International Center for
Quantum-field Measurement Systems for
Studies of the Universe and Particles
WPI research center at KEK

Hunting Dark Matter at Kamioka Underground

Bui Tuan Khai[1], T. Barbera[2], Suerfu Burkhant[1], D. Chernyak[3], C. Ferrari[2], M. Garcia-Sciveres[1,4], M. Hasegawa[1], K. Hattori[1], K. Ichimura[3], K. Ishidoshiro[1,3], Y. Kamei[3,5], K. Kiuchi[6], R. Kriboo[1], A. Kusaka[4,6], X. Li[3], J. Lin[3], B. Russell[2], A. Suzuki[1,4], J. Suzuki[7], O. Tajima[7], V. Takhistov[1], S. Yoshida[8]

[1] QUP, KEK
[2] Laboratory for Nuclear Science, MIT
[3] Research Center for Neutrino Science (RCNS), Tohoku University
[4] Physics Division, Lawrence Berkeley National Laboratory (LBNL)
[5] Center for Advanced Photonics, The Institute of Physical and Chemical Research (RIKEN)
[6] Department of Physics, Faculty of Science & Graduate School, The University of Tokyo
[7] Department of Physics, Faculty of Science, Kyoto University
[8] Department of Physics, Graduate School of Science, Osaka University

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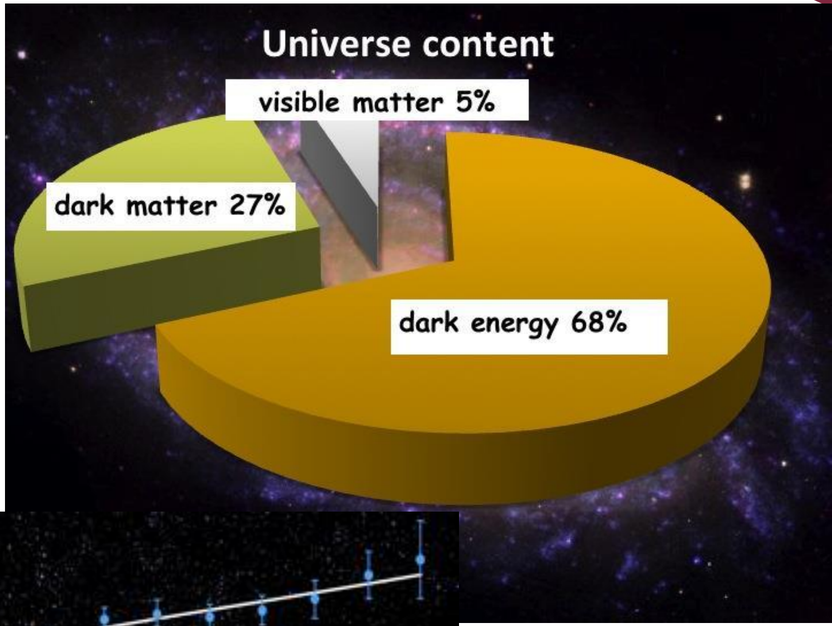
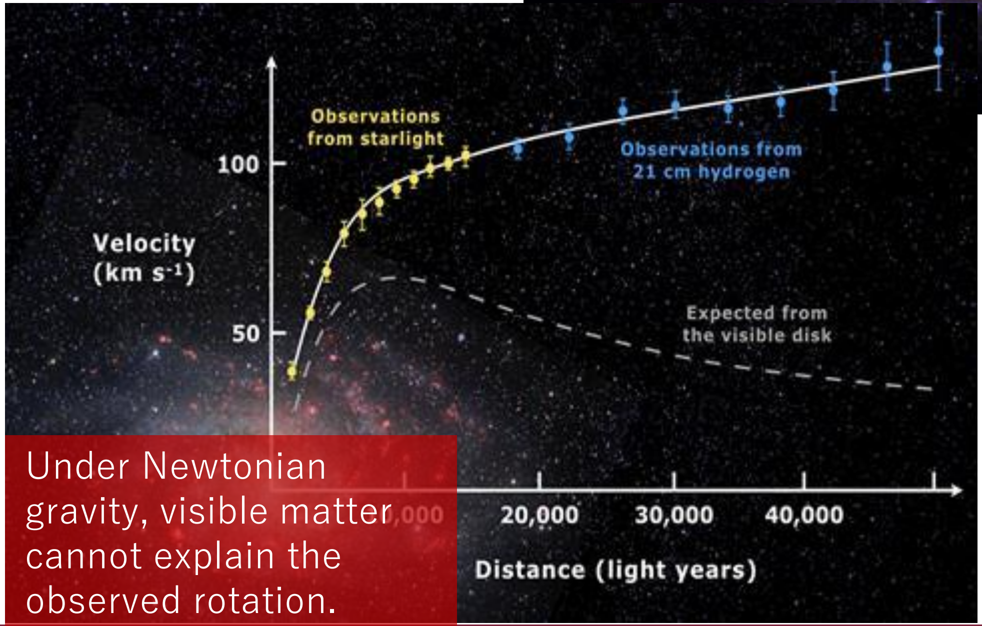
Dark Matter: what we know so far

- Makes up roughly >80% of matter in the universe.
- Invisible (that's why it's called "dark matter" - DM)
- DM is not made up of Standard Model (SM) particles
- Evidence for DM is solid





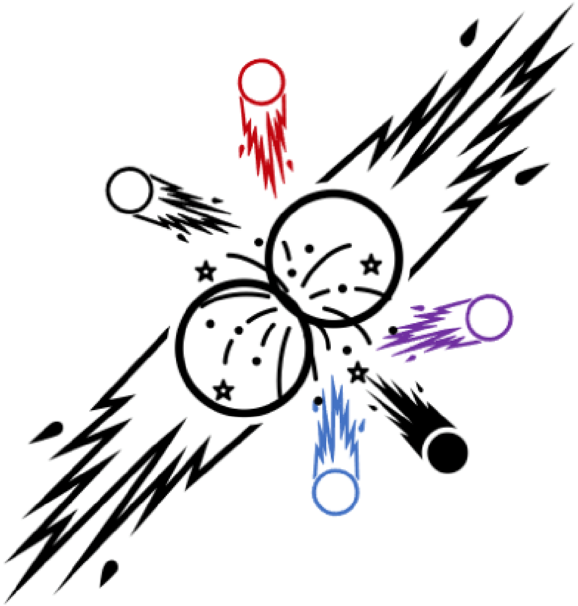
Under Newtonian gravity, visible matter cannot explain the observed rotation.

Dark Matter: how to detect?

- Detecting dark matter (DM) involves exploiting interactions with SM
- Three possible ways to study DM

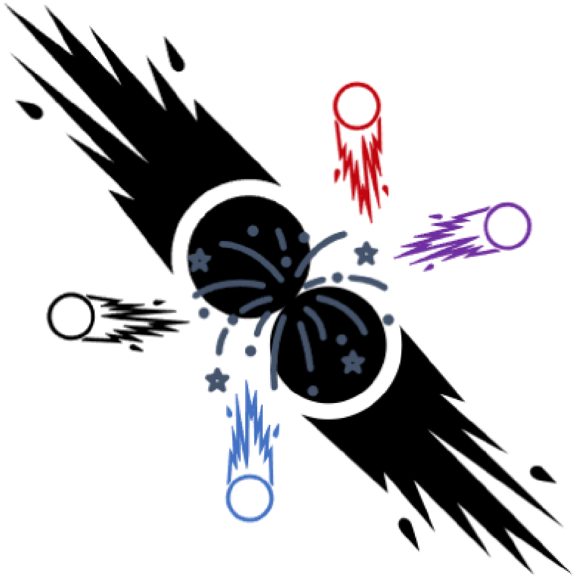
Make it!

Dark matter can be produced in collisions between Standard Model particles



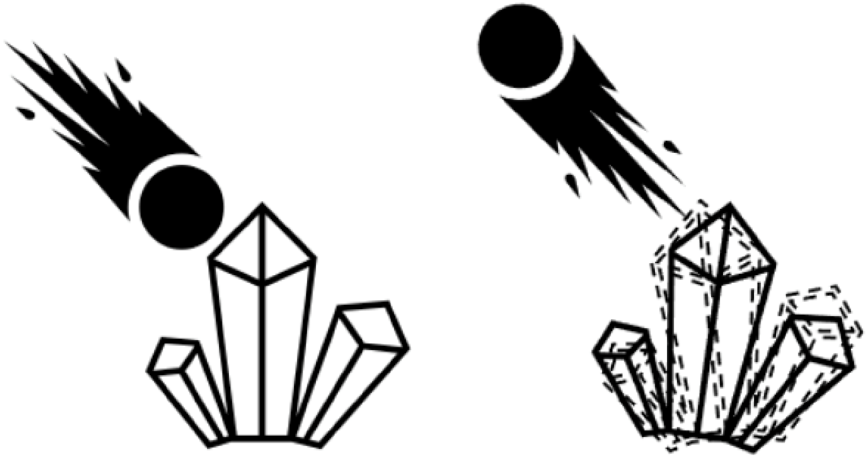
Break it!

Dark matter annihilations can create Standard Model particles



Shake it!

Dark matter collides with a target causing observable changes



Credit: mjzurowski.github.io/dm

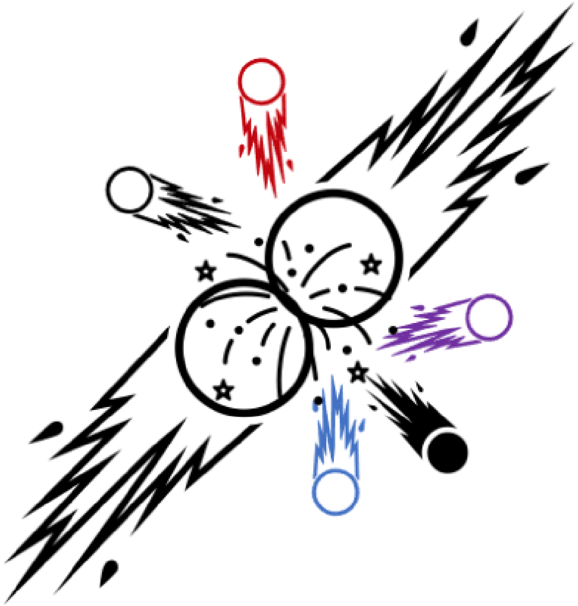
Dark Matter: how to detect?

- Detecting dark matter (DM) involves exploiting interactions with SM
- Three possible ways to study DM

Our Light DM group is interested in this

Make it!

Dark matter can be produced in collisions between Standard Model particles



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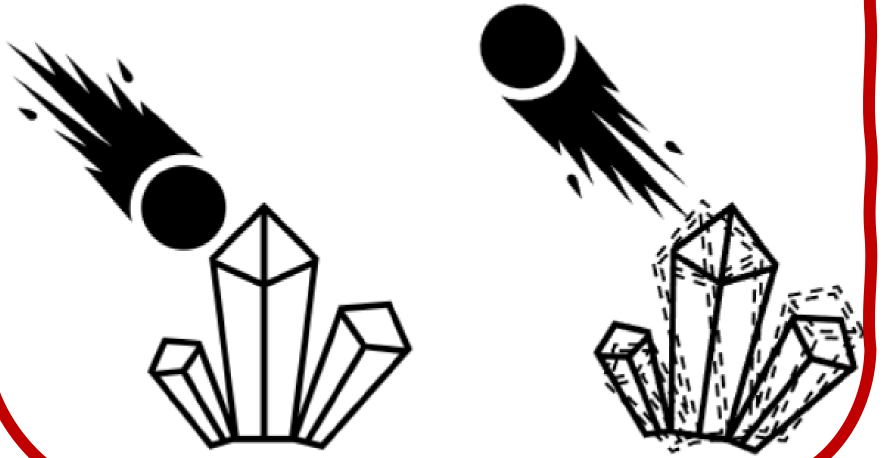
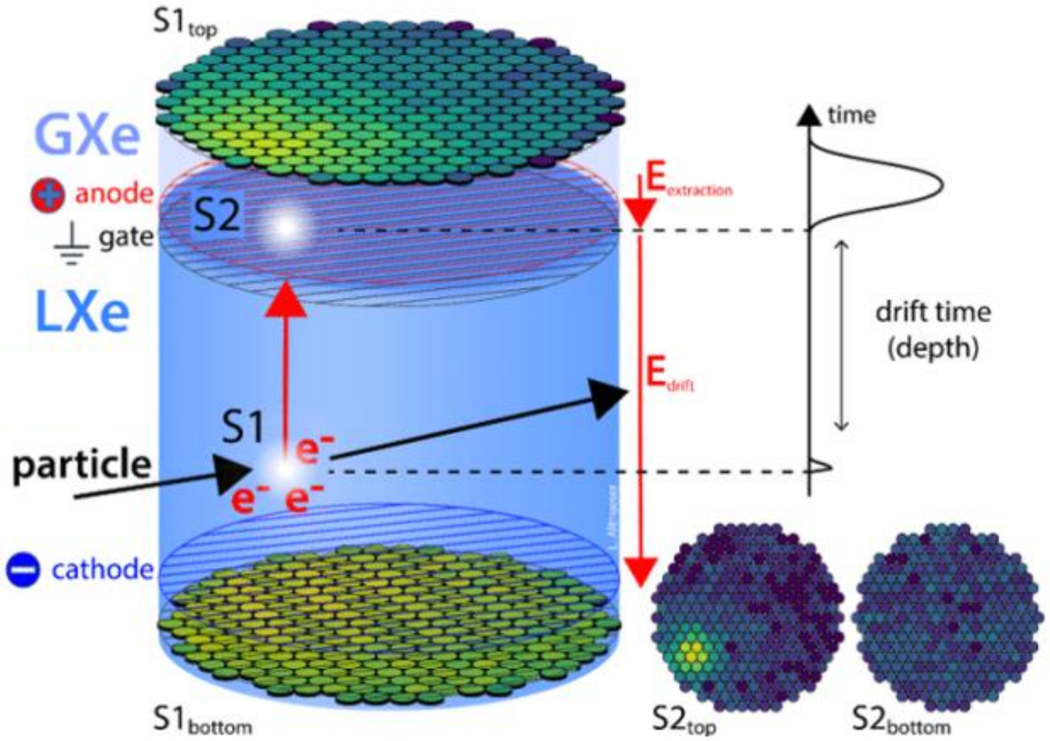
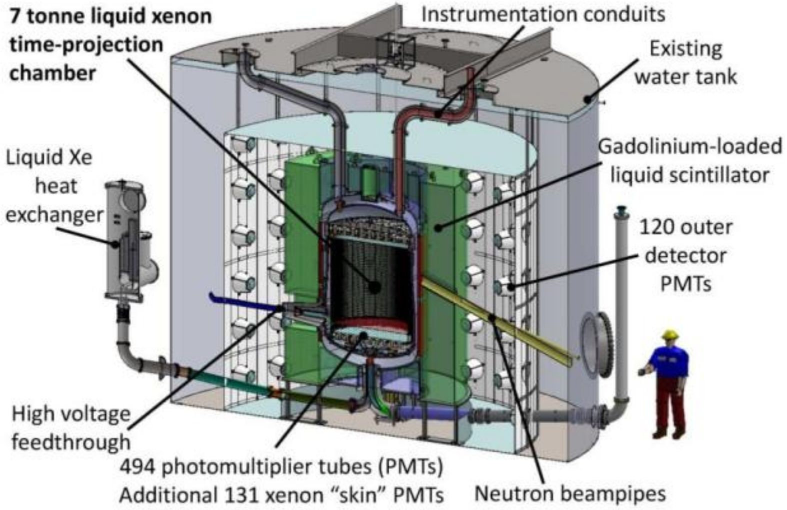
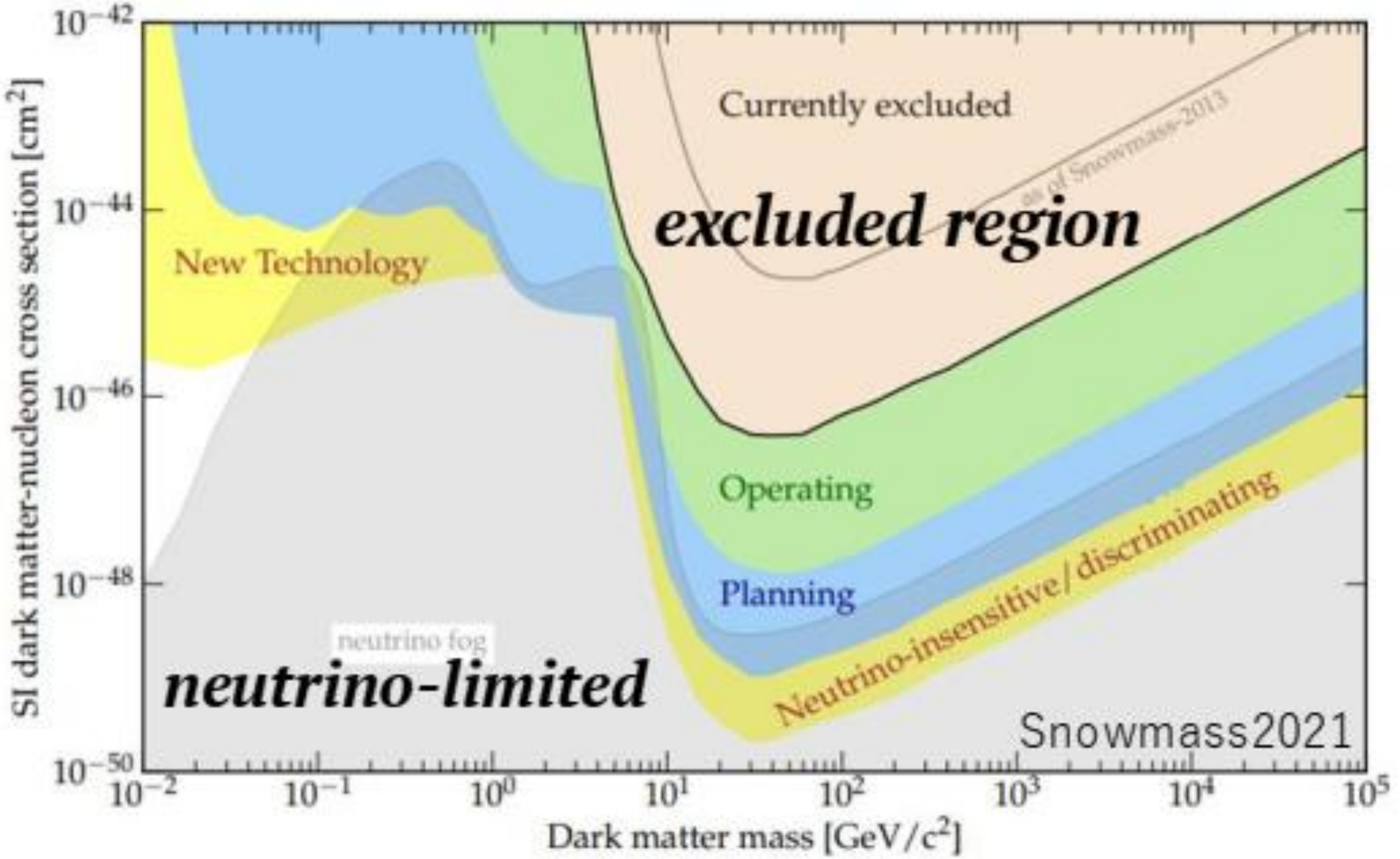


Credit: mjzurowski.github.io/dm

Current status of Dark Matter



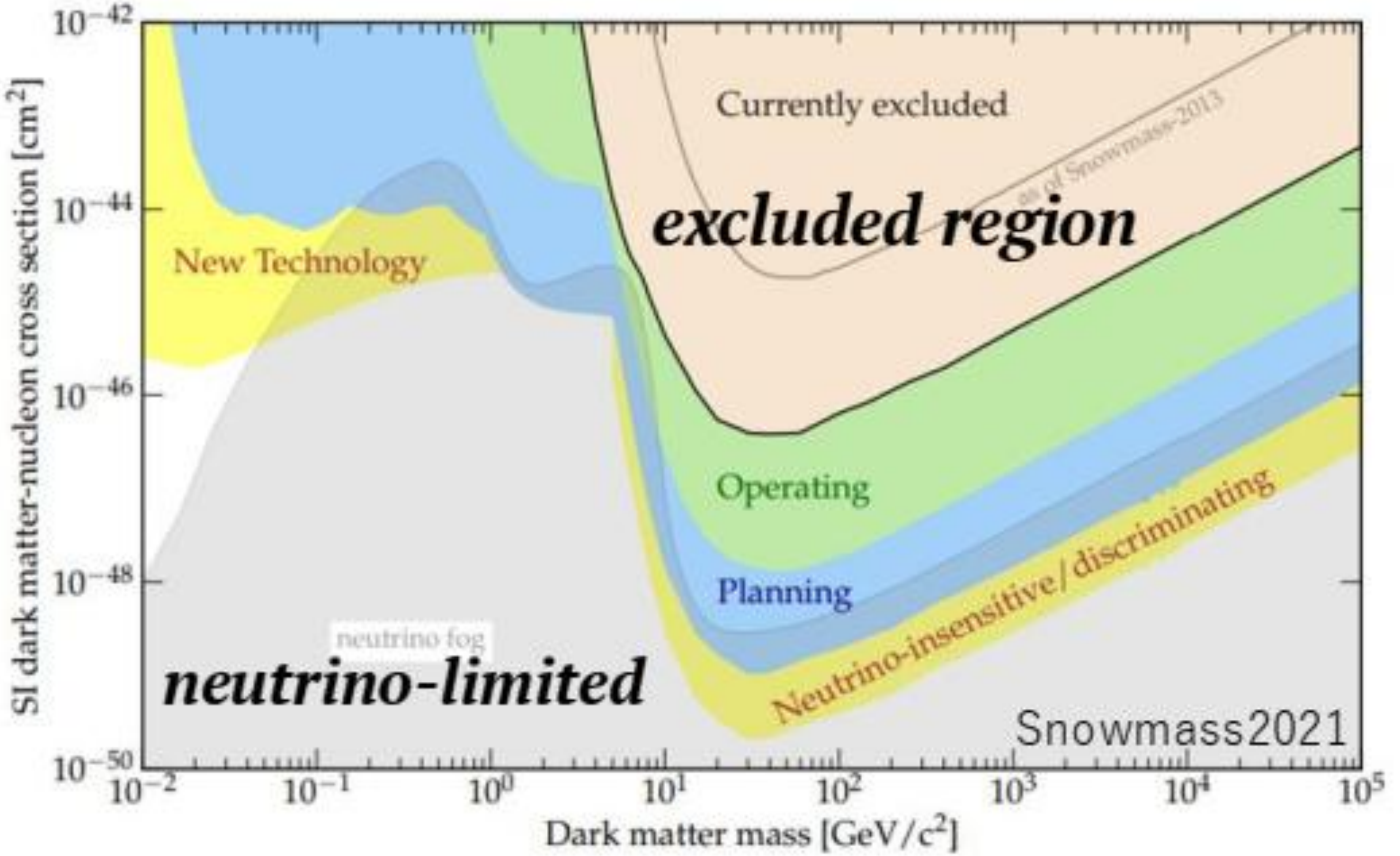


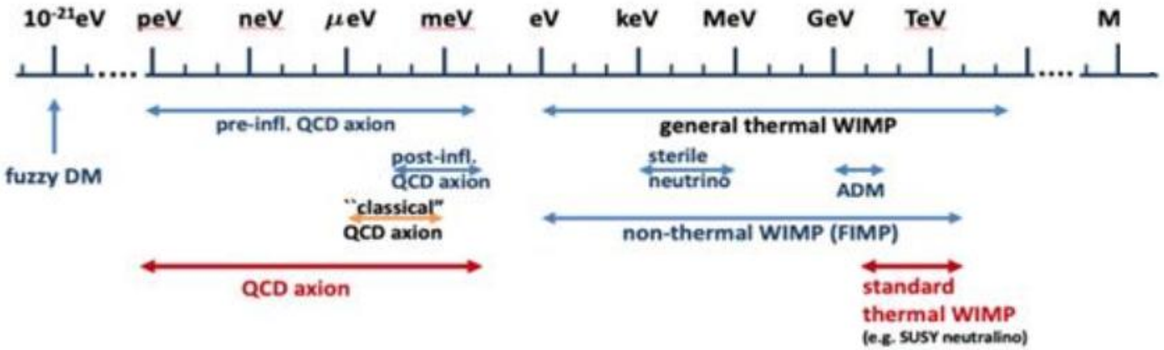


- Leading experiments: TPC + dual-phase gas
  (LZ, XENONnT, PandaX, DarkSide, …)
- Touching ν-floor: XENONnT

Current status of Dark Matter

- Next: low-mass dark matter (m<1GeV)
- Appear in variety of theories previously unexplored
- requires: low-threshold high-sensitivity

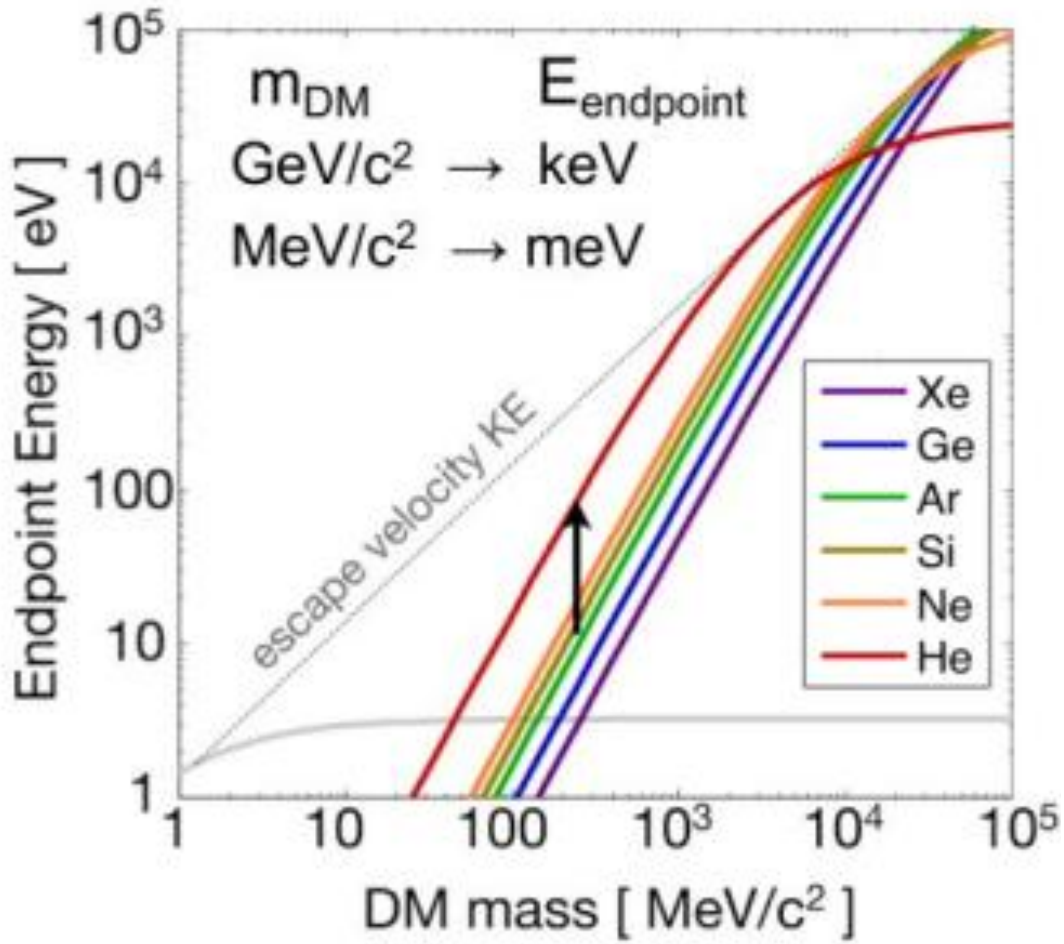




- Leading experiments: TPC + dual-phase gas (LZ, XENONnT, PandaX, DarkSide, …)
- Touching ν-floor: XENONnT

Low threshold Transition Edge Sensor

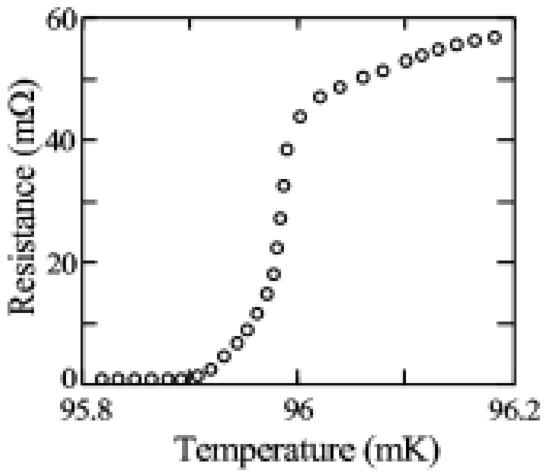
from D. Mckinsey, SNOLAB workshop 2021



- Search for NR DM in mass range down to 100MeV, the recoil energy: about tens of **eV.**

⇒Not **keV scale** in tonne-scale experiment

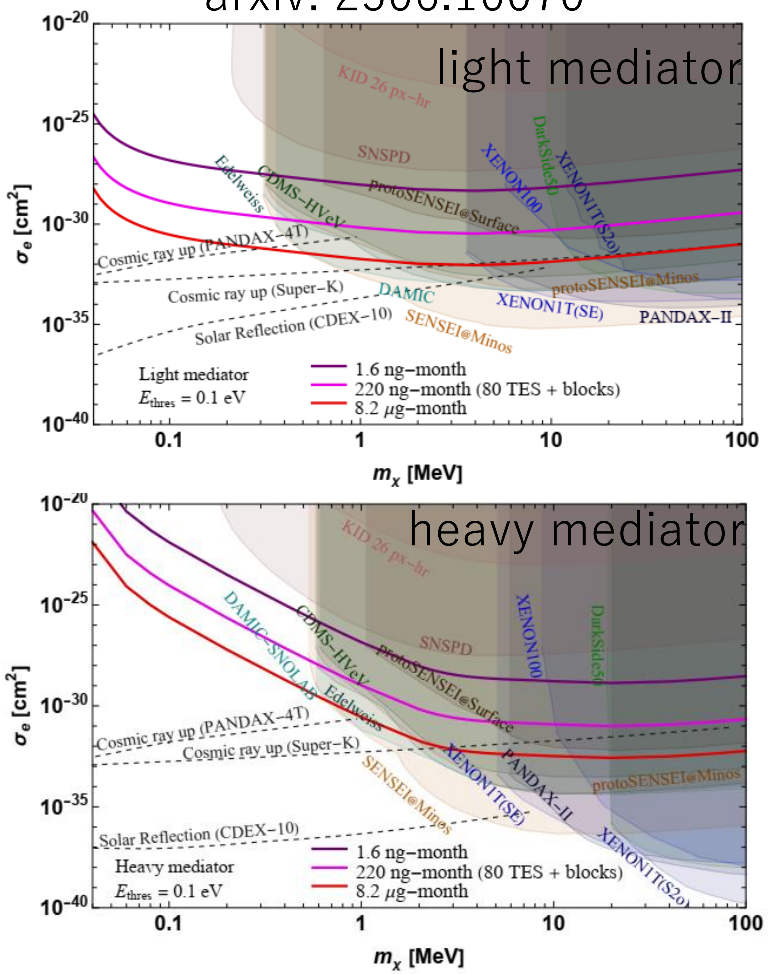
- Not possible in ionization or scintillation, but possible for phonon detection



⇒detector based on Transition Edge Sensor (TES), highly sensitive to temperature perturbations.

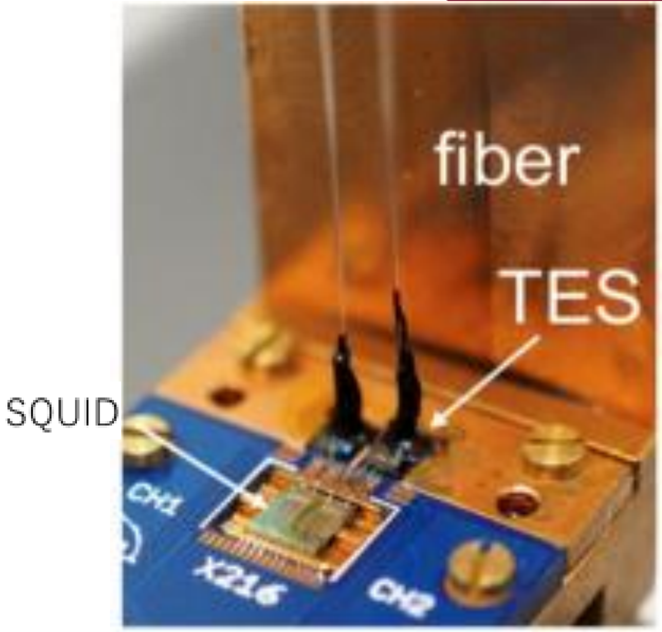
Kamioka DM project: Optical TES for ERDM search

arxiv: 2506.10070

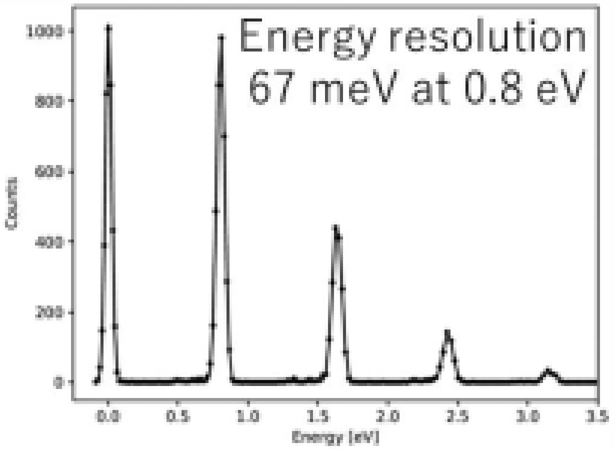


- Optical TES developed at QUP
- Sensitive to single photon/electron at eV scale
- Multiplexing readout: R&D
- Targets: Al, GaAs, CaF2
- Electron-Recoil (ER) search for DM down to sub-MeV mass range

⇒**long-term (5 years) project**



Coupled with a fiber



Many alternative ideas

TOHOKU UNIVERSITY · 東京大学 THE UNIVERSITY OF TOKYO · KYOTO UNIVERSITY · Saitama University · 筑波大学 University of Tsukuba · 大阪大学 OSAKA UNIVERSITY · NICT · RIKEN · BERKELEY LAB Lawrence Berkeley National Laboratory · Massachusetts Institute of Technology

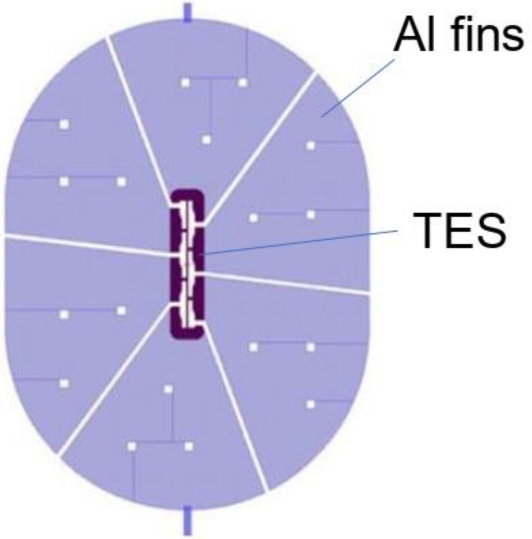
- MeV-scale DM search with superconductors
- Sub-GeV DM search with spin-dependent interaction with ^{19}F
- Inelastic DM search ^{180m}Ta
- Directional DM search with $ZnWO_4$/diamond NV center
- Hidden photon search with Dirac Materials
- DM searches on Si, GaAs, Sapphire, Graphene,
- …

⇒ All are in R&D phase

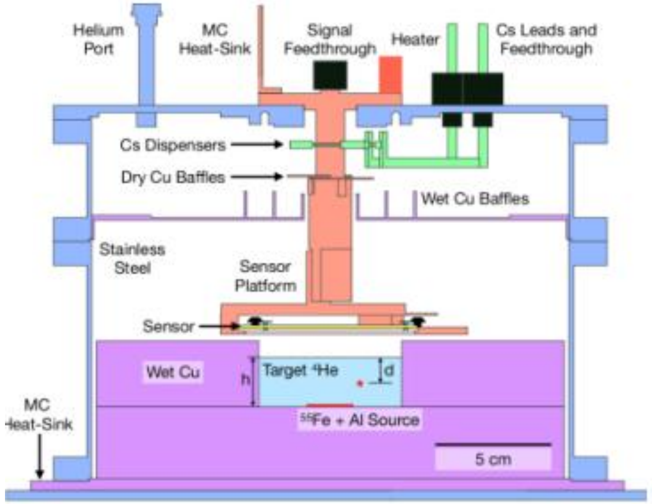
⇒ As a first step, partner with **TESSERACT** to do a first underground run of **HeRALD** (using **liquid Helium** as target) to probe nuclear recoil down to the 100 MeV scale

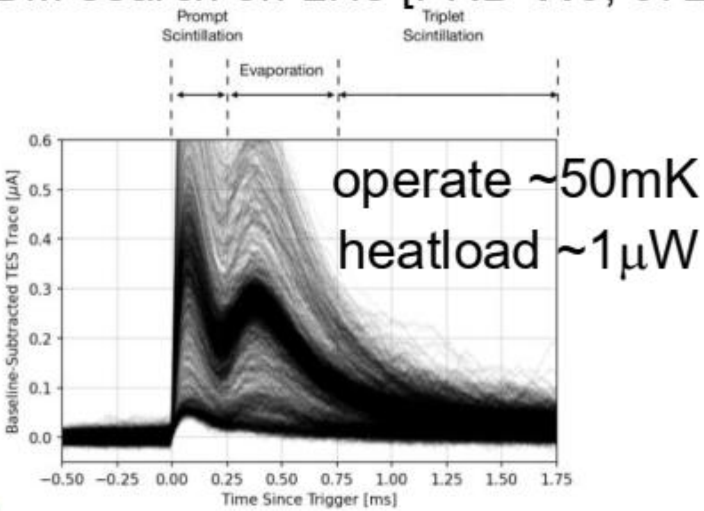
Low threshold TES in HeRALD

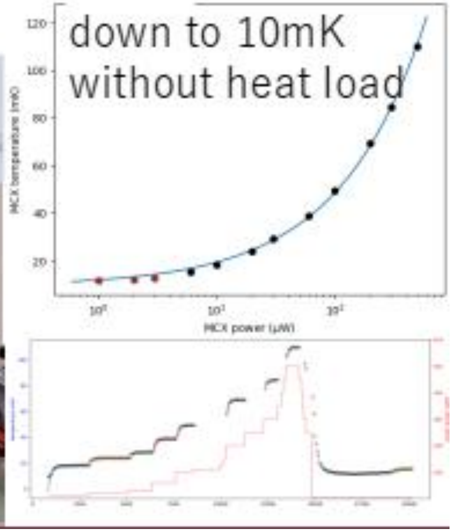
Appl. Phys. Lett. 118, 022601 (2021)



HeRALD detector concept for DM search on LHe [PRD **110**, 072006]

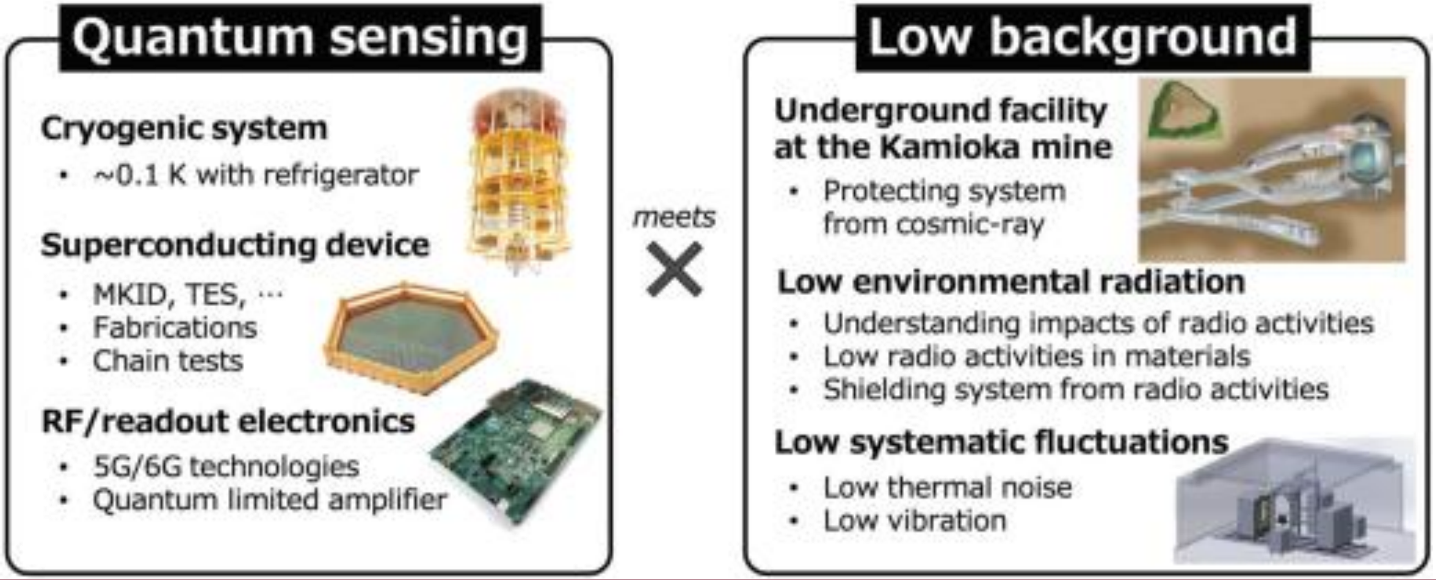


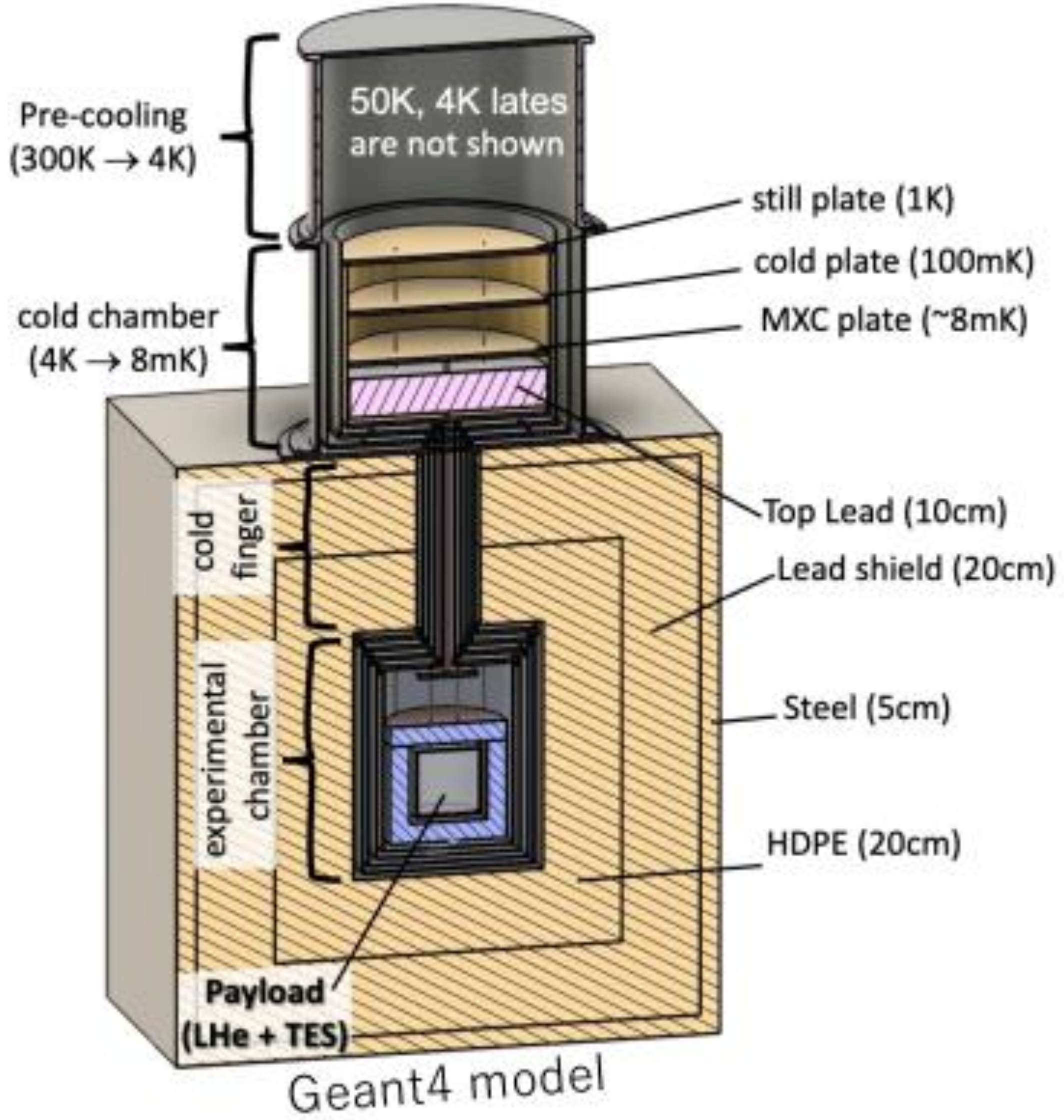




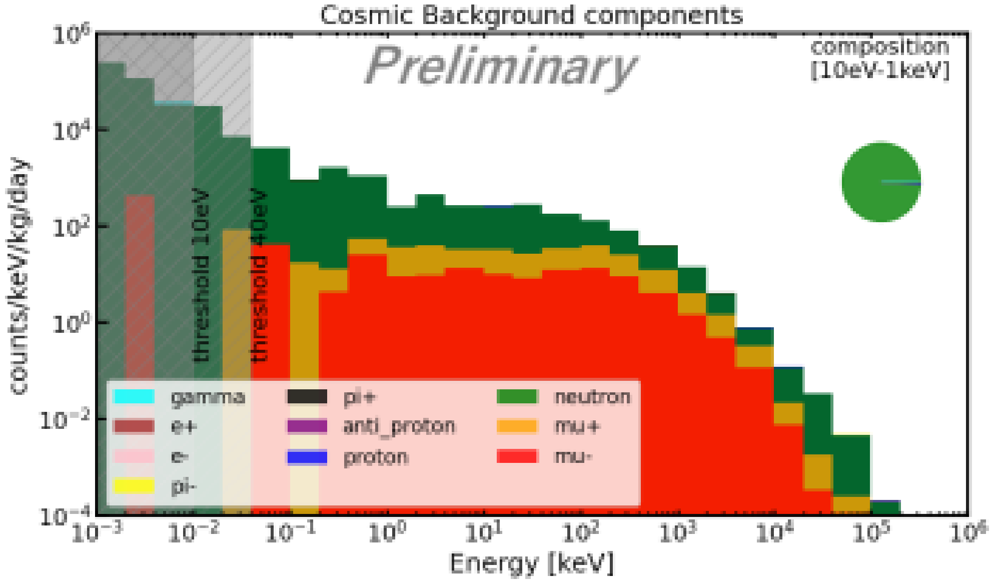
Low background environment

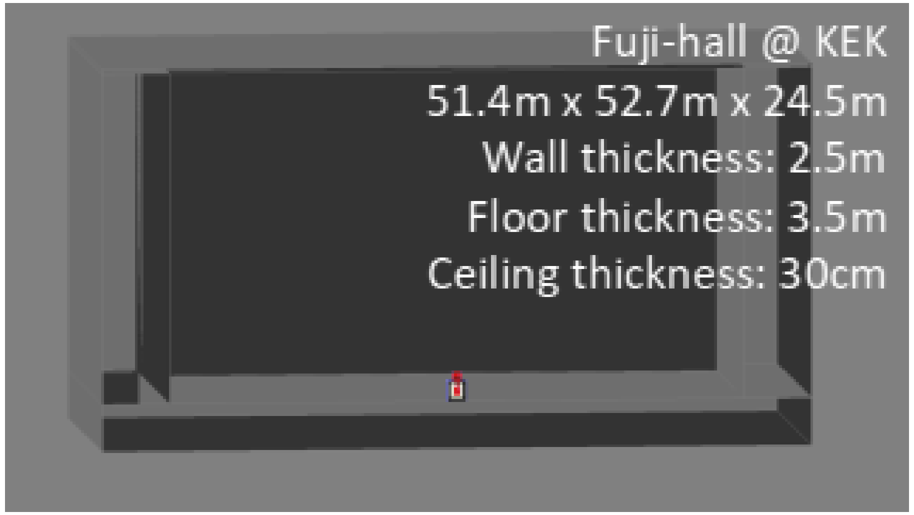
- Light dark matter interaction is
  - material dependent
  - model-dependent (coherent excitation vs electron recoil, etc.)
- It is crucial to test ***multiple dark matter targets*** in a ***low-background setup***





Cosmic BKG: Are we safe above ground?



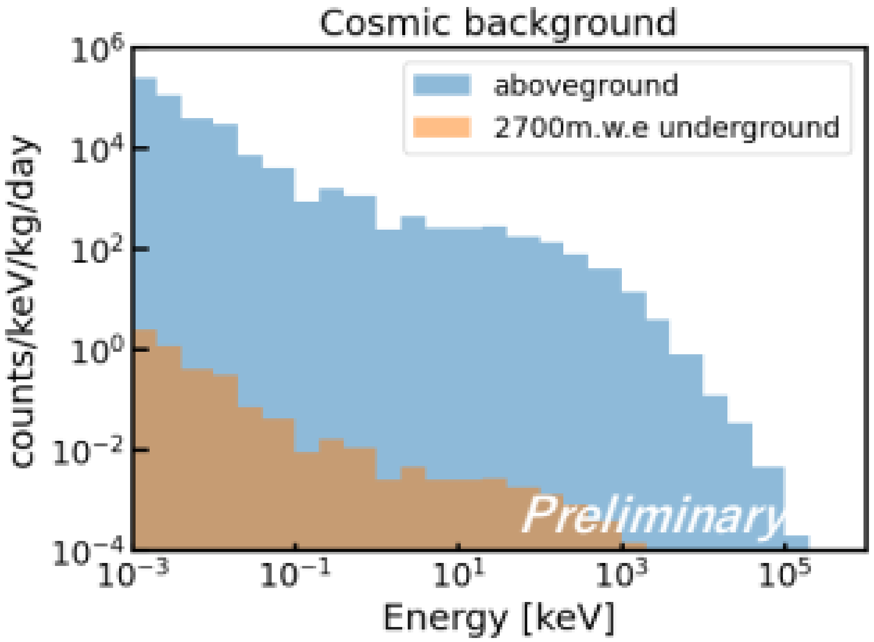


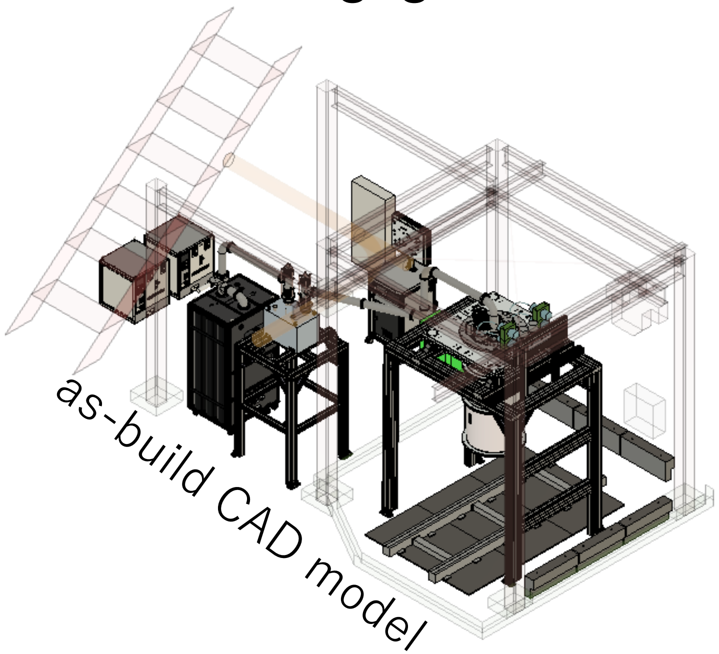
- Cosmogenic background is problematic for many tonne-scale experiments.
- We estimate the cosmogenic background at Fuji-hall at KEK (where we place our DR) using CRY (LLNL).
- Background observed in LHe is huge!

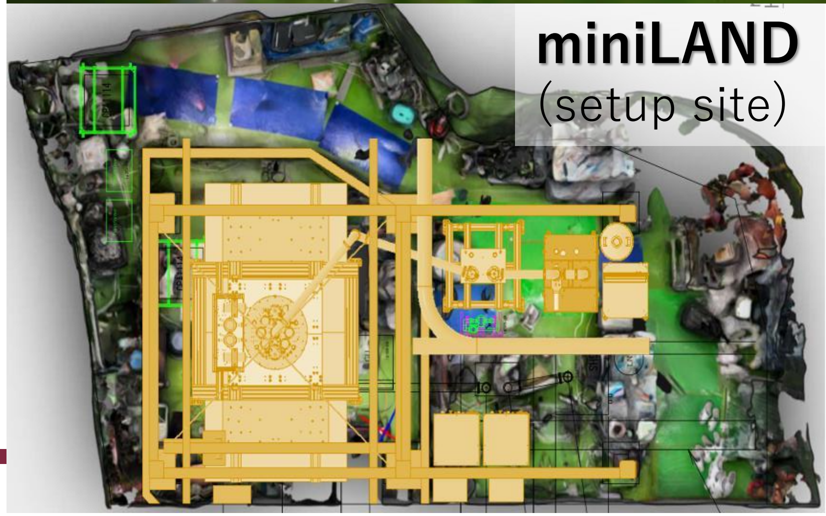
⇒ Need underground (moving cost is high)

Low background environment

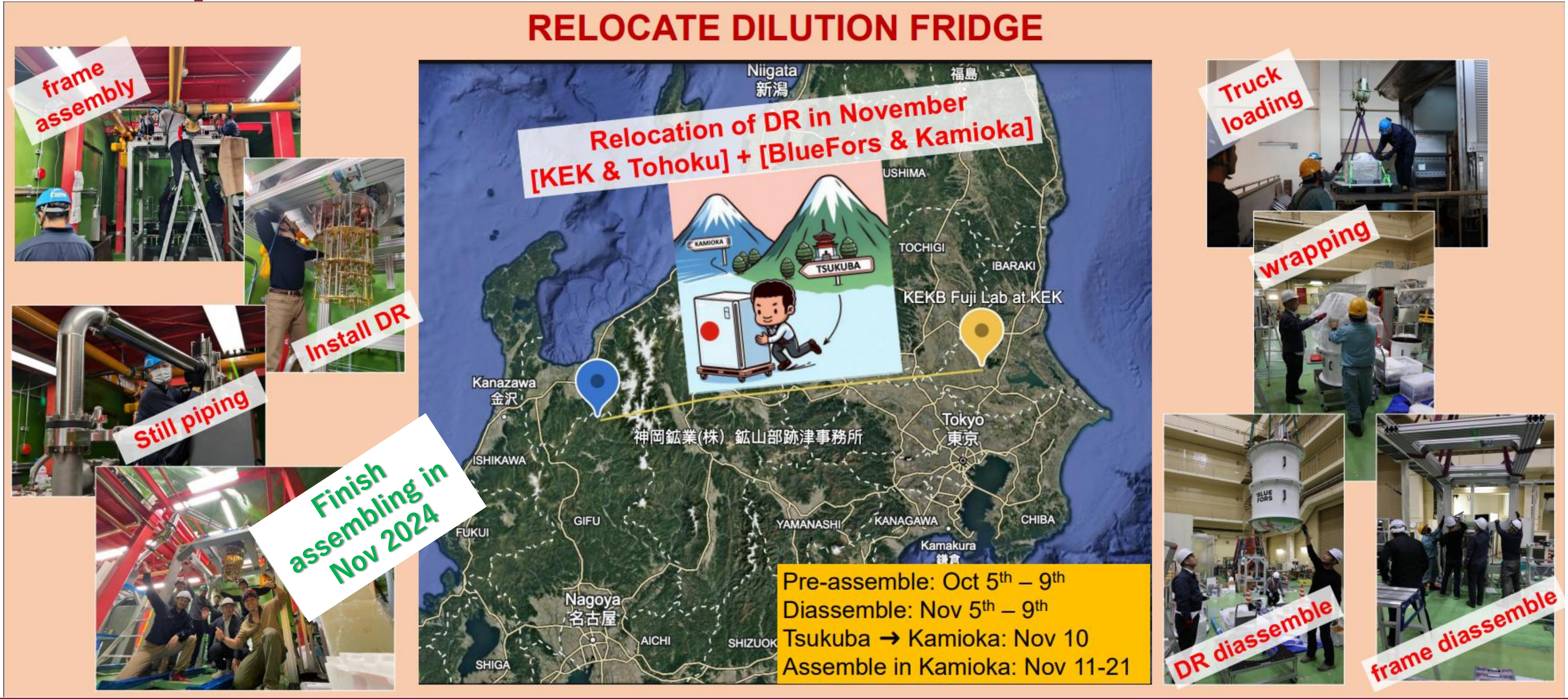
- Cosmogenic background is problematic for our experiment.
- Kamioka 2700 m.w.e underground: same site with other neutrino and DM experiments (SK, KamLAND, XMASS, …)
- Shielding the cosmic rays (1/10^5 times)
- Cosmic background can be reduced to a negligible level.







Fridge relocation + assembly in Kamioka: accomplished in November 2024



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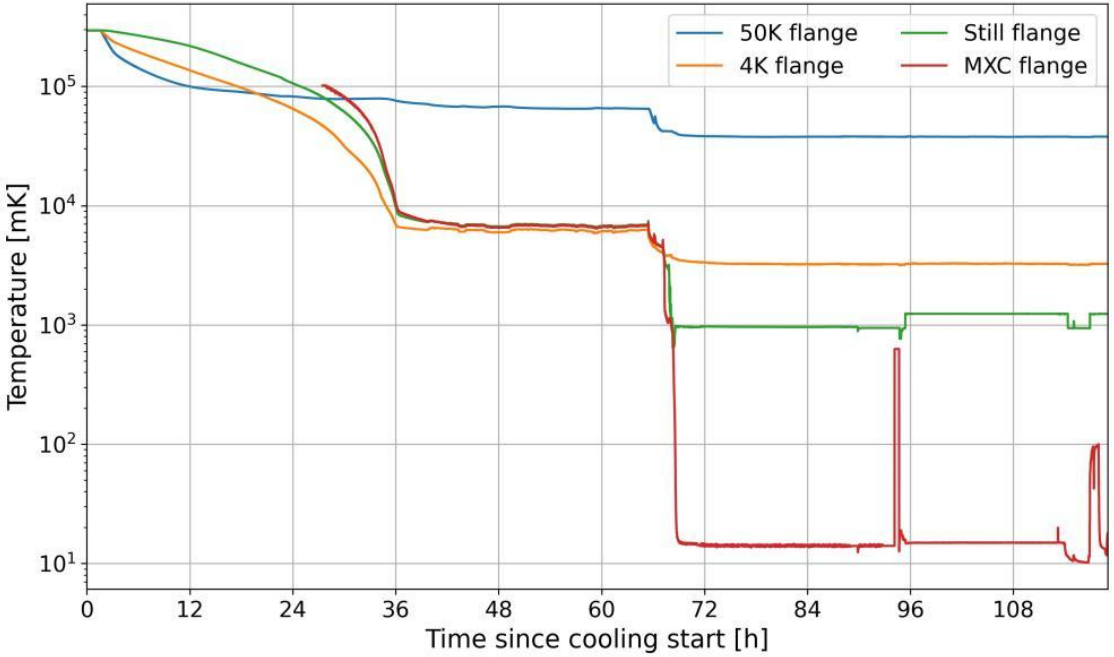
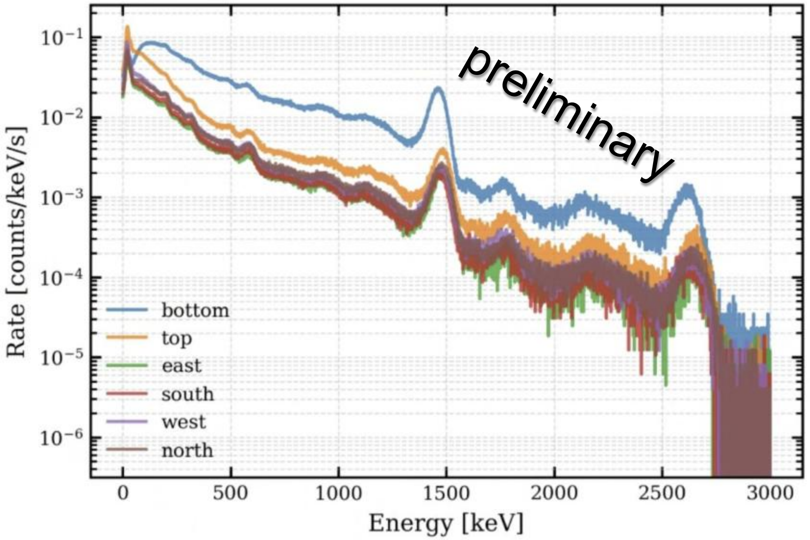
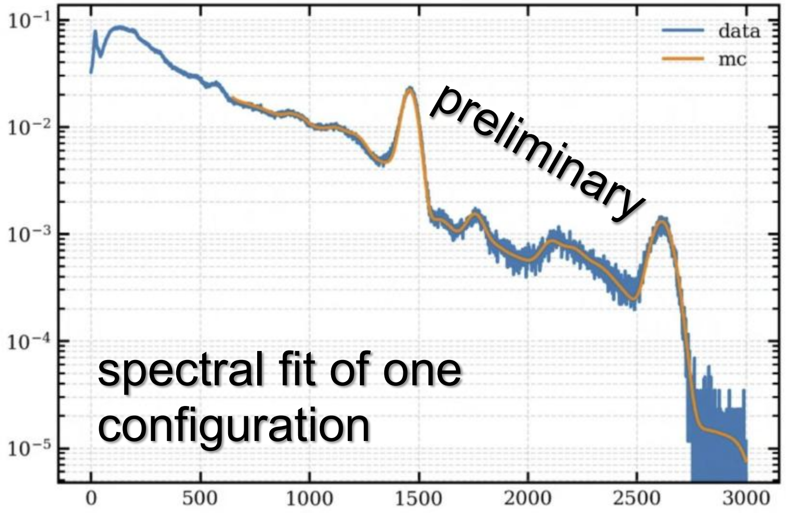


After a long preparation time, the fridge was relocated from Tsukuba to Kamioka Underground Observatory. It is placed in the KamLAND area.

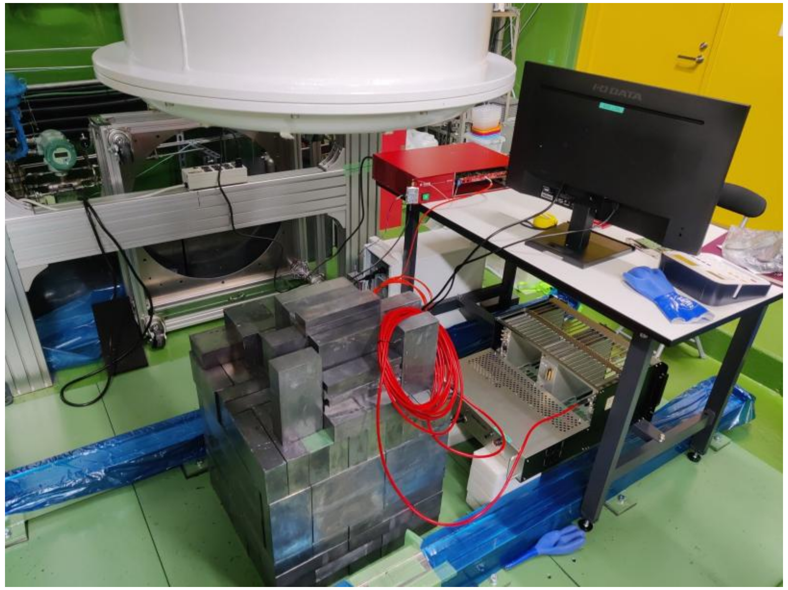
DR can cool down to ~10 mK.

Measure gamma background with NaI(Tl)



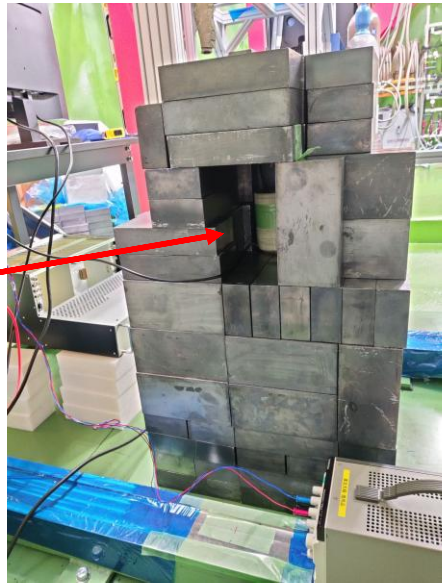


- 3” NaI(Tl) shielded with at least 15cm of lead with window in each direction.
- Custom-made PMT base and preamplifier.
- Calibration with ^{22}Na, ^{57}Co, ^{60}Co, ^{137}Cs, ^{133}Ba
- 2 weeks of data taking.

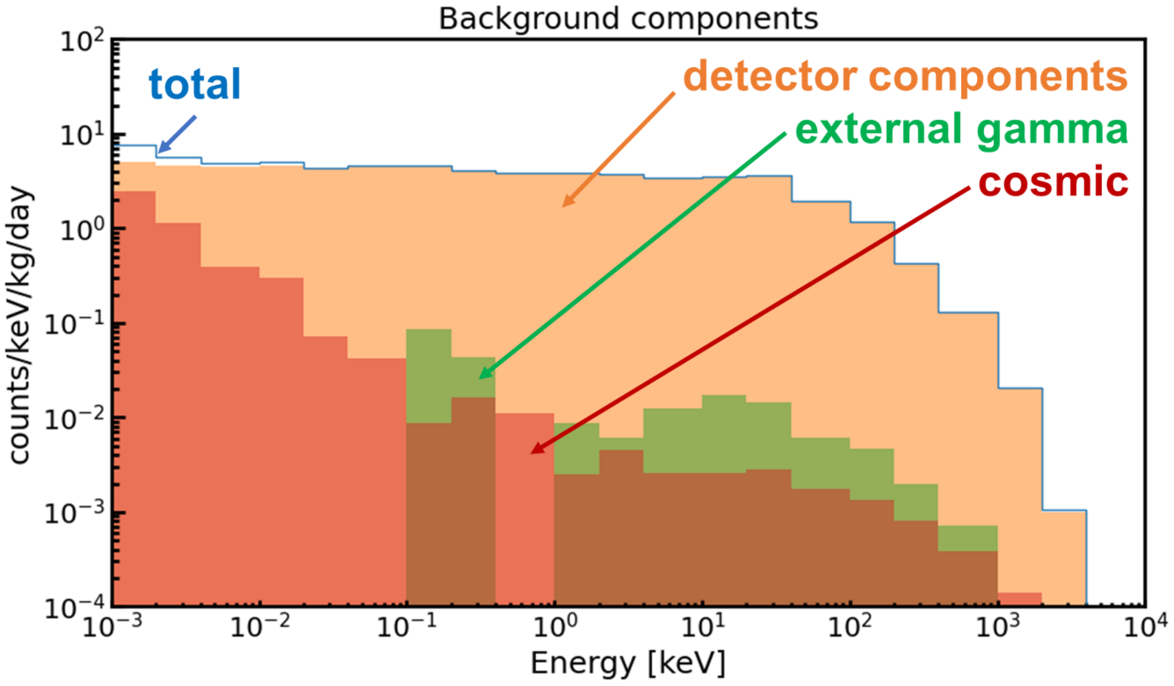


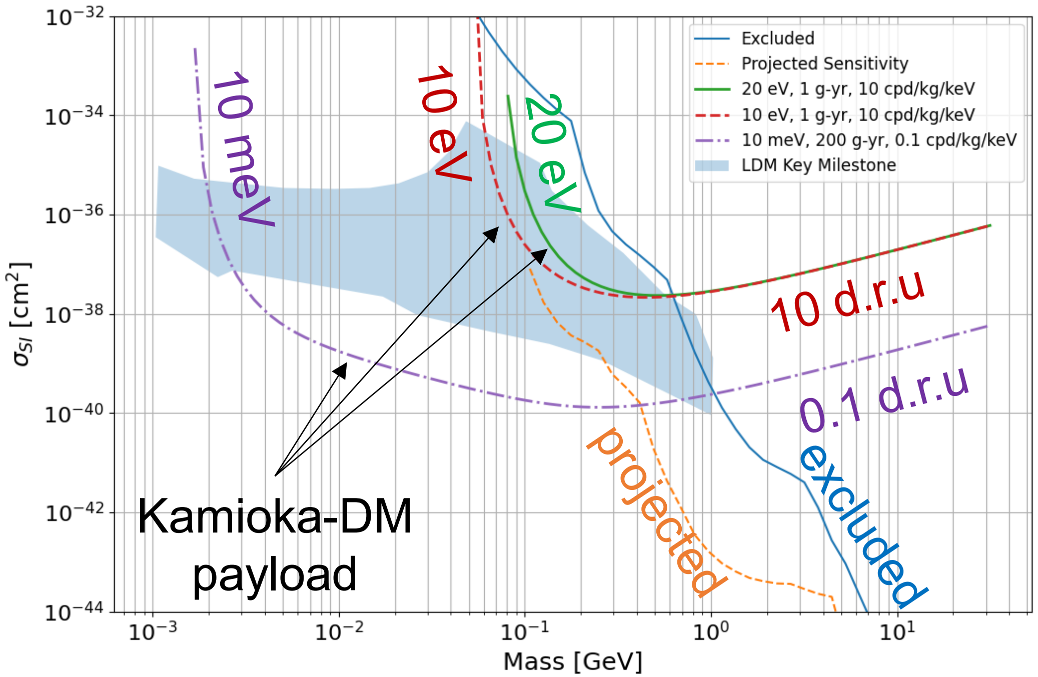
Measure right below the DR

Open window at each direction



1st payload: LHe with Berkeley TES

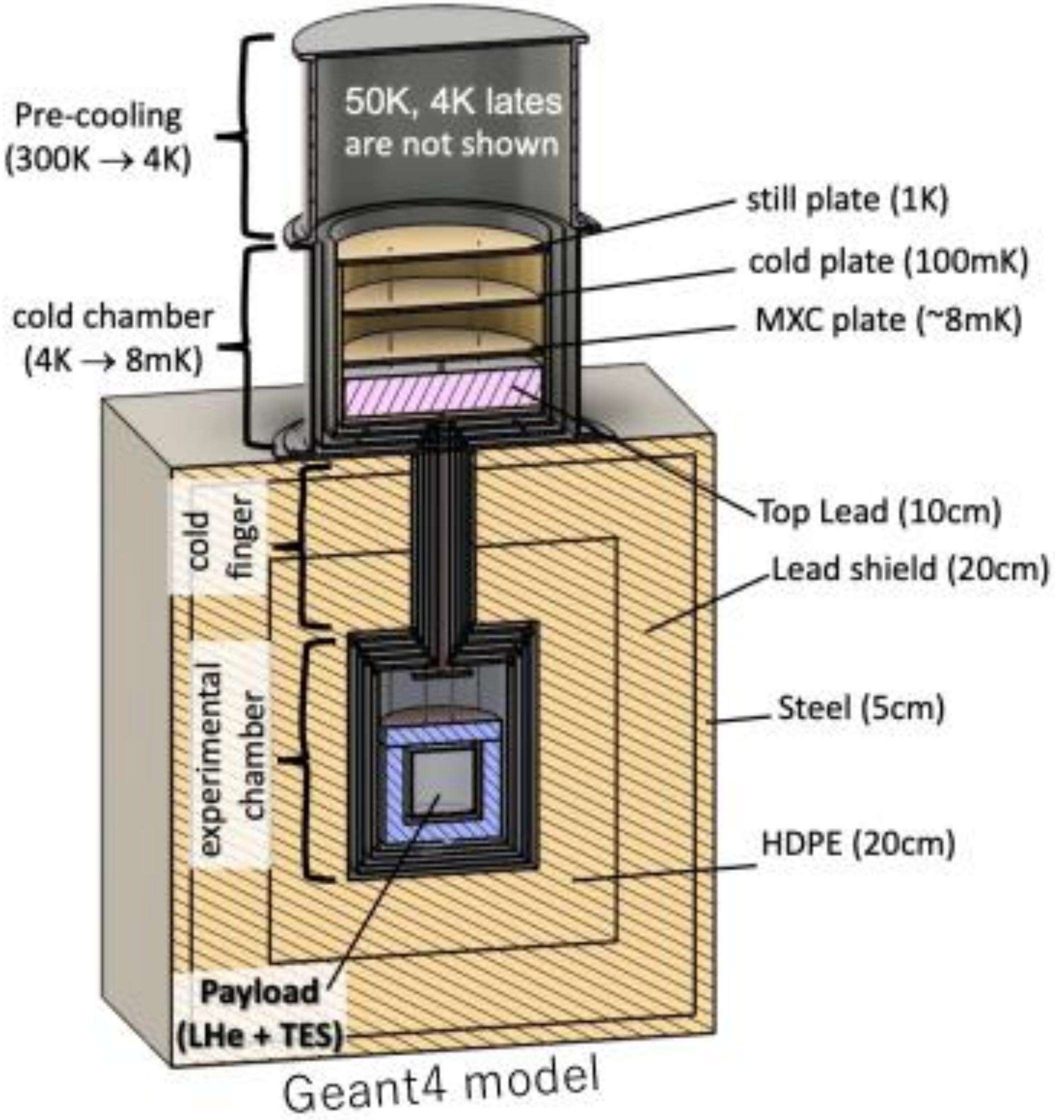




- Background level is expected <10 d.r.u, mainly background from detector components.
- Neutron BKG will be estimated soon.
- The first payload of our experiment will be LHe with TES Microcalorimeters developed by TESSERACT.
- DM mass range depends on TES threshold

Shielding design and install

- Initial design concept: a bottleneck design to reduce line-of-sight from ambient γ/n
- A few challenges on dilution fridge and shield: cost, complexity, and time to build



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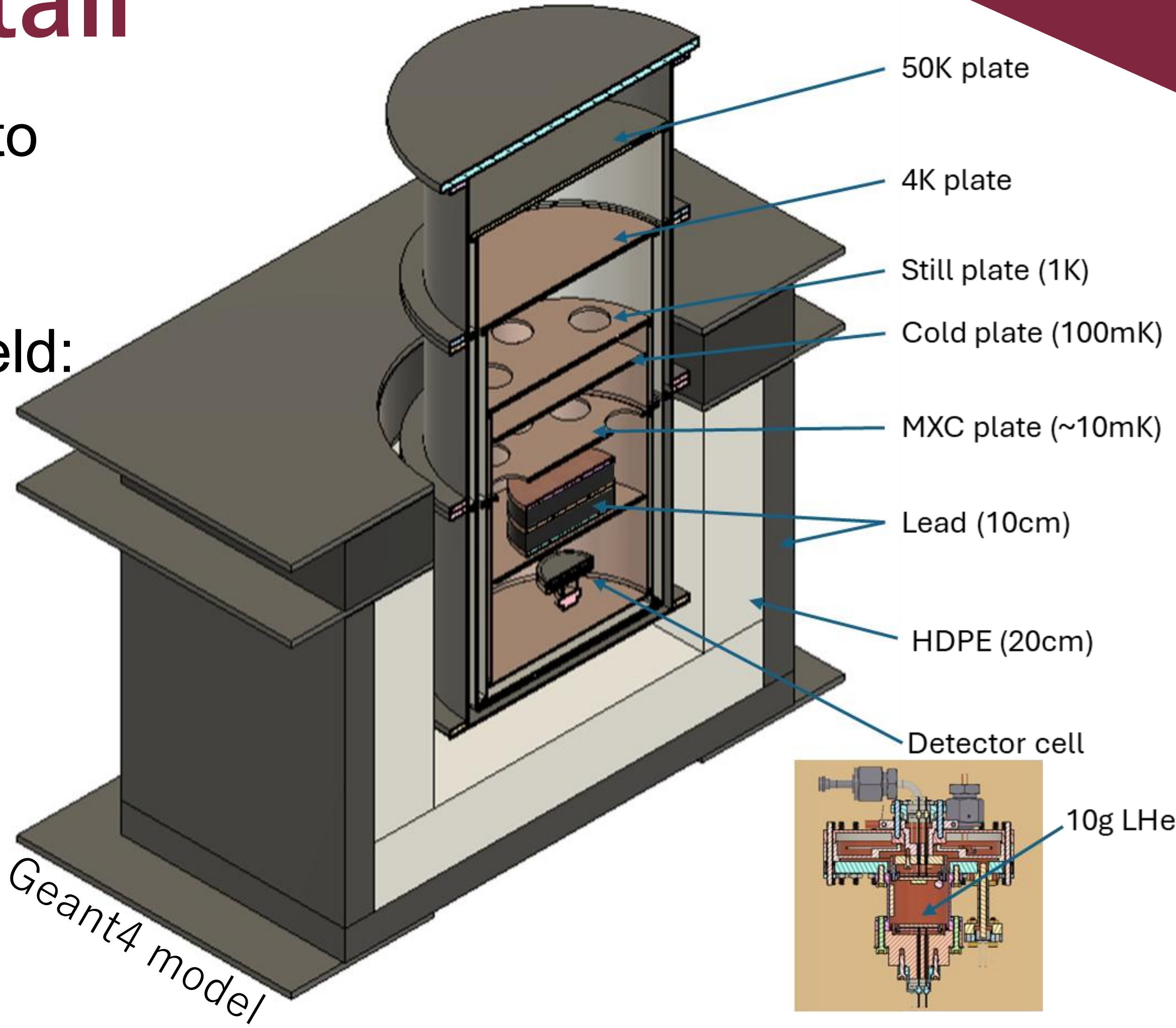
- Design the shield for current DR:
  - HDPE (20cm) for shielding neutrons
  - Pb (10cm, 5t/each-half) for shielding γ

⇒ May extend in future



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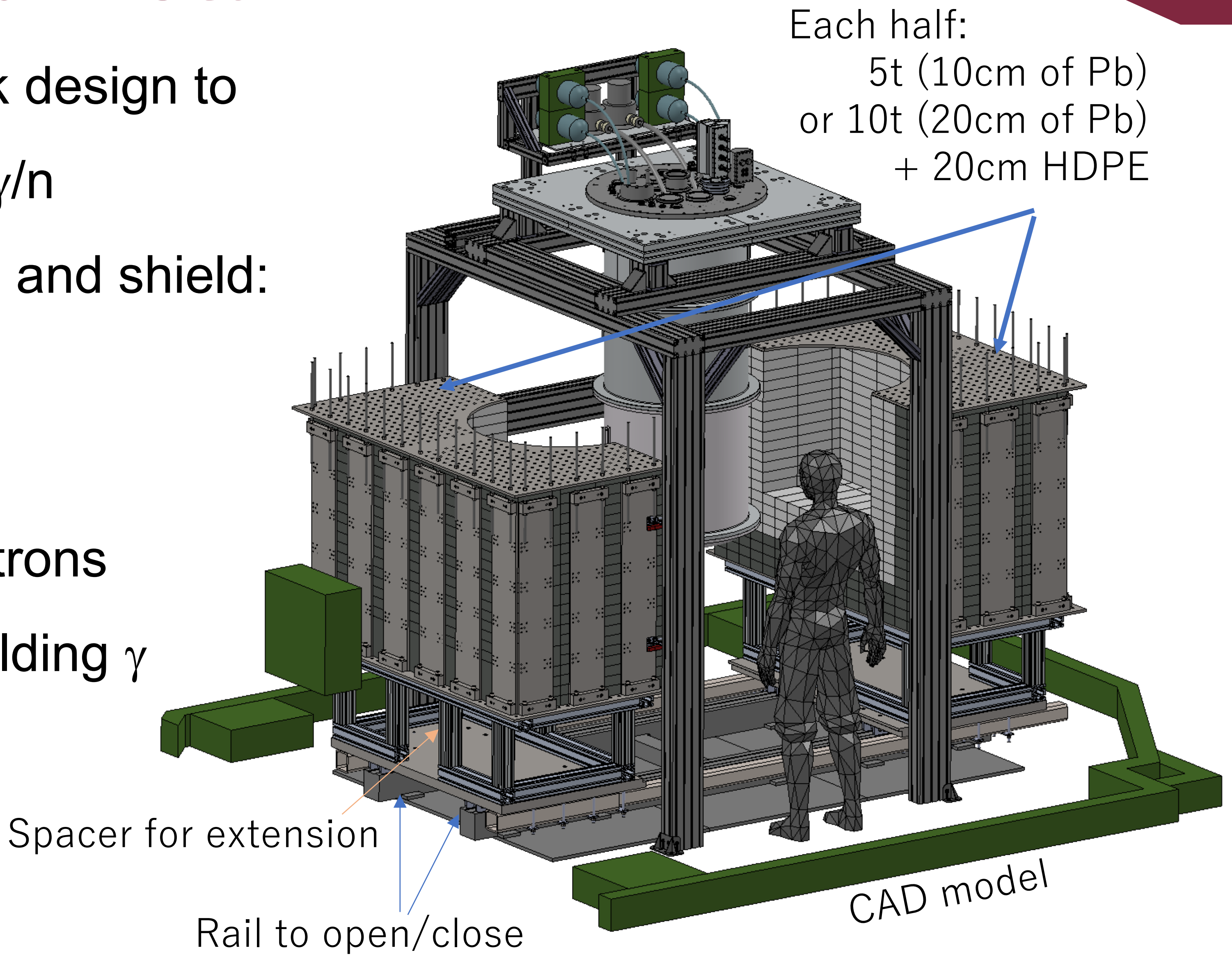
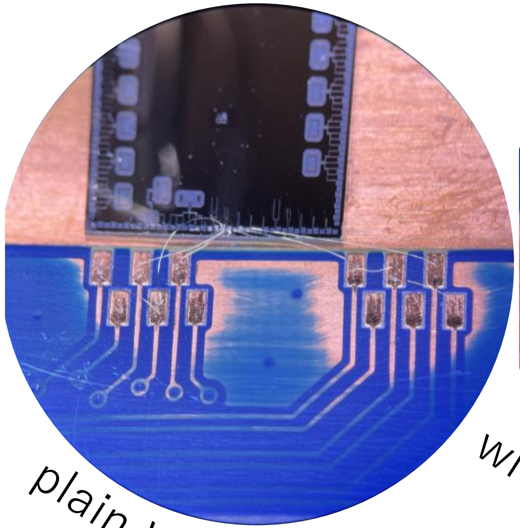
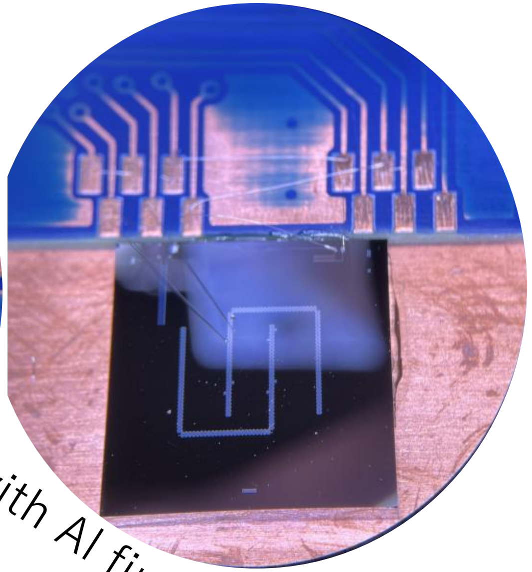
  ⇒ May extend in future
  - Rails to open/close the shield
  - Space for future extension



Detector Readout: TES



plain W

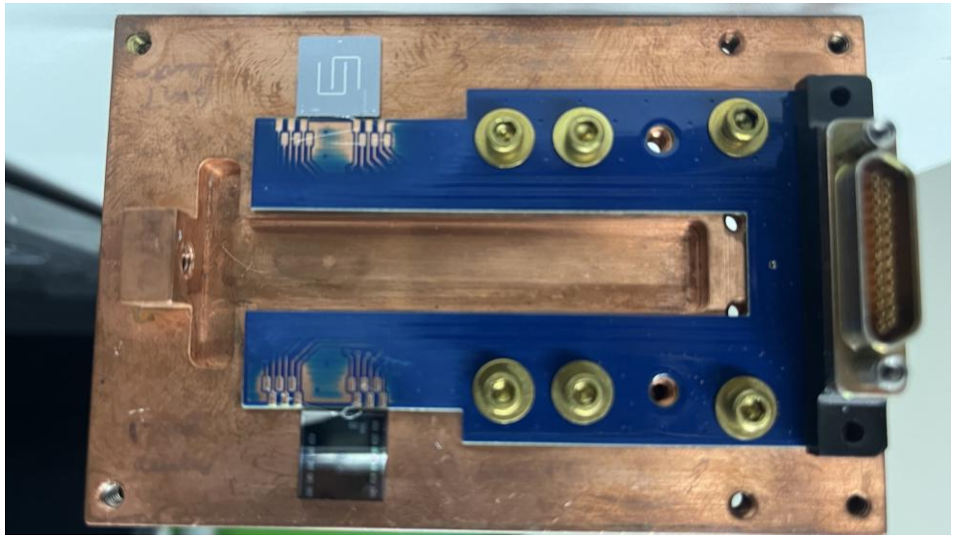


with Al fin

- TES sensors from LBNL are installed in our DR
- 2 small TES wafers and a blue PCB with DB25 output are mounted on a copper base.

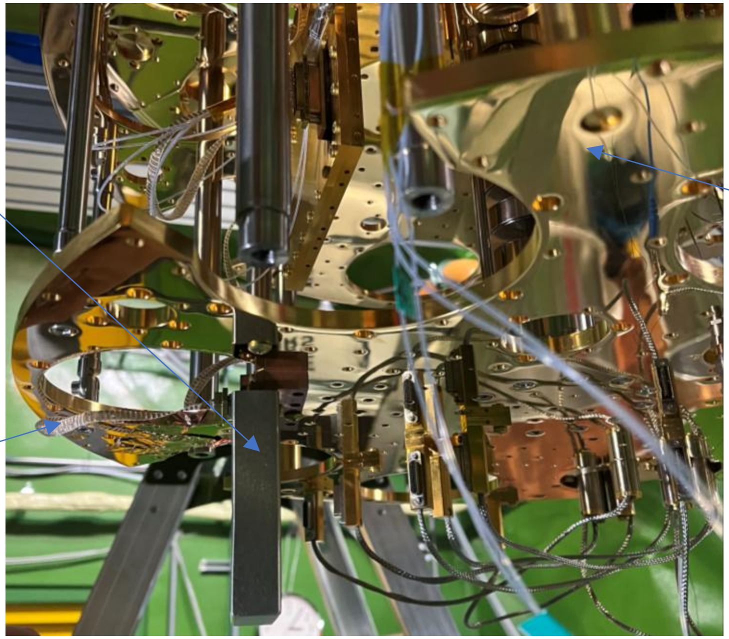
⇒ TES sensors were wire-bonded at KEK.

- DB25 will be connected to the SQUID box at 100mK stage.



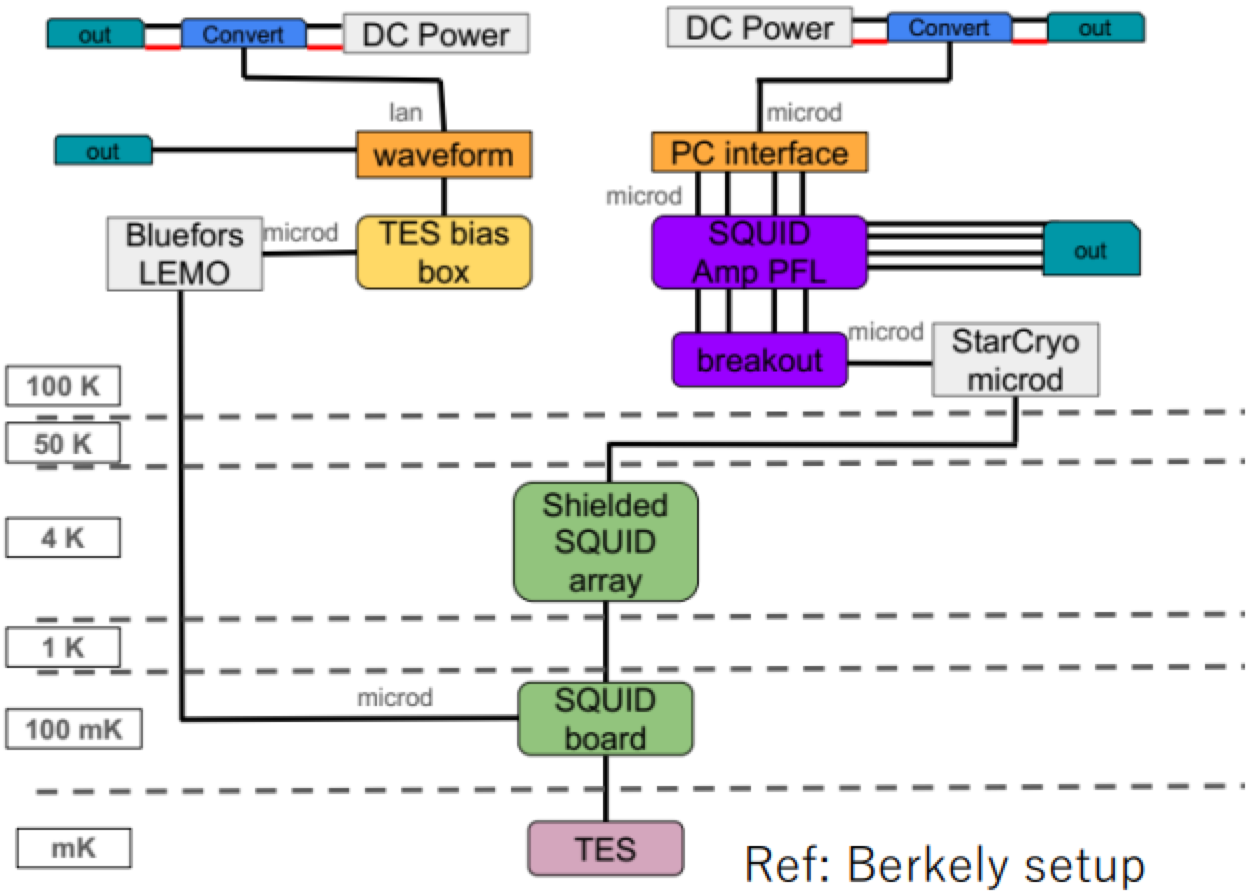
TES box inside μ-metal shield

Loom-wire to SQUID



Mixing chamber plate

Detector Readout: SQUID



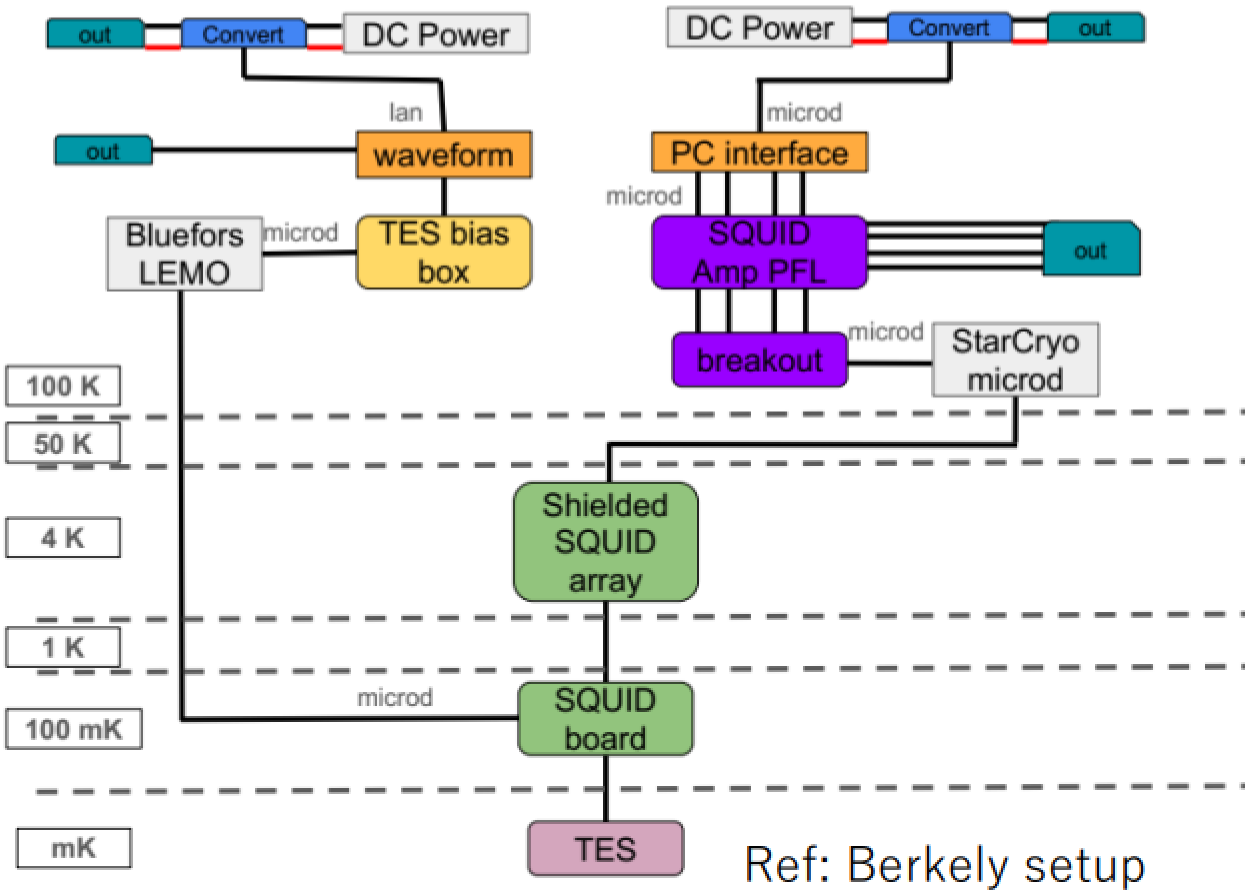
Ref: Berkely setup

- TES is used to detect DM
- TES produces very tiny signal

⇒ Need a highly-sensitive + low-noise amplifier

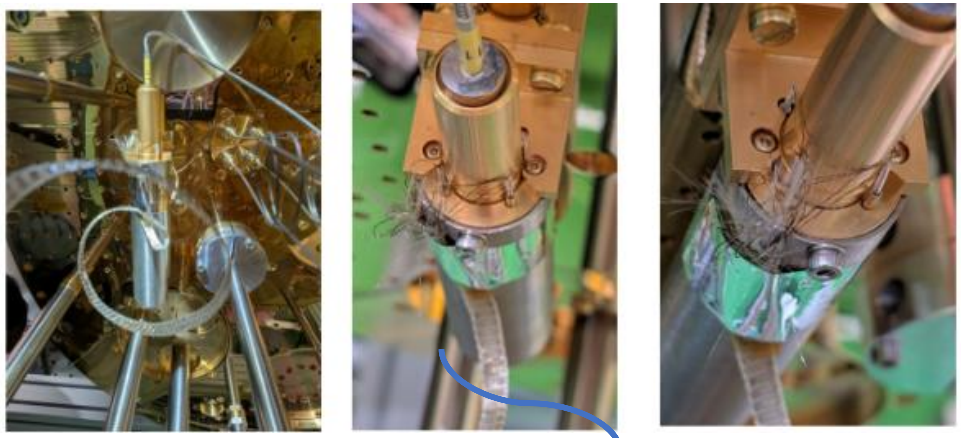
⇒ SQUID from StarCryo, operated at cryogenic temperature

Detector Readout: SQUID



Ref: Berkely setup

2nd stage: SQ1550 @ 4K



Loom wire

1st stage: AR4825 @ 100mK

- *Setup for TES and SQUID is finished.*
- *Measurements from TES and SQUID are ongoing.*

Take home message

- We are fabricating a detector system to search for DM at the low-mass scale (well below 1 GeV) using Transition Edge Sensor (TES) technology.
- Fridge commissioning and site preparation are on-going
- Different simulations are performed to estimate the backgrounds from detector components, cosmogenic, and external gamma/neutron.
- The first payload will be LHe and Berkeley TES sensor, probe for DM down to 100 MeV/c^2.
- The next payload (QUP-Kamioka DM project), we will implement the Optical TES developed at QUP with multiplex readout.
- Opportunities for other rare-event searches

END

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WPI research center at KEK

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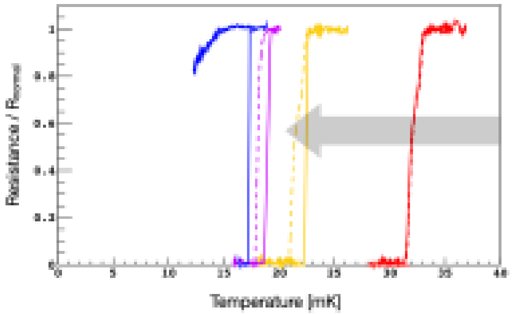
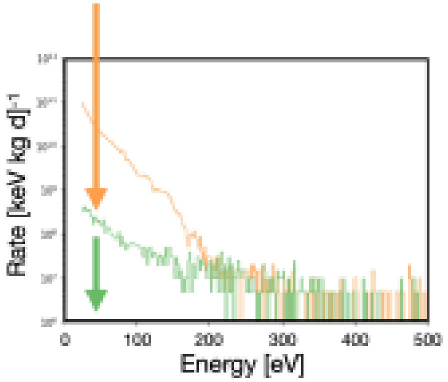
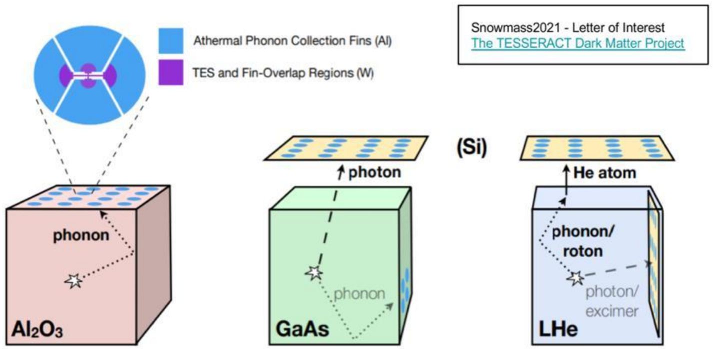
Extra slides

SPICE/HeRALD (TESSERACT)







from S. Hertel, TAUP 2023

1. **Push TESs to meV Thresholds**

- ☐ Reduce T_c to <20mK
- ☐ Reduce TES volume (heat capacity)
- ☐ Eliminate parasitic heat loads (IR, RF, etc.)

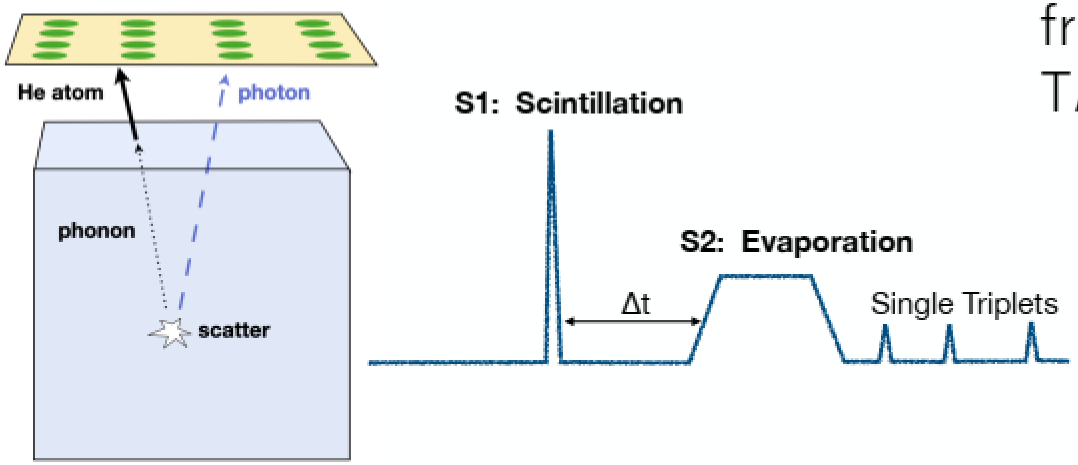
2. **Minimize Low Energy Excess**

- ☐ Eliminate clamps
- ☐ Utilize multi-channel coincidence
- ☐ Optimize fabrication methods, materials, material amounts, …

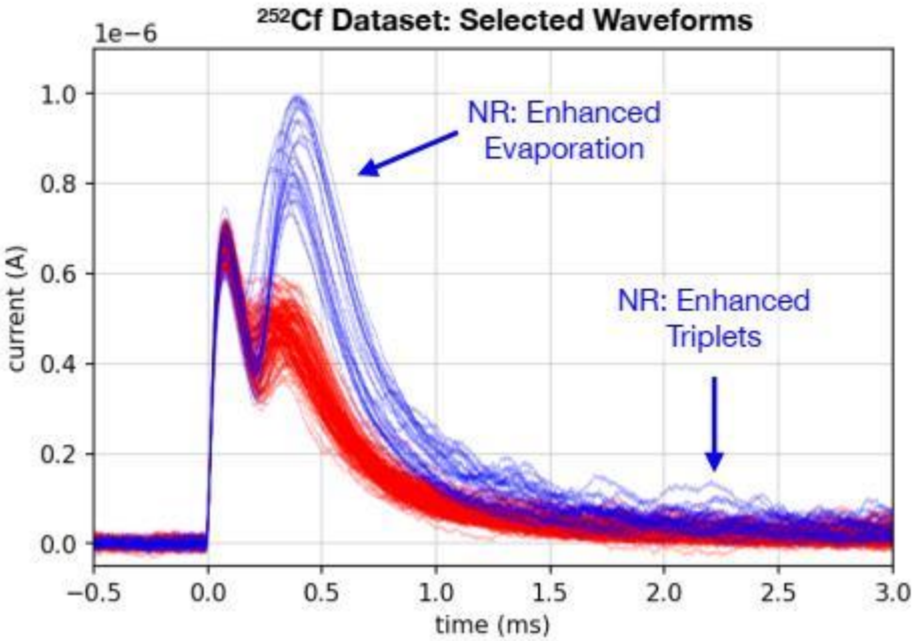
3. **Apply these meV Sensors to Diverse Target Materials**

- ☐ DM coupling via optical phonons (SPICE)
- ☐ Standard NR on light nucleus with gain mechanism (HeRALD)

ER/DR discrimination in LHe



from S. Hertel, TAUP 2023



LHe is pure, freezes other gas, has multiple detection channels:

We expect 2 signals from LHe:

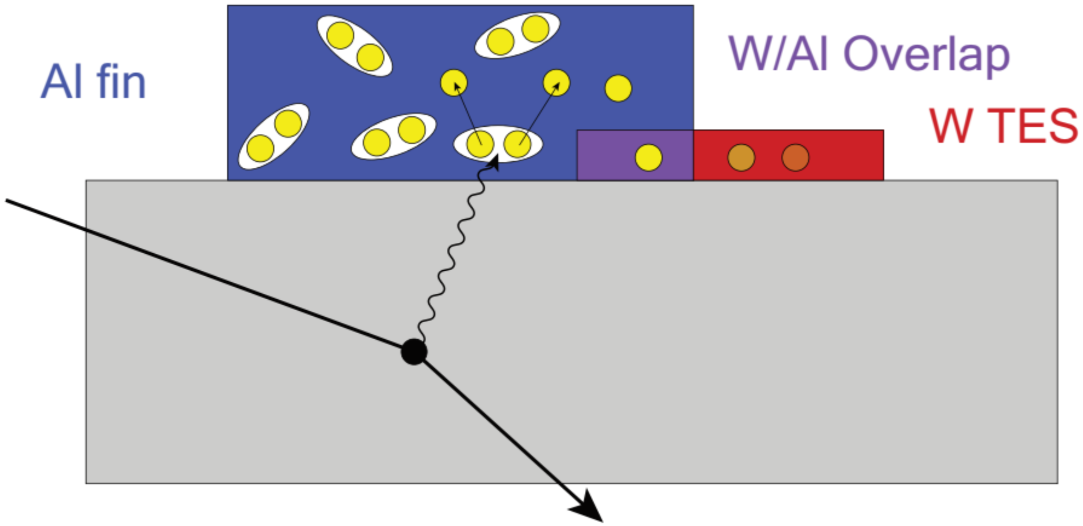
- S1: Prompt Scintillation
- S2: delayed evaporation

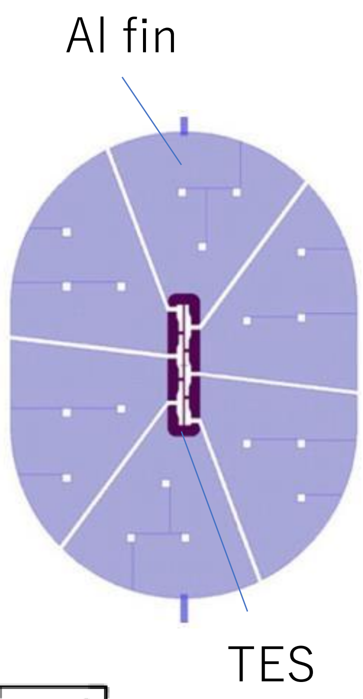
*the delayed time of S2 depends on the depth

The delayed evaporation (S2) signals on ER and NR response with different amplitude.

⇒ ER/NR discrimination

arxiv: 2301:08699





- DM interaction produce small excitations (athermal).
- Athermal excitations will interact with the superconducting Al fins

⇒ break Cooper pairs, creating quasiparticles.

- These quasiparticles will randomly travel throughout the Al fin

⇒ reaching and trapped in the overlap region with TES

⇒ which will have a suppressed T