Background simulation and control schemes in the CDEX-50 experiment

Junzheng Wang

CDEX collaboration, Tsinghua University

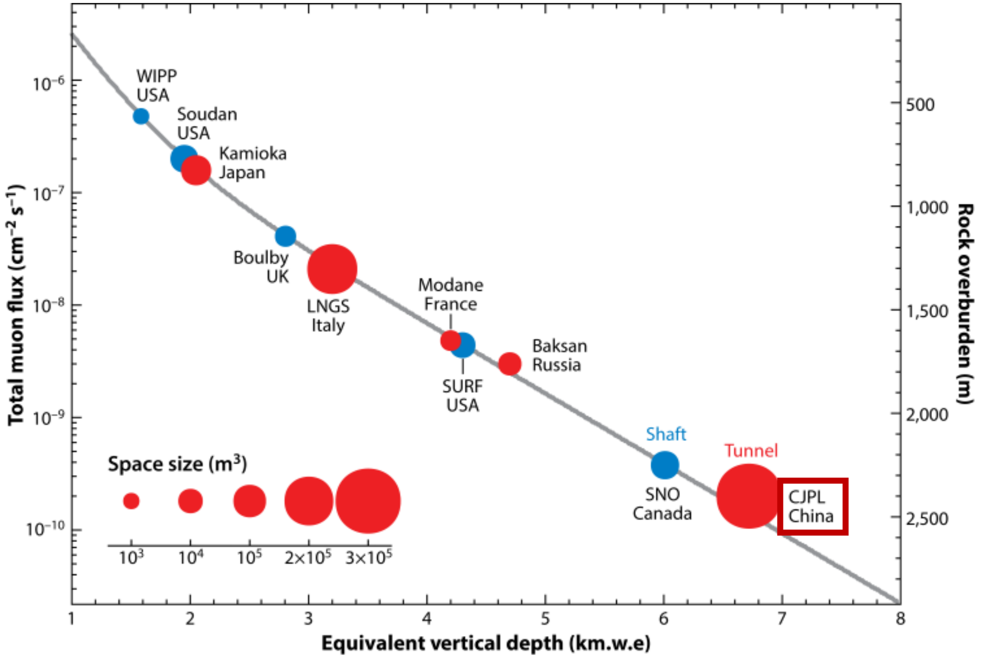
wangjz22@mails.Tsinghua.edu.cn

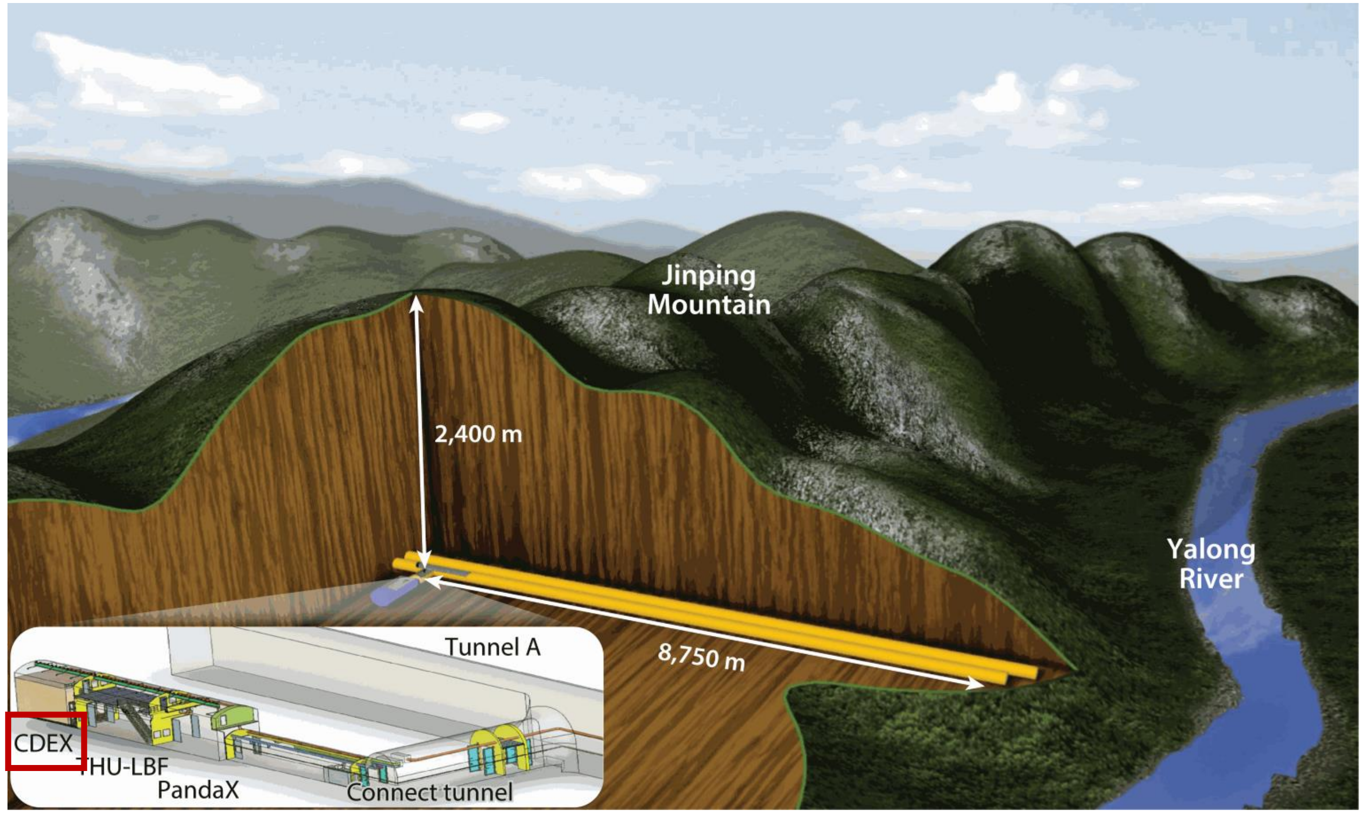
Outline

- Introduction of CDEX experiment
- CDEX-50 experiment construction
- Background simulation and control schemes[1]
- CDEX-50 background model [1]
- Summary

Introduction of CDEX experiment

- CDEX: China Dark matter Experiment.
- Physics target: direct searches for dark matter using germanium detectors.
- Laboratory: CJPL, China Jinping Underground Laboratory.
  - Deepest rock overburden
  - Largest available space
  - Lowest muon flux



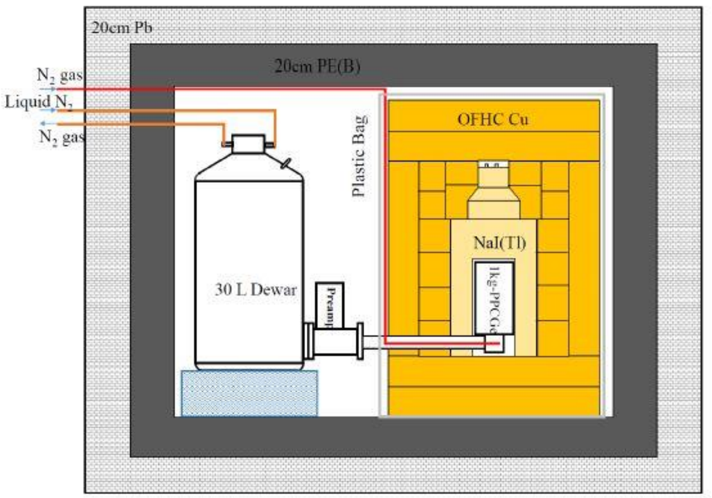


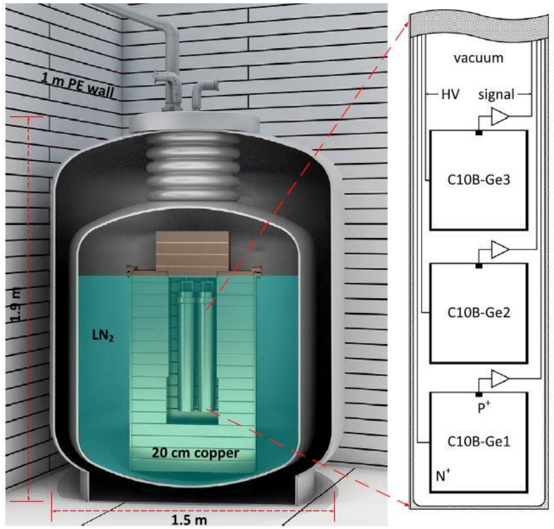
CDEX Roadmap

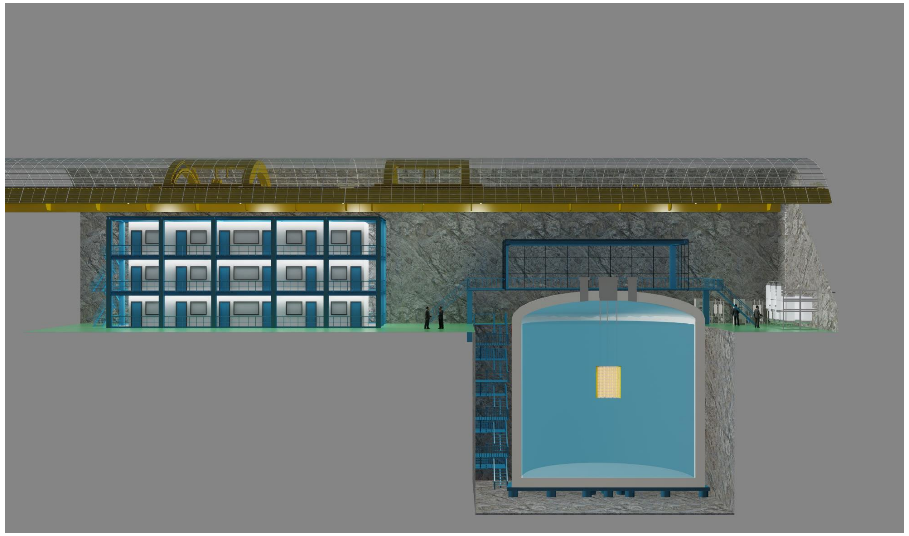
- CDEX-1: Development of PPC Ge detector, bkg understanding, since 2011;
- CDEX-10: Performances of Ge detector array immersed in LN_2, since 2016;
- CDEX-50: ~50 kg Ge detector array immersed in LN_2, under preparing.

CDEX-1 → CDEX-10 → CDEX-50

CJPL- I | CJPL- II

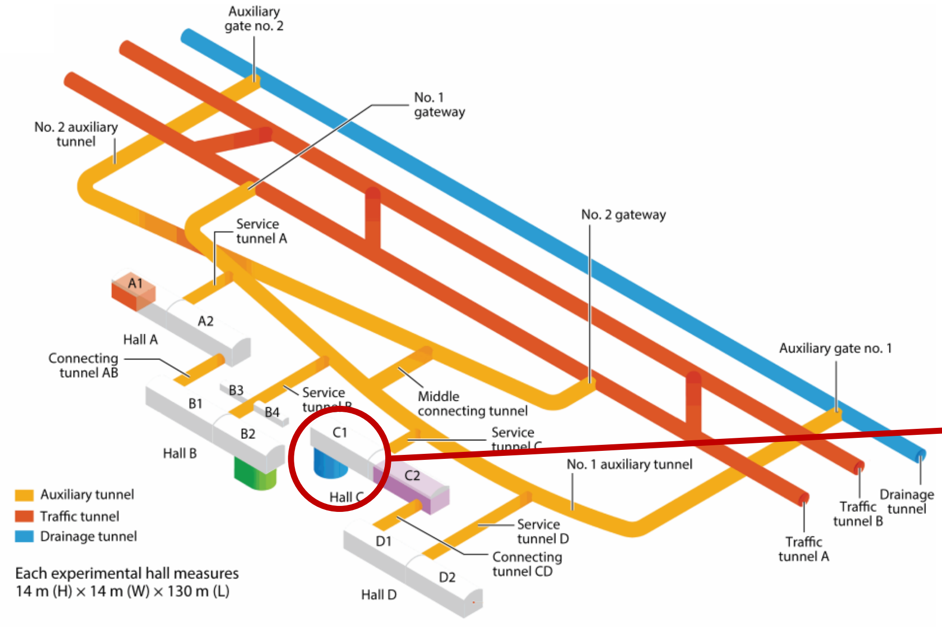


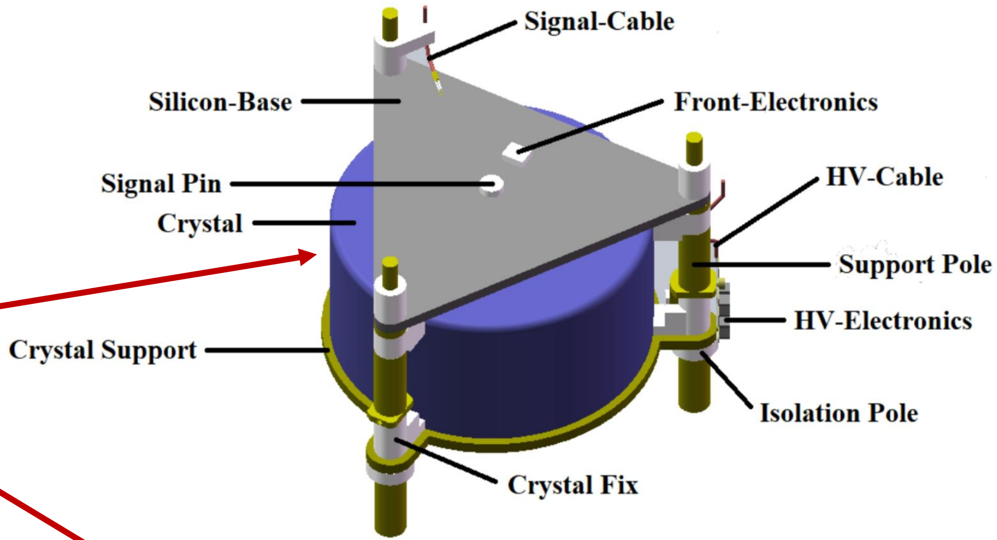


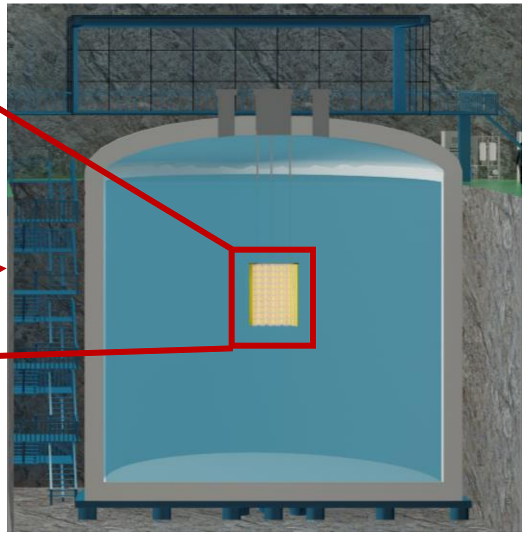


CDEX-50 experiment construction

- **Located at CJPL-Ⅱ, hall C1.**
- **Φ 13 m, *H* 13 m LN_2 cylinder tank.**
- **5 detector strings, 10 units for each.**
- **Φ 80 mm, *H* 40 mm, 1 kg unit.**

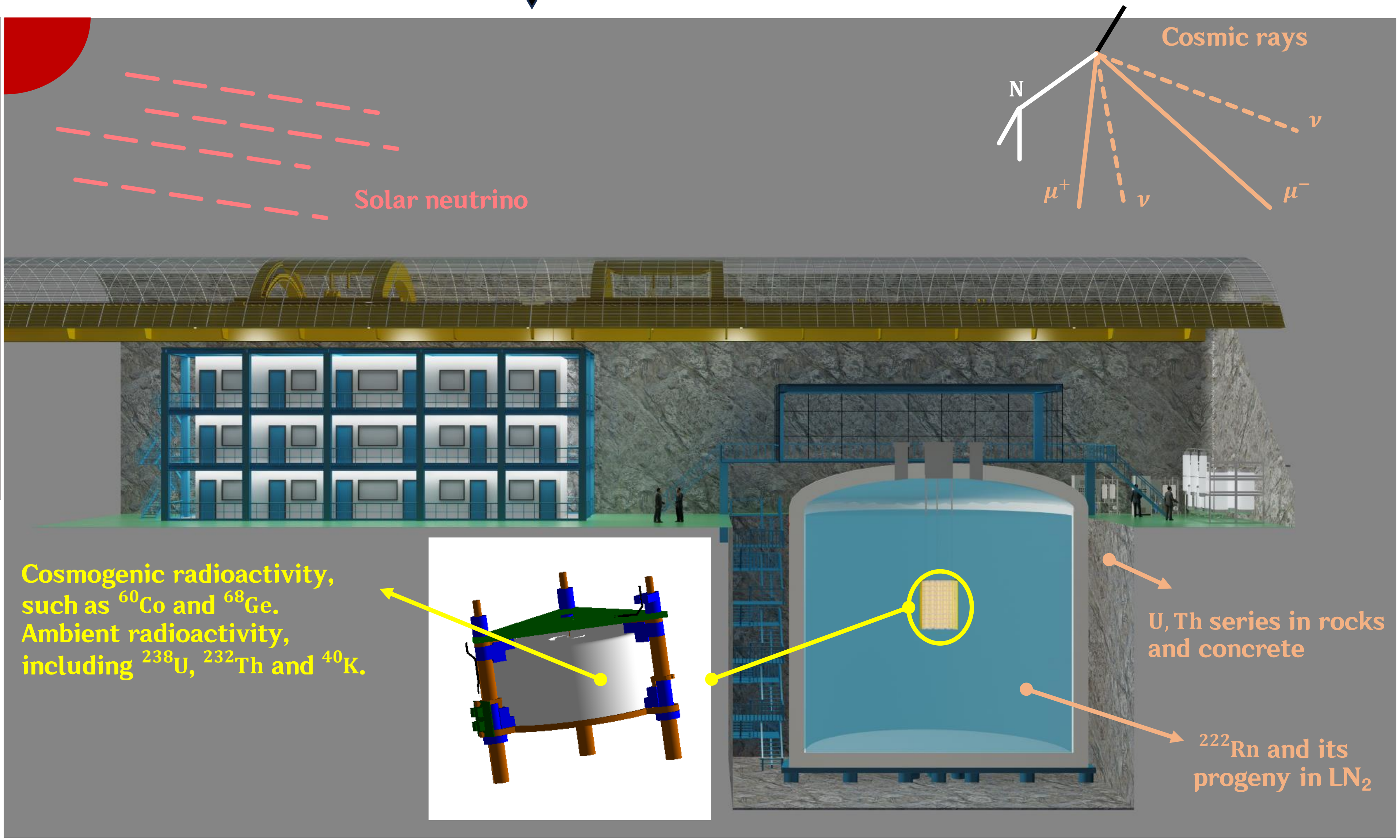






Background sources

- Environment
  - Muno
  - U, Th
  - Rn
- Detector components
  - Cosmogenic
  - Ambient
- Solar neutrino

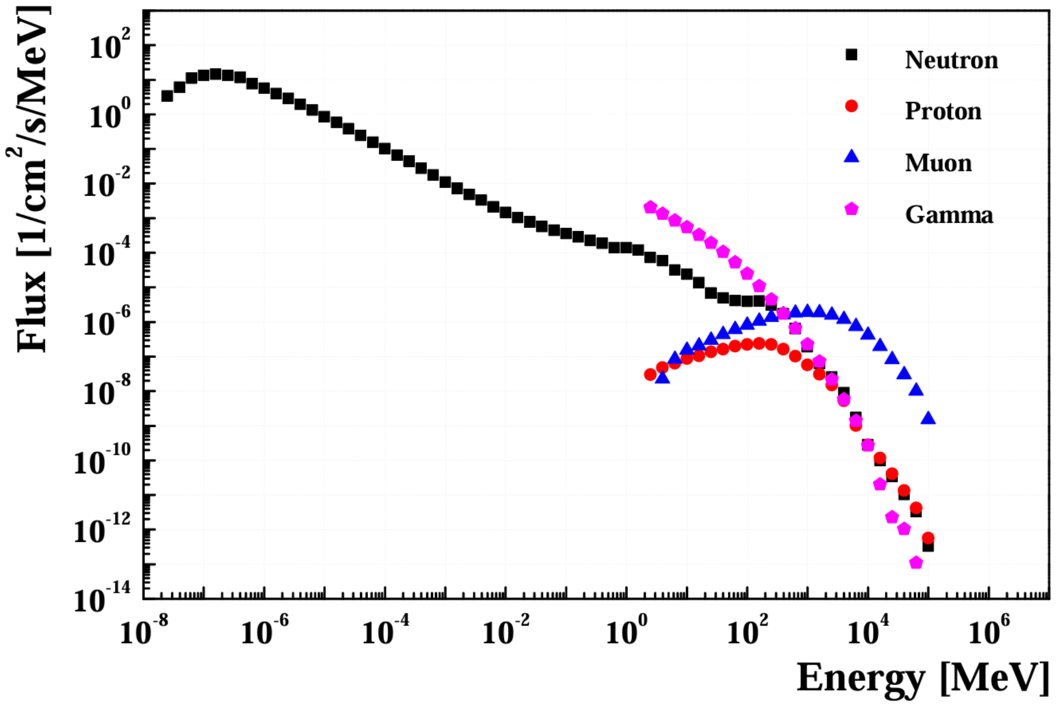


Background sources from environment

- **Muon-induced background**
  - CJPL **2400 m** rock overburden.
  - $\sim 1\ \mathrm{cm^{-2}min^{-1}}$ at sea level $\rightarrow 2.1 \times 10^{-8}\mathrm{cm^{-2}min^{-1}}$ in CJPL[2].
- **U, Th series in rocks and concrete**
  - Neutron related effects: spontaneous fission; (α, n).
  - γ arise from long-lived radionuclides.
- **6.5 m thick LN_2** can lower the sources above to a negligible level.
- The ^{222}Rn in LN_2 is expected to be $0.4\ \mu\mathrm{Bq/kg}$ after purification.

Cosmogenic radioactivity

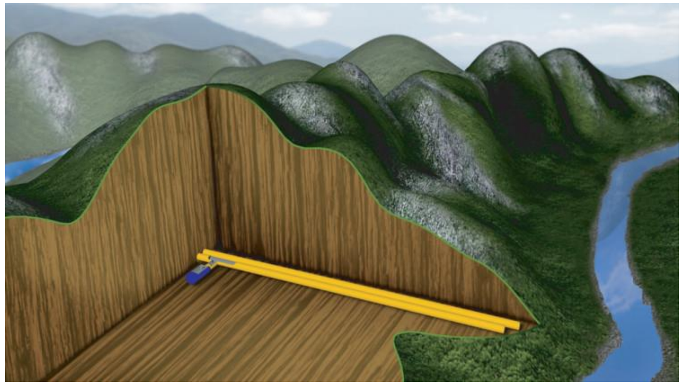
- CRY (Cosmic-ray Shower Library) is used to generate spectra of cosmic-rays.
- Geant4 is used to simulate particle interactions between cosmic-ray and target&shield with *Shielding* physics list.
- Background control methods during different processes of detector.



Fabrication
~60 days
Underground storage

Transportation
~65 days
Transportation shield

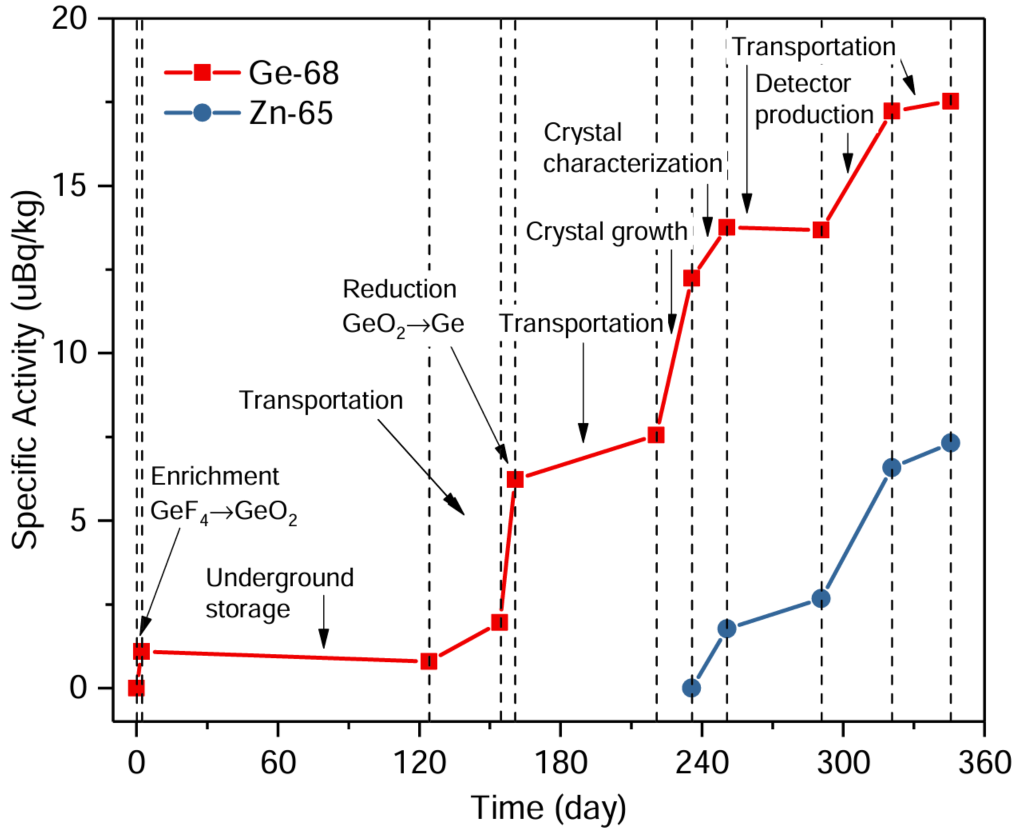
Cooling time
~3 years
Underground laboratory



Cosmogenic radioactivity

- Specific activities of the cosmogenic radionuclides of the germanium crystal as well as copper.

Radionuclides variation over time[3]



Copper

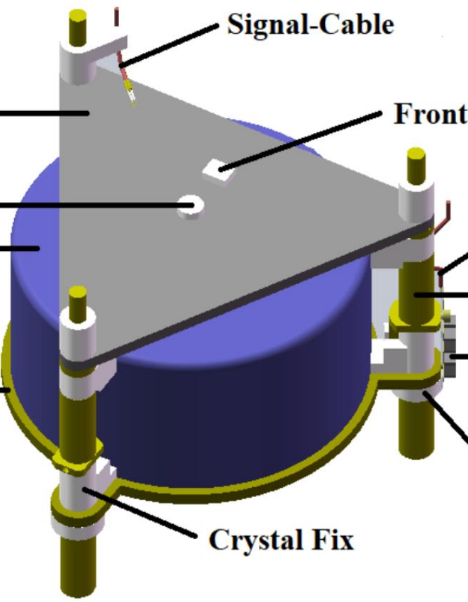
Radionuclide	Activities (μBq/kg)
^{54}Mn	2.38×10^{-2}
^{57}Co	5.32×10^{-3}
^{60}Co	3.27

Germanium crystal

Radionuclide	Activities (μBq/kg)
^{3}H	9.93×10^{-1}
^{65}Zn	3.26×10^{-1}
^{68}Ge	1.06

Ambient radioactivity

- Primordial radionuclides with long half-lives (^{238}U, ^{232}Th and ^{40}K) introduced in the material during manufacturing.
- Components of detector and their radionuclides activities:
  - Data of copper comes from purity copper samples used in CDEX-50.
  - Upper limits are given at 90% C.L.



Components	Activities ($\mu Bq/kg$)		
	^{238}U	^{232}Th	^{40}K
HV-Cable	$< 2.4 \times 10^2$	< 12	$< 3.2 \times 10^3$
Signal-Cable	< 51	< 19	$< 2.9 \times 10^3$
Electronics	$< 1.3 \times 10^5$	$< 3.0 \times 10^3$	$(5.2 \pm 0.1) \times 10^4$
Copper	< 1.3	< 0.58	< 5.8
PTFE	$< 1.7 \times 10^3$	< 60	$< 3.7 \times 10^2$
Silicon	< 38	< 19	$< 3.0 \times 10^3$

SAGE package

- SAGE[4] package (**S**imulation and **A**nalysis for **G**ermanium **E**xperiments).

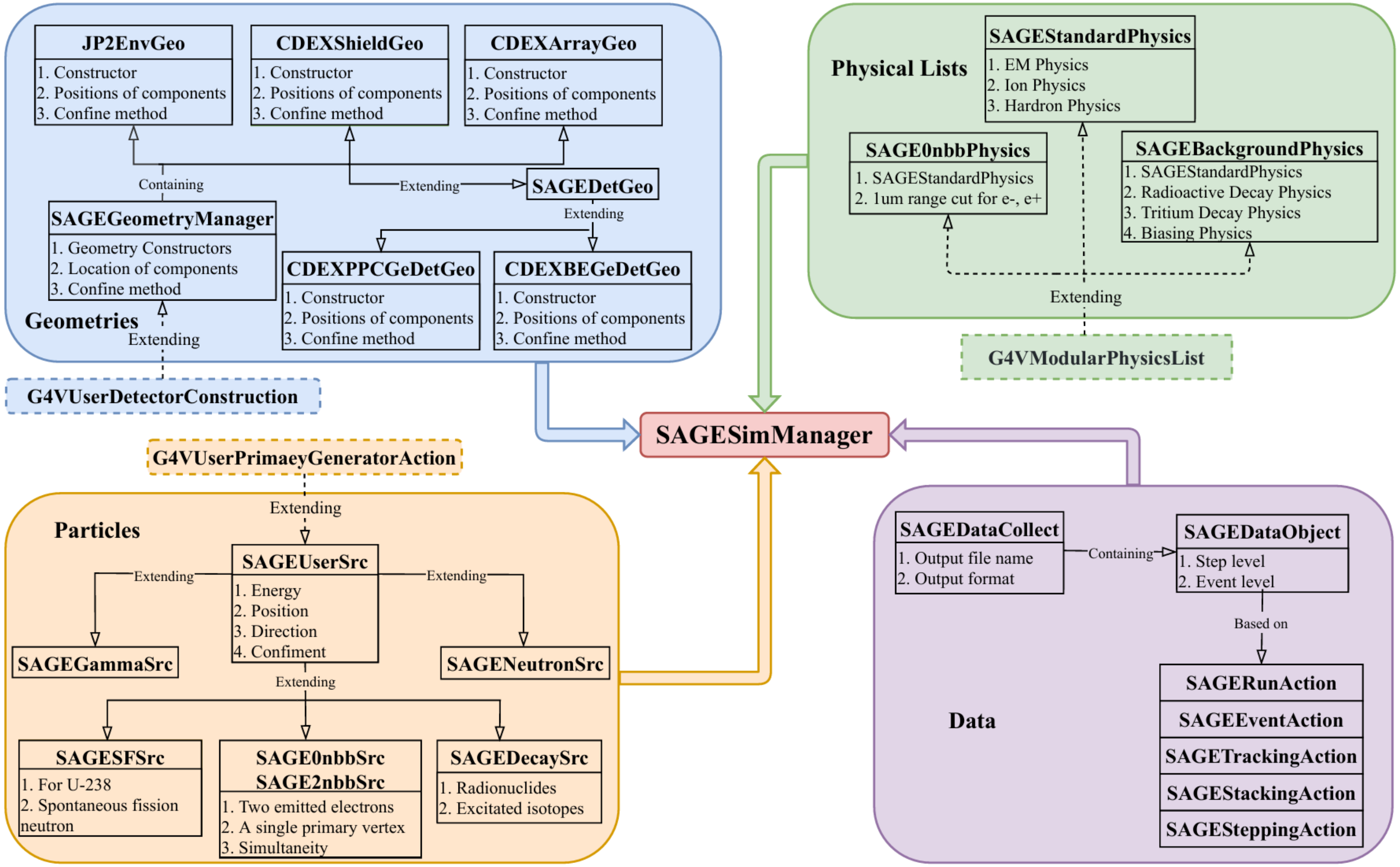
```
"Mode" : "Simulation",
"Physics" : "Background",

"Array":
{
    "HeightGap" : 0.0,
    "RadiusGap" : 0.0,
    "HeightN" : 5,
    "RadiusN" : 5,
    "Material" : "enriched"
},

"Particle":
{
    "Type" : "Decay",
    "Isotope" : "Co-60",
    "Distribution": "Component",
    "Confine" : "physGe",
    "Beam" : 100000
},

"Output" : {
    "Filename": "CosmogenicCobalt60",
    "DataMode": "event"
}
```

Physics list

Geometry

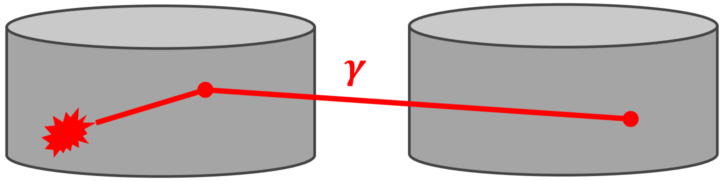
Source

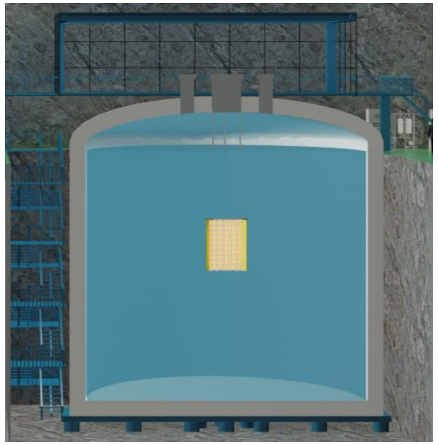
Output

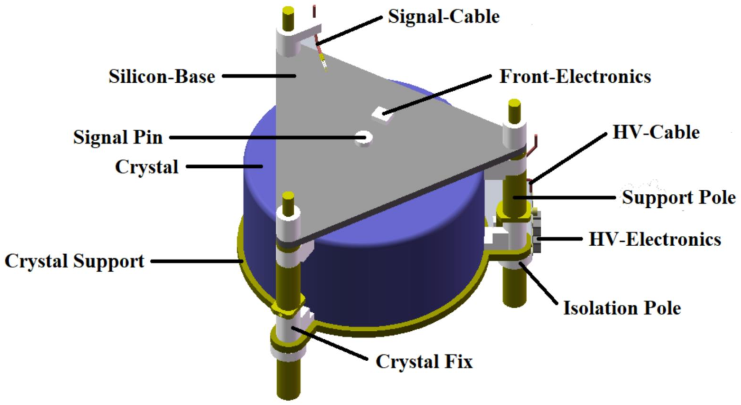


Geant4 Simulation of radionuclides

- CDEX-50 geometry.
- Generate 10^9 radionuclides for each radionuclide in each component.
- Decay chains are assumed to be in secular equilibrium.
- Time window representing the response time of Ge detector: 10 μs.
  - Decay chains breaking.
  - Cascade radiations.
  - Self-anticoincidence.







- Conversion from simulation result to background model:

$$R\left[\frac{\text{counts}}{\text{kg}\cdot\text{keV}\cdot\text{day}}\right] = A\left[\frac{\text{Bq}}{\text{kg}}\right] \times M[\text{kg}] \times \frac{counts}{primaries} \times units$$

Count rate ← $R\left[\frac{\text{counts}}{\text{kg}\cdot\text{keV}\cdot\text{day}}\right]$

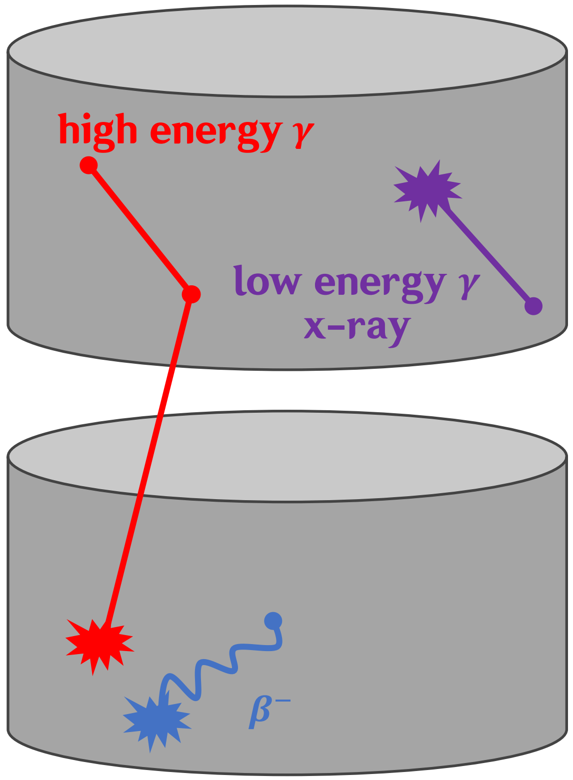
Survival probability ← $\frac{counts}{primaries}$

Geant4 simulation of radionuclides

- Survival probability in ROI (2-2.5 keV) of each radionuclide in each component.

Radionuclides in crystal

Radionuclide	Survival Probability[%]
^{3}H	100.0
^{49}V	100.0
^{54}Mn	82.57
^{55}Fe	100.0
^{57}Co	89.20
^{60}Co	64.62
^{63}Ni	100.0
^{65}Zn	93.91
^{68}Ge	100.0
^{68}Ga	78.32

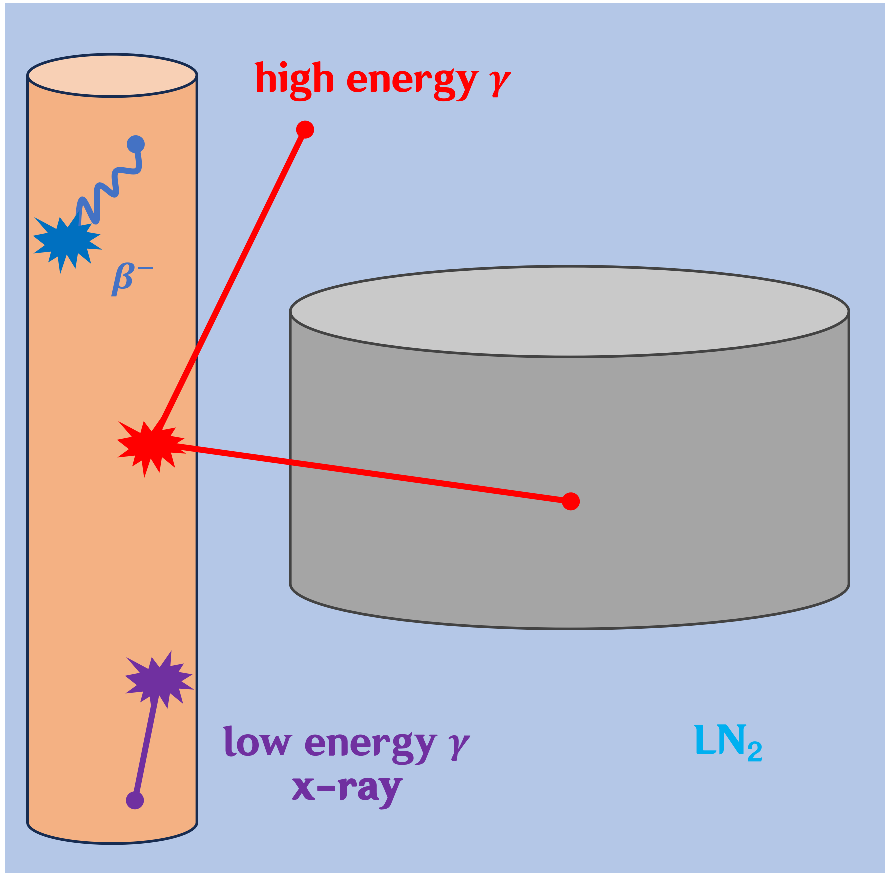


Geant4 simulation of radionuclides

- Survival probability in ROI (2-2.5 keV) of each radionuclide in each component.

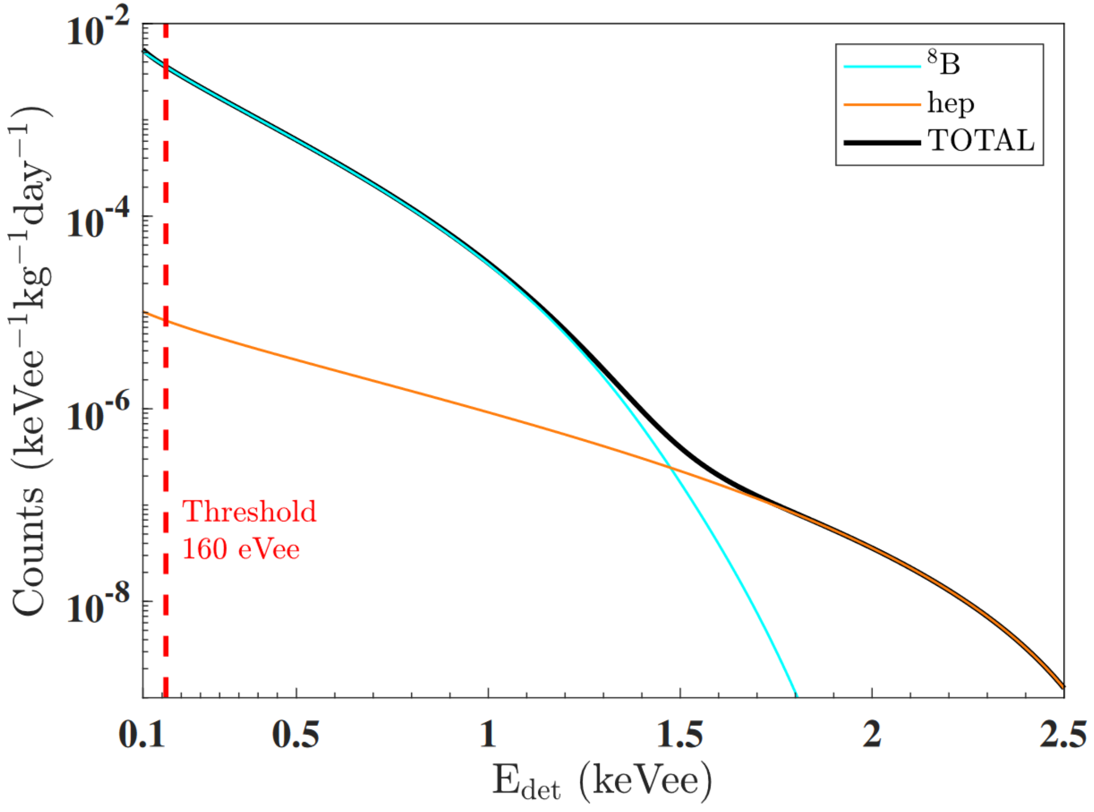
Radionuclides in outer components

Radionuclide	Components	Survival Probability[%]
^{60}Co	Crystal Support	68.23
	Support Pole	71.01
^{238}U	Silicon-Base	71.03
	Crystal Support	71.49
	Support Pole	74.73
^{228}Th	Silicon-Base	71.27
	Crystal Support	74.23
	Support Pole	75.52



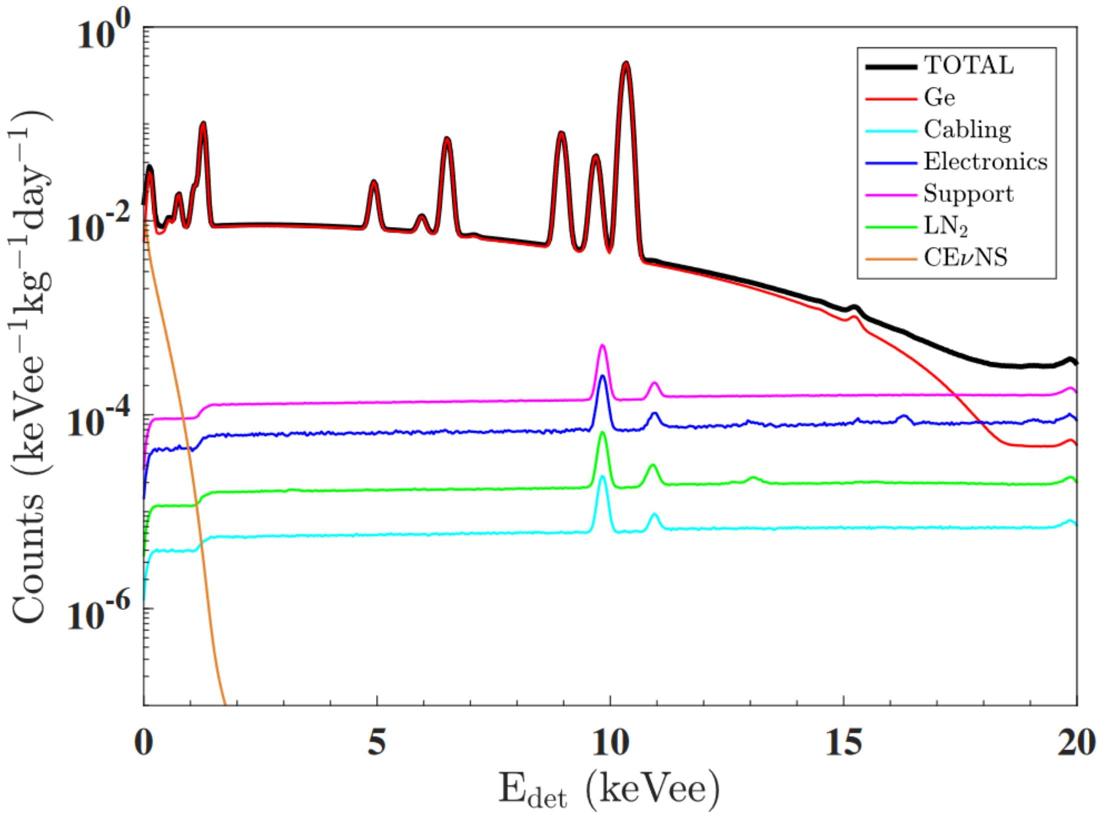
Background from solar neutrino

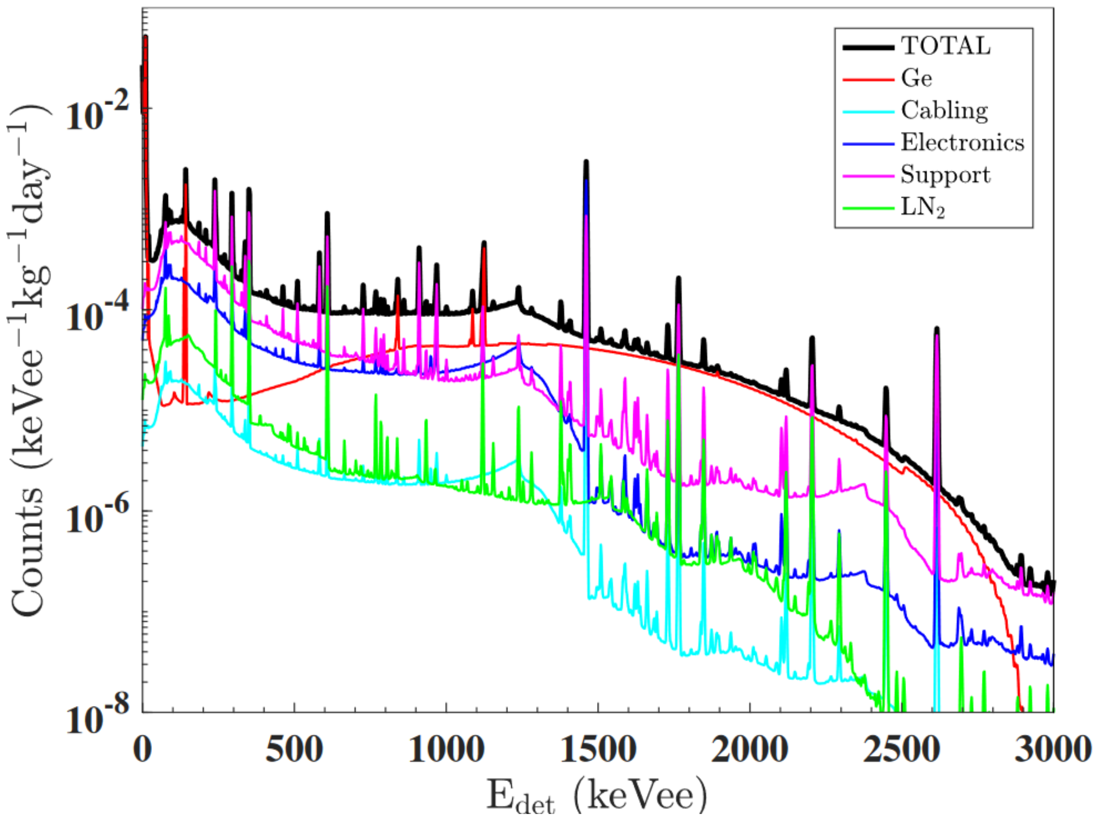
- Solar neutrino induced background above energy threshold ($\mathcal{O}(100)$ eV) within SM mainly comes from CEνNS.
- Scattering rate of CEνNS is calculated based on theoretical formula.
- Rate in ROI: 1.32×10^{-8} cpkkd.
- Mainly from ^{8}B and hep neutrino.
- Drop steeply below 2.5 keV.



CDEX-50 background model

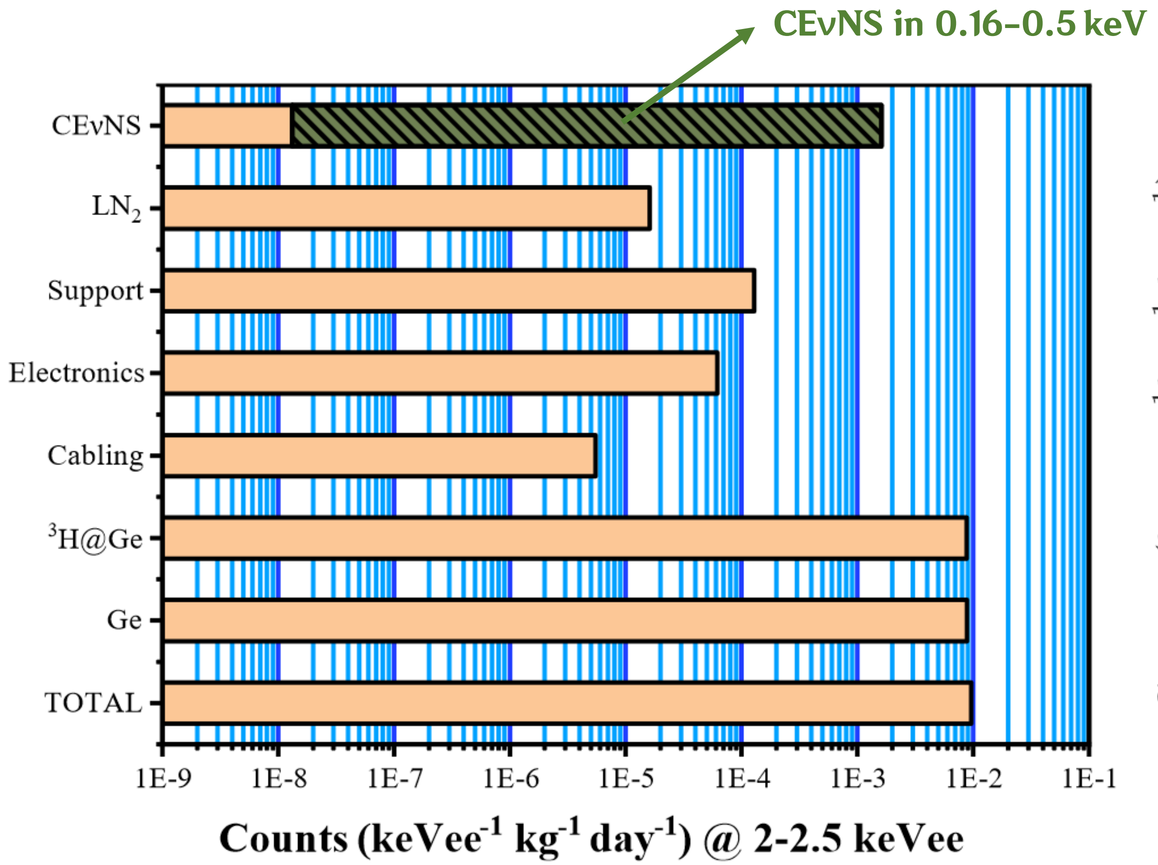
- **Total spectrum in 0-20 keVee and 0-3000 keVee.**
  - **0-20 keV: dominated by ^{3}H β^{-} decay.**
  - **>1.5 MeV: dominated by ^{68}Ga and ^{60}Co in Ge crystal.**



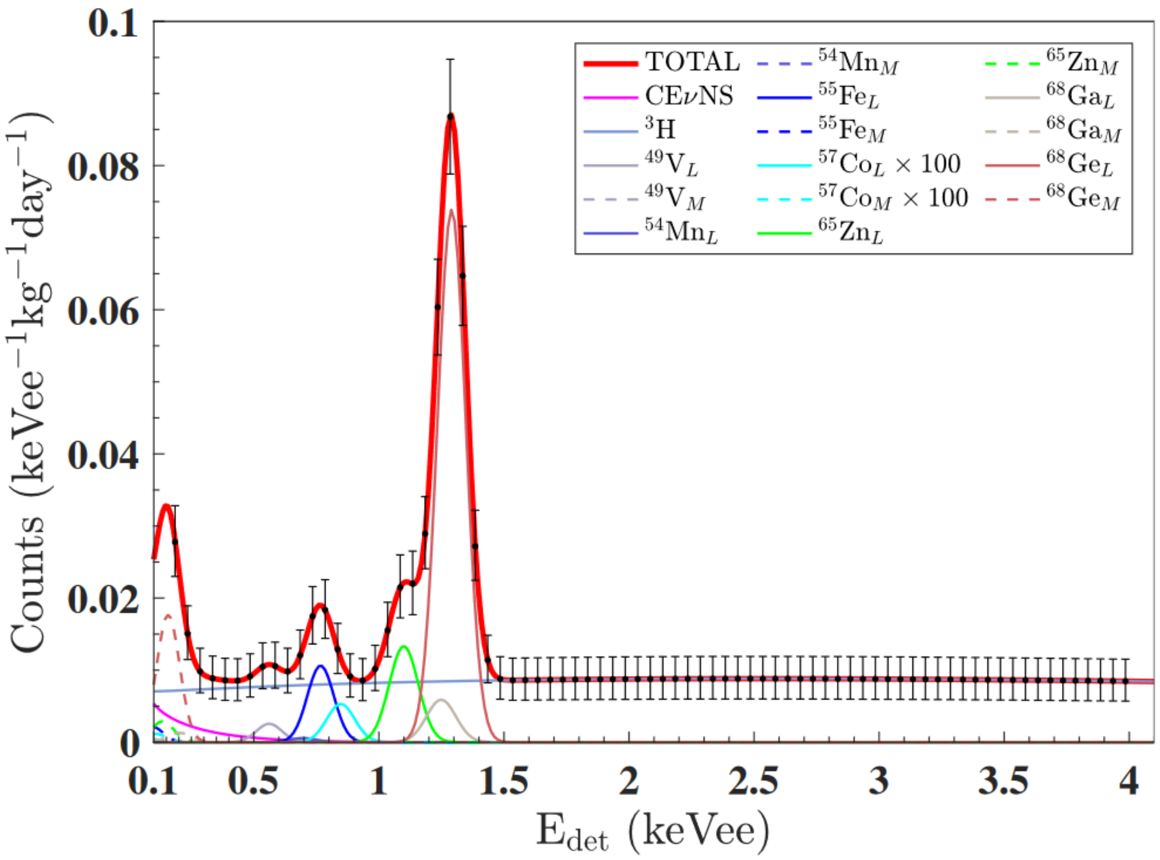


CDEX-50 background model

- Contribution in ROI of various sources.
  - Total ~0.01 cpkkd.
  - Dominated by ^3H.



- Expected spectrum in 0.16-4.01 keV.
  - ^3H β^- decay.
  - X-rays from cosmogenic radionuclides.
  - CEvNS.



Summary

- CDEX-50 is the next generation dark matter project using a 50-kg Ge detector array.
- Different background sources are analyzed:
  - Environment.
  - Detector components.
  - Solar neutrino.
- Several schemes are performed to control the background:
  - Background control in detector fabrication and transportation; cooling time.
  - Purified LN_2 and copper.
  - Self-anticoincidence.
  - ……
- Background model of CDEX-50 is obtained through SAGE.
  - Total background level in ROI is calculated to be ~0.01 cpkkd, dominated by ^3H.

Reference

- [1] X. P. Geng *et al.* arXiv:2309.01843
- [2] Z. Y. Guo *et al.* Chinese Phys. C., 45, 025001 (2021)
- [3] Q. Y. Nie *et al.* JINST, 19, P03002 (2024)
- [4] Z. She *et al.* JINST, 16, T09005 (2021)

Thank you for listening!

Appendix1: ^{3}H in SAGE

- ^{3}H is treated as a stable isotope in Geant4.
- SAGE make it decay automatically with *SAGETritiumPhysics*.

```
void SAGETritiumPhys::ConstructProcess()
{
    // Make tritium unstable
    G4ParticleDefinition *H3 = G4Triton::Definition();
    H3->SetPDGStable(false);

    // Remove G4Decay process, which requires a registered decay table
    G4VProcess *decay = 0;
    G4ProcessManager *processMan = H3->GetProcessManager();
    G4ProcessVector *processVec = processMan->GetAtRestProcessVector();
    for (G4int i = 0; i < processVec->size() && decay == 0; i++)
    {
        if ((*processVec)[i]->GetProcessName() == "Decay")
            decay = (*processVec)[i];
    }
    if (decay)
        processMan->RemoveProcess(decay);

    // Attach RDM, which is a rest-discrete process
    H3->GetProcessManager()->AddProcess(new G4RadioactiveDecay(), 1000, -1, 1000);
}
```

```
// Radio active decay physics and add user defined data base
auto radioactiveDecayContainer = new G4RadioactiveDecay();
G4int Z = 1;
G4int A = 3;
G4String file_name = "../userData/Z1.A3";
// const char* nv = (const char*)file_name;
radioactiveDecayContainer->AddUserDecayDataFile(Z,A,file_name);
RegisterPhysics(new G4RadioactiveDecayPhysics());
RegisterPhysics(new SAGETritiumPhys());
```

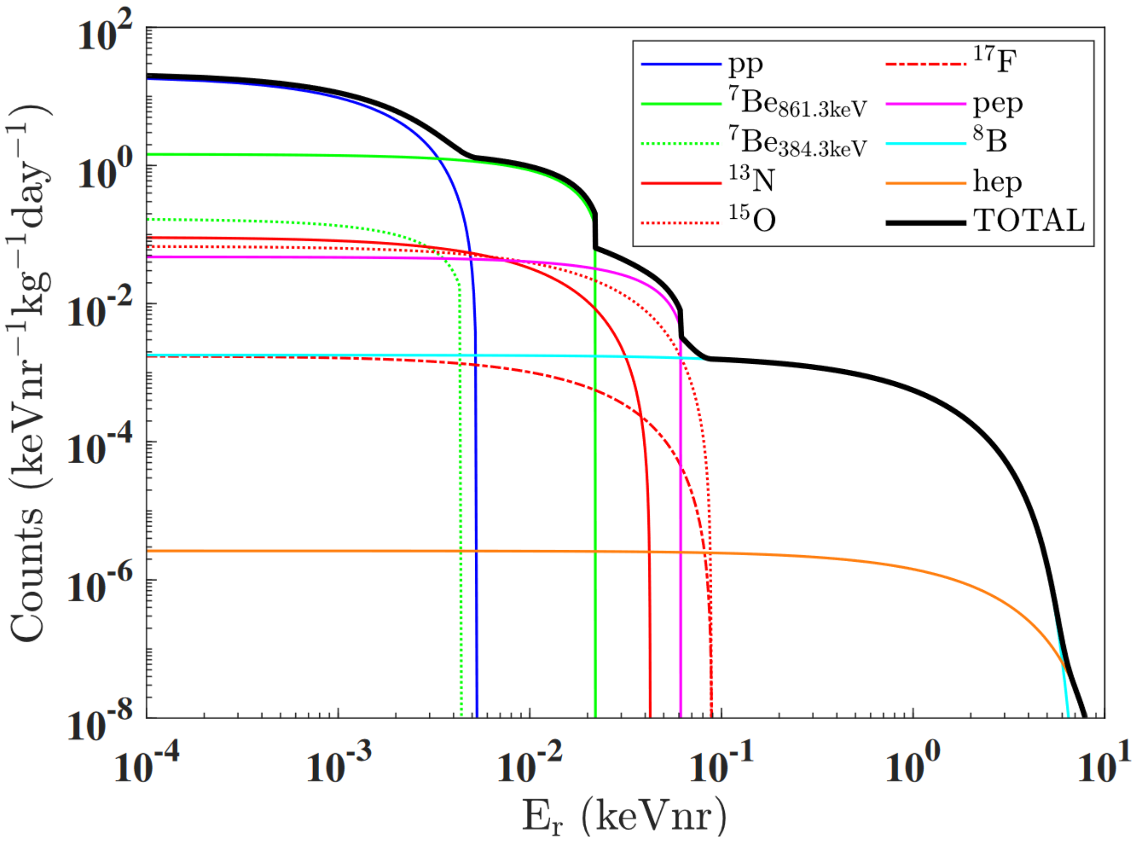
Appendix2: Scattering rate of CEνNS

- **Calculation formula:**

$$\frac{d\sigma(E_r,E_\nu)}{dE_r}=\frac{G_f^2}{4\pi}Q_\omega^2\left(1-\frac{m_N E_r}{2E_\nu^2}\right)F^2(E_r)$$

$$\frac{dR}{dE_r}=N_T\int_{E_\nu^{min}}^{\infty}\frac{d\Phi}{dE_\nu}\frac{d\sigma(E_r,E_\nu)}{dE_r}dE_\nu$$

- $\frac{d\Phi}{dE_\nu}$ comes from the B16-GS98 solar model (high-metallicity or HZ mode).



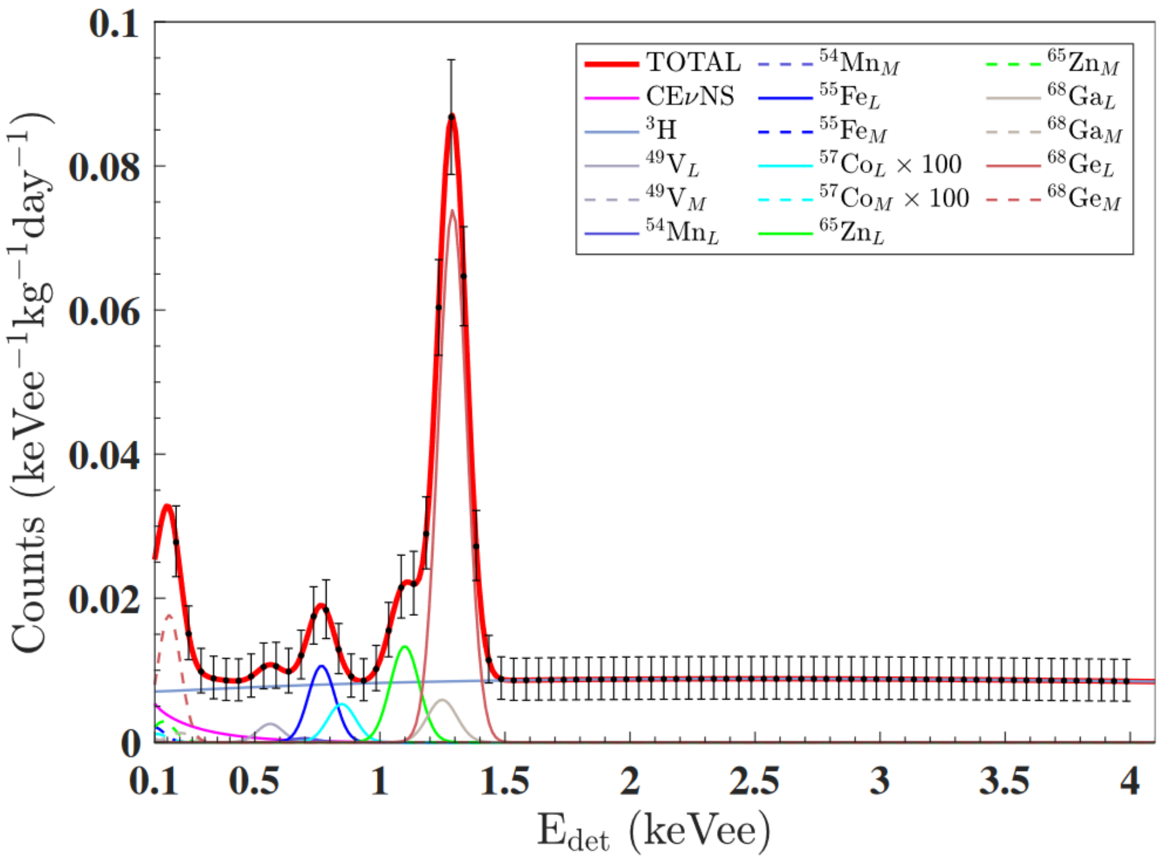
Appendix3: Calculation of expect spectrum

- **Differential event rate of ^3H decay:**

$$N(E_e) = \sqrt{E_e^2 + 2E_e m_e}(Q - E_e)^2 (E_e + m_e) f(E_e)$$

- **Background formula:**

$$B(\theta) = \theta_1 \cdot N(E_{det})$$
$$+ \sum_i^{2-8} \theta_i \cdot \frac{1}{\sqrt{2\pi}\sigma} \exp(-\frac{(E_{det} - E)^2}{2\sigma^2})$$
$$+ \sum_i^{2-8} r_{M/L} \cdot \theta_i \cdot \frac{1}{\sqrt{2\pi}\sigma} exp(-\frac{(E_{det} - E)^2}{2\sigma^2})$$
$$+ \sum_i^{9-10} \theta_i \cdot N_T \int_{E_\nu^{min}}^{\infty} \frac{d\Phi}{dE_\nu} \frac{d\sigma(E_r, E_\nu)}{dE_r} dE_\nu$$



Appendix4: Spectrum of cosmogenic radionuclides

- Spectrum of cosmogenic radionuclides in 0-20 keVee and 0-3000 keVee.
  - 0-20 keVee: β^- decay and x-rays.
  - >20 keVee: γ rays, β and EC decay.