- Is the floor where:
 - You cannot make a 5-sigma discovery with a perfect 1000 ty experiment?
 - where you expect 1 neutrino event?
 - where your limits will stagnate even if you increase the exposure?
 - where your limits are dominated by neutrino rate systematics?
- And as an experiment, you experience the floor as a softening of your performance over many 10-100 tonne-years of exposure



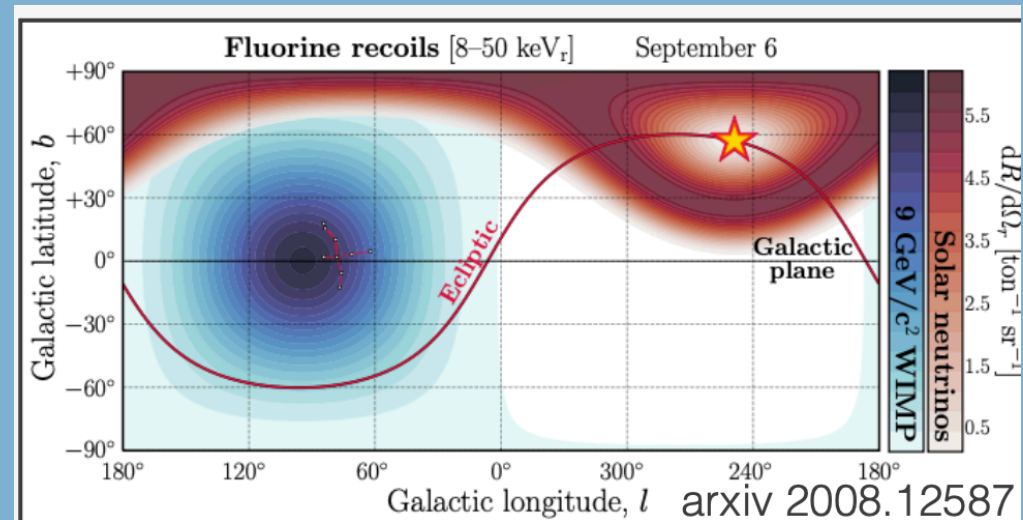
A NICE DEFINITION FROM O'HARE:



Fog on the horizon: a new definition of the neutrino floor for direct dark matter searches
<https://arxiv.org/abs/2109.03116>

DIRECTIONAL DM

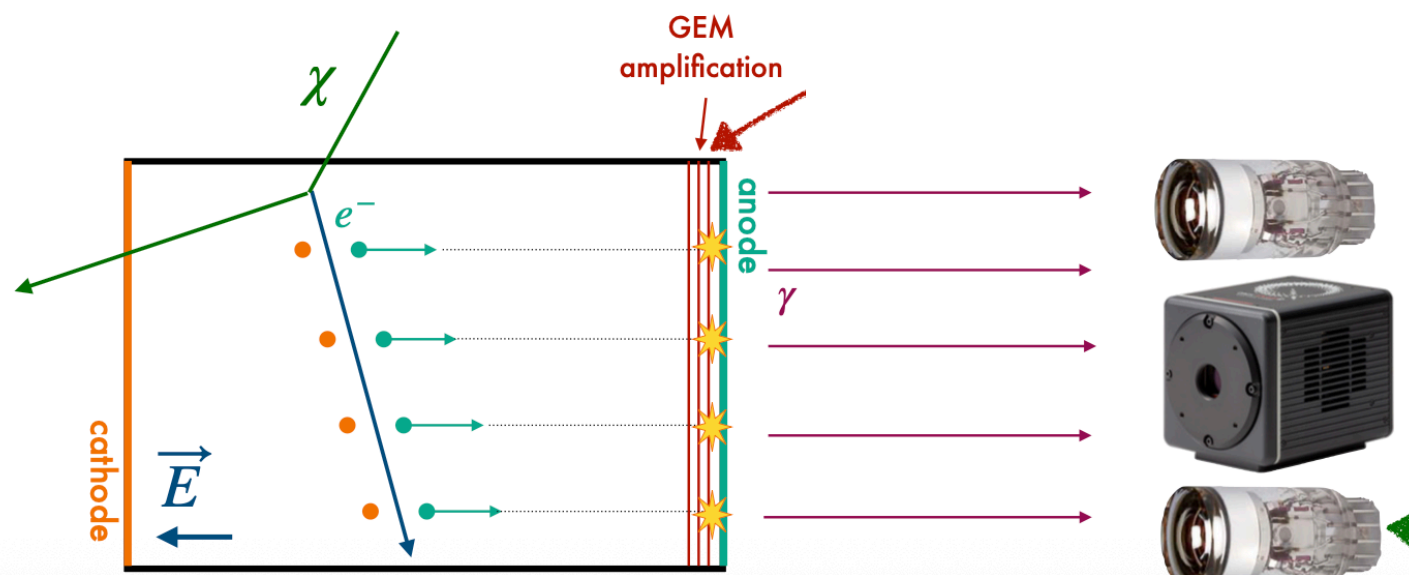
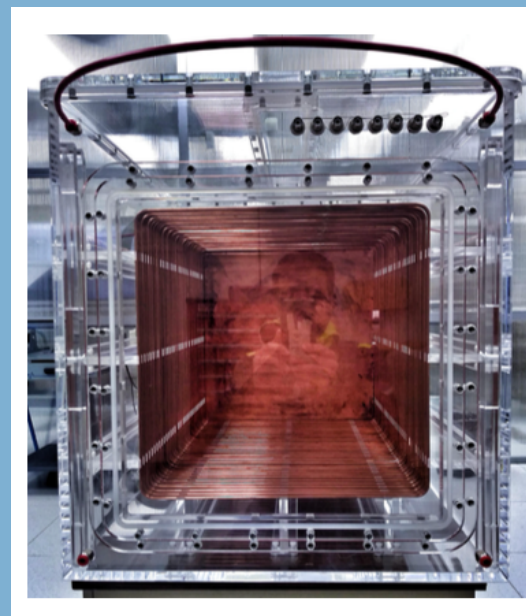
- One hope of making constraints below the floor is to have directional sensitivity:
- since dark matter has a velocity component with respect to us, we can distinguish dark matter and neutrinos
- Direction: the constellation Cygnus



CYGNO

Commissioning and design of the cygno-04 detector at LNGS, IDM2026

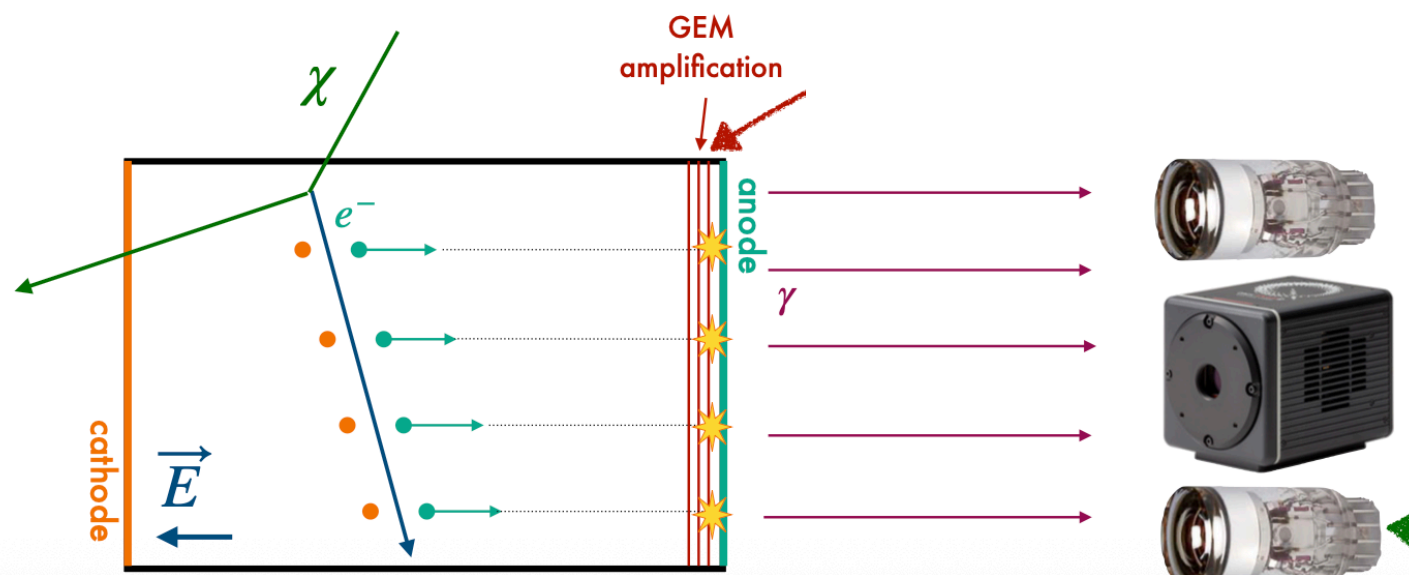
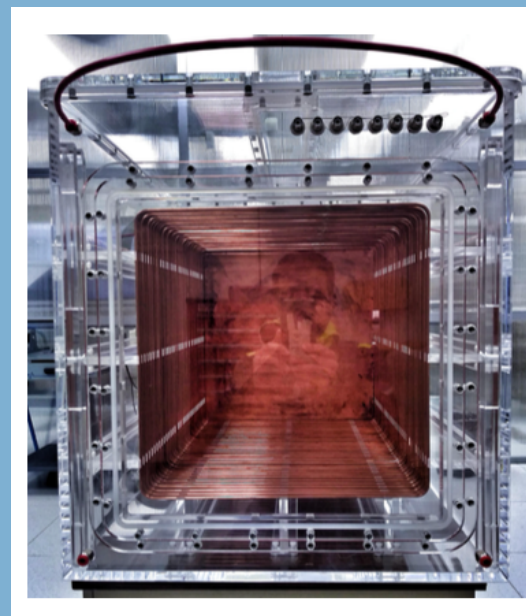
- Typical directional method: gaseous time projection chamber with high enough spatial resolution to reconstruct the track
- GEM (gas electron multiplier—amplification of the charge track which is read out by PMTs



CYGNO

Commissioning and design of the cygno-04 detector at LNGS, IDM2026

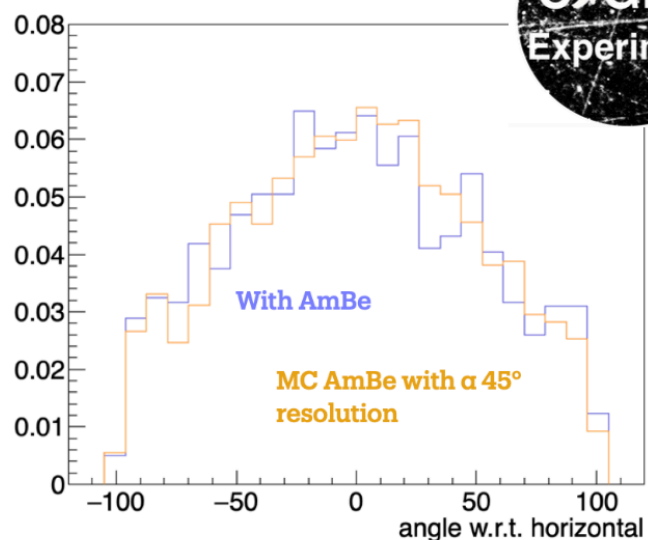
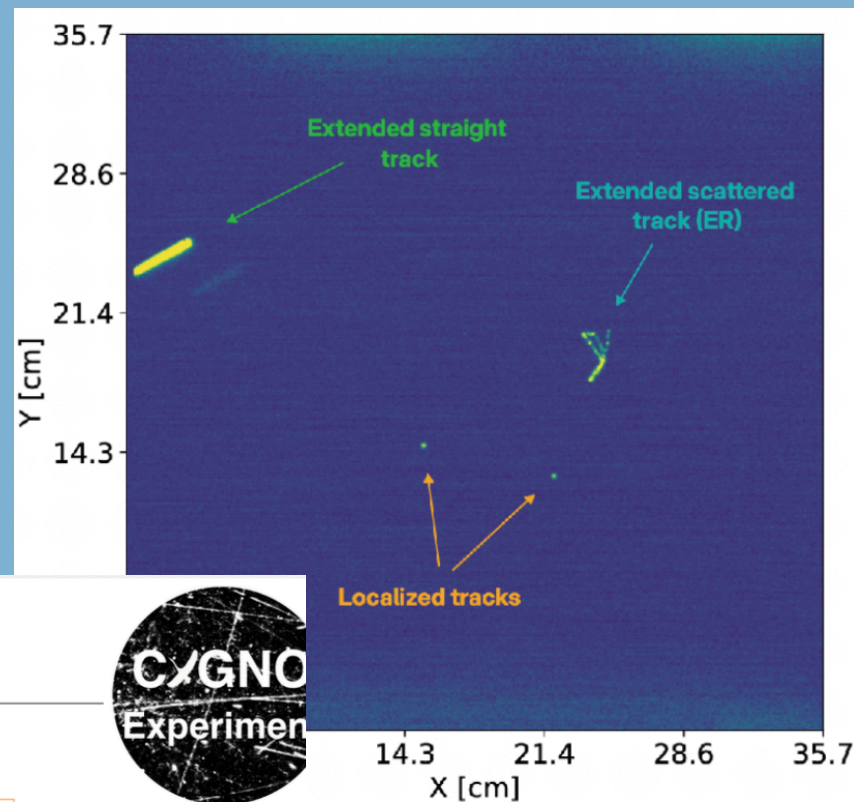
- Typical directional method: gaseous time projection chamber with high enough spatial resolution to reconstruct the track
- GEM (gas electron multiplier—amplification of the charge track which is read out by PMTs
- 1-atmosphere He+CF₄ gas in O(1 cubic meter TPC)



CYGNO

Commissioning and design of the cygno-04 detector at LNGS, IDM2026

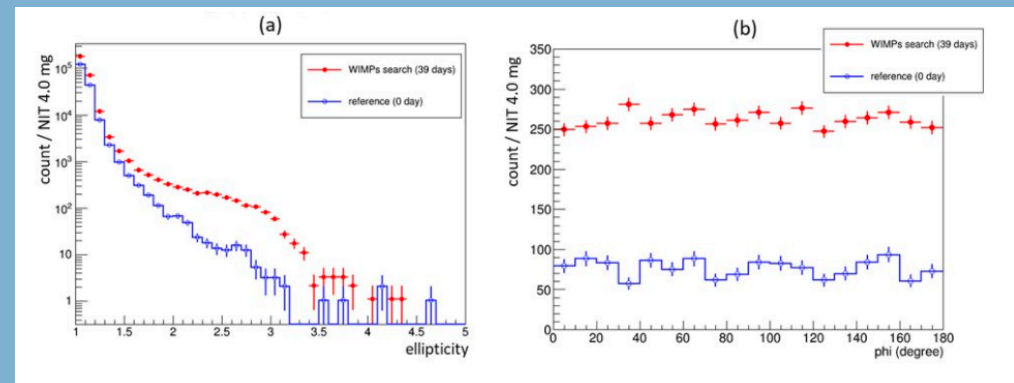
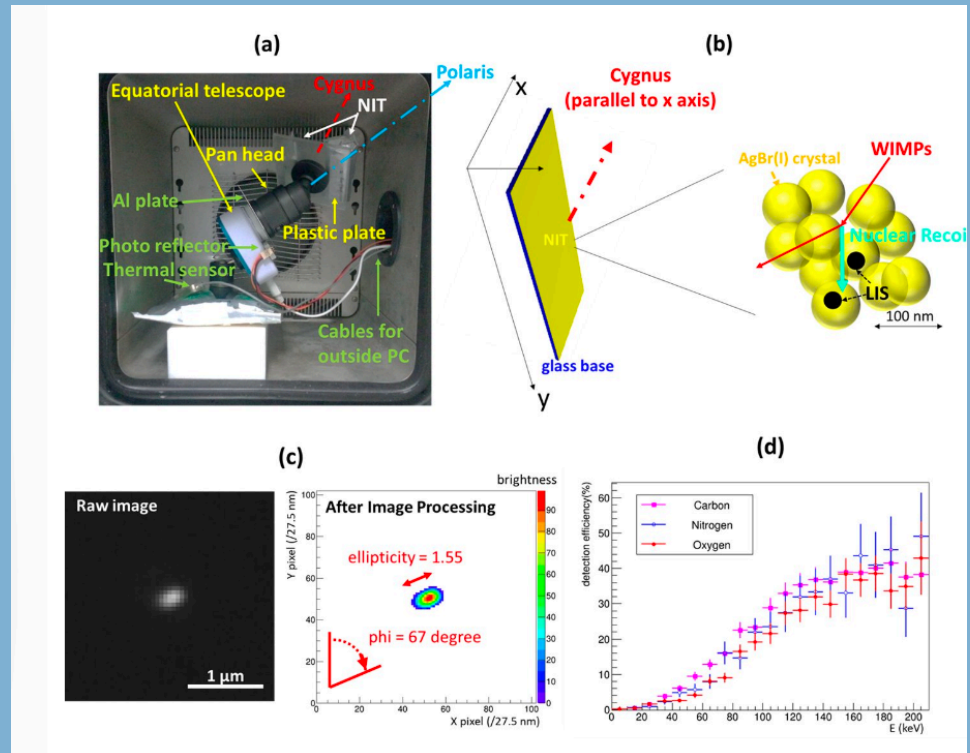
- Energy and X,Y coordinates read-out with a high granularity camera, while PMTs capture more of the energy as well as gives high-precision timing.
- Shielded and operated underground— allows better understanding of the detector backgrounds as the overground recedes
- Next step: 30 cubic meters



DIRECTIONAL DM: EMULSION

- Another way of gaining directional sensitivity is to use nuclear emulsions— films, which can be microscopically evaluated
- By mounting on a telescope mount, can ensure that the emulsion always has the same face towards cygnus
- $\sim 20^\circ$ resolution at 60 keV
- Made two films, mounted one on the telescope, and analysed one immediately after fabrication
- No excess, limits in the $\sim 10^{-30} \text{cm}^2$ scale for WIMP-mass DM

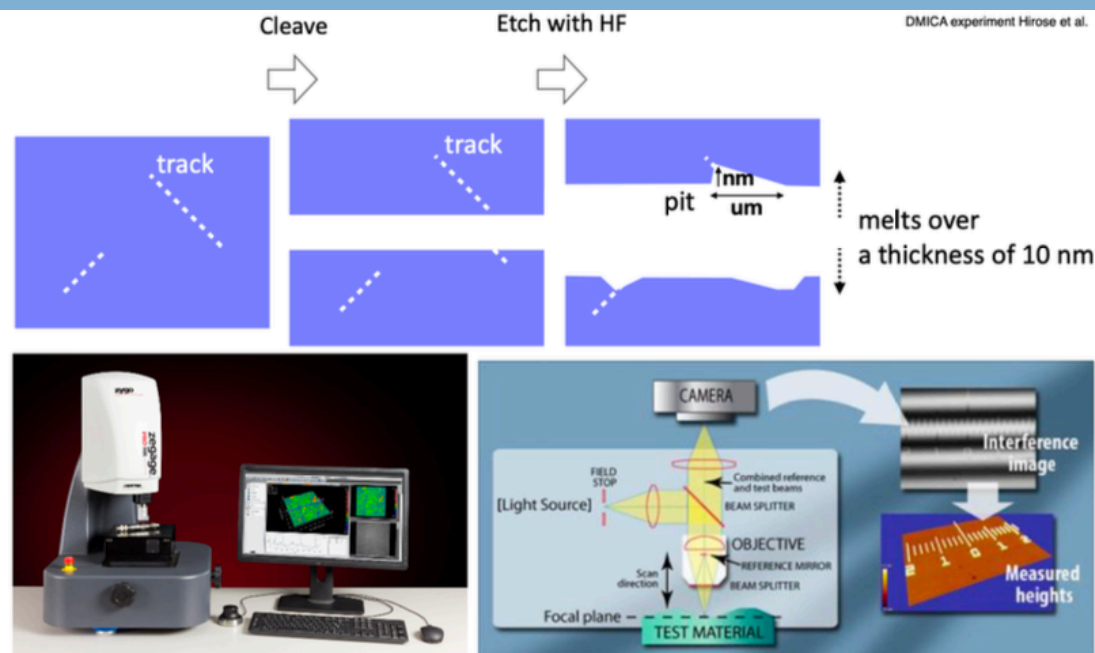
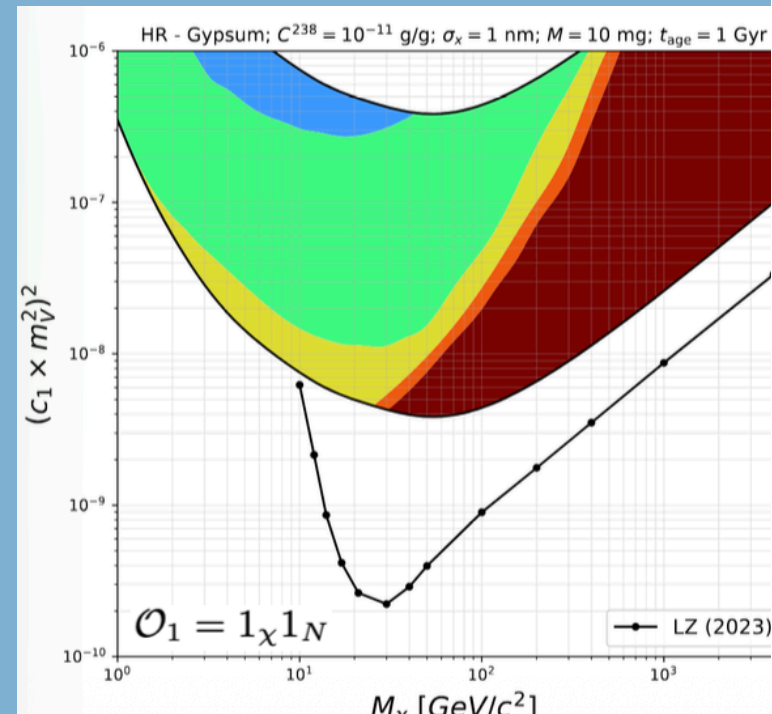
First direction sensitive search for dark matter with a nuclear emulsion detector at a surface site 2310.06265v2



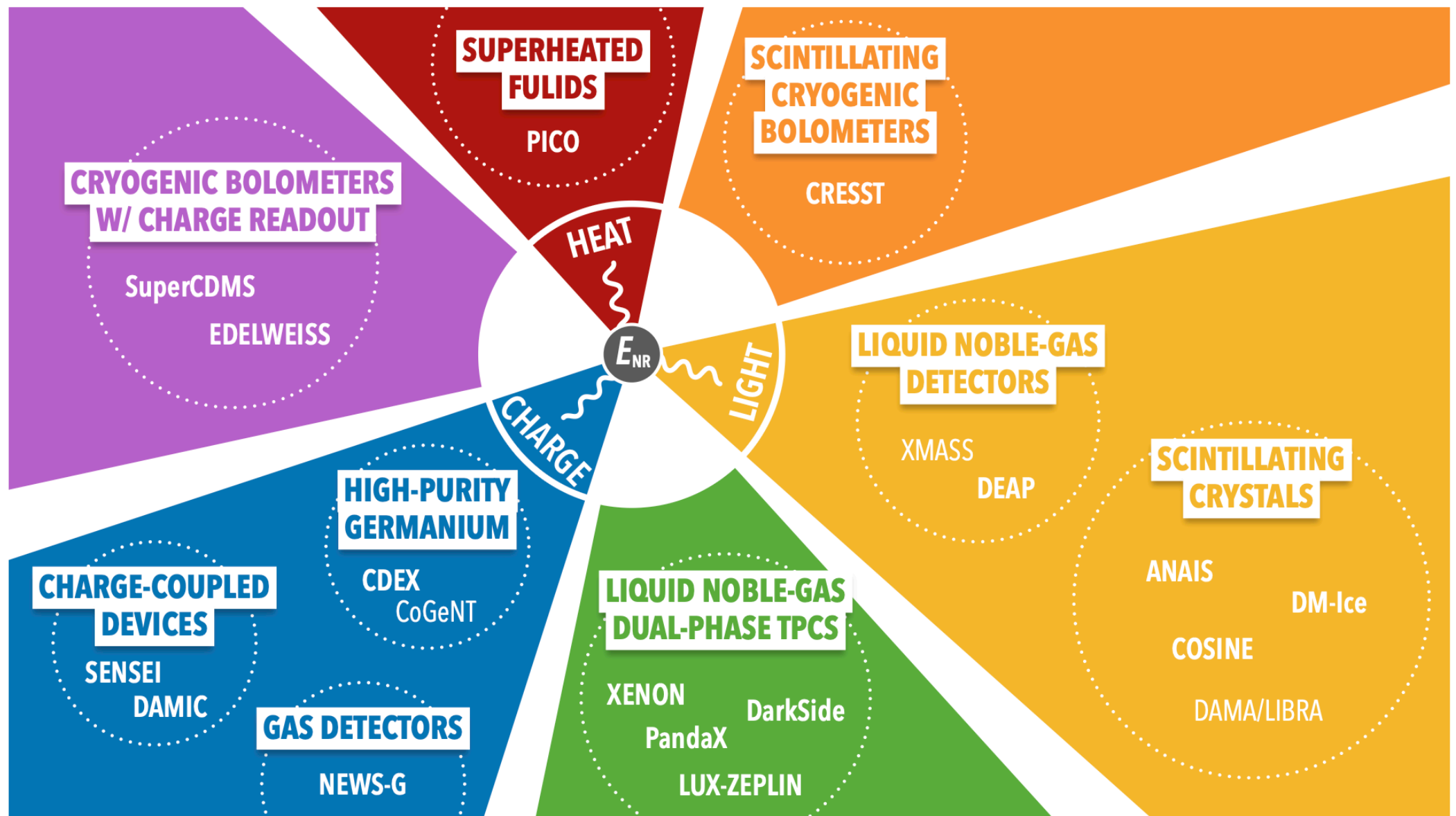
PALEODETECTORS

- Nuclear recoils can make small tracks in rocks
- A way to get enormous exposures, giga-years available
- Requires very extensive analysis and automated scanning machinery to make work— so far, an ambition!
- DMICA aims for a tonne-year
- Very detailed understanding of backgrounds and aging will be required for these to make discovery in addition to limits

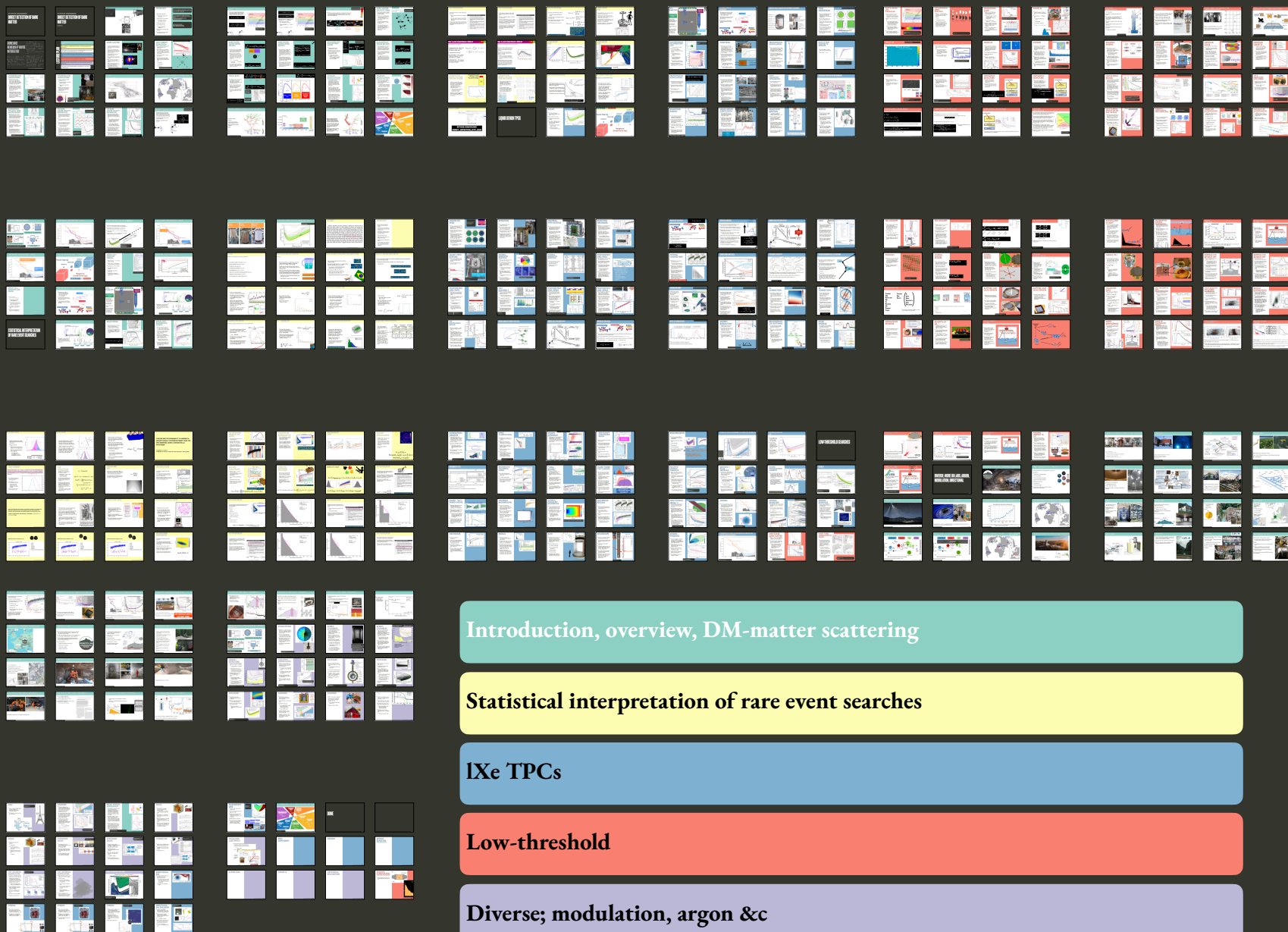
Paleo-Detectors: An Alternative Approach to Direct Detection
Dionysios P. Theodosopoulos IDM 2026



SIGNATURES OF A DARK MATTER RECOIL



DONE



Introduction, overview, DM-matter scattering

Statistical interpretation of rare event searches

IXe TPCs

Low-threshold

Diverse; modulation, argon &c

github.com/kdund/direct_detection_ictp_2026/

includes link to slides