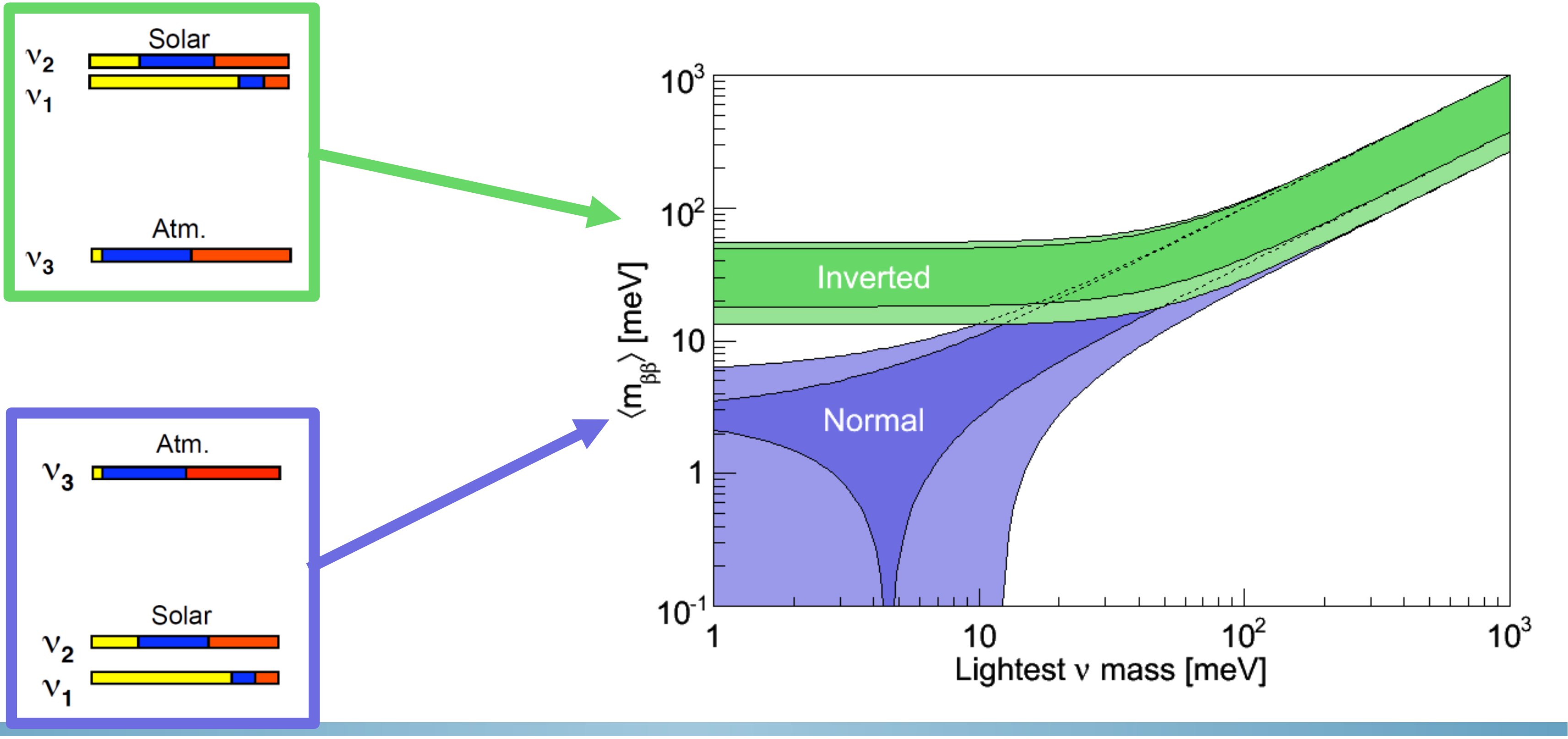
CUPID-Mo: a double beta decay experiment with $Li_2{}^{100}MoO_4$ scintillating bolometers

Anastasiia ZOLOTAROVA

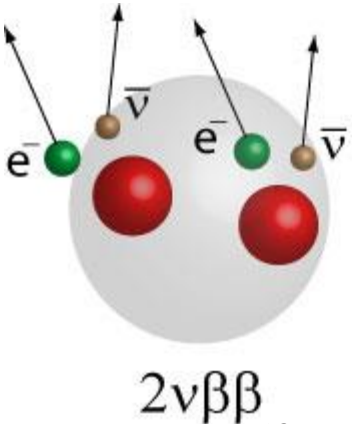
Neutrino masses

- Neutrino oscillation discovery proved that neutrinos do have mass
- But their absolute mass scale and hierarchy are still open questions:



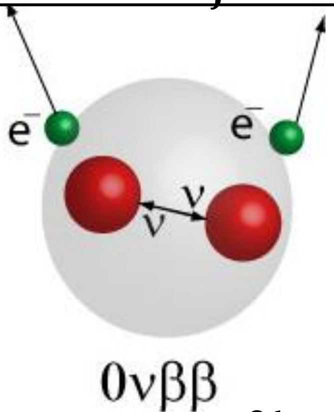
Double Beta Decay

Allowed by SM:



$T_{1/2}$ (2νββ): ~ 10^{18}-10^{21} years

Forbidden by SM, possible **only if neutrinos are Majorana** particles:

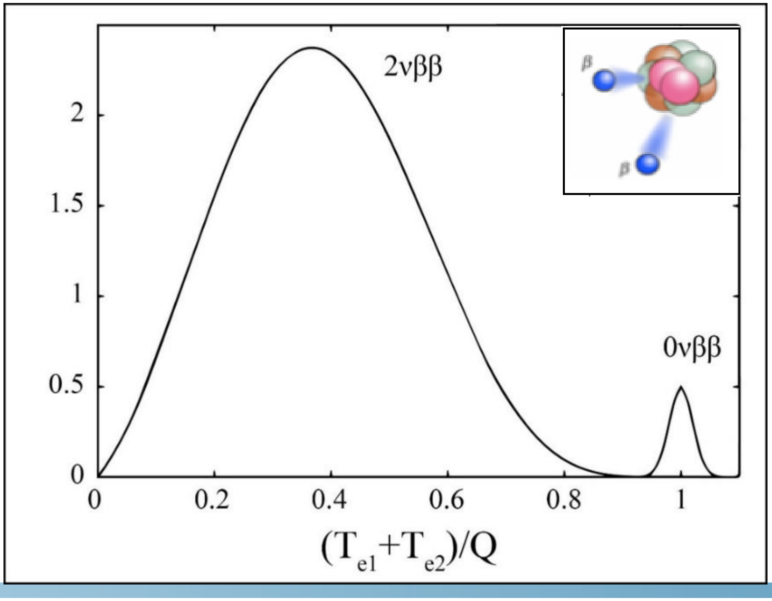


$T_{1/2}$ (0νββ): > 10^{24} - 10^{26} years

- Challenge is to reduce background as much as possible

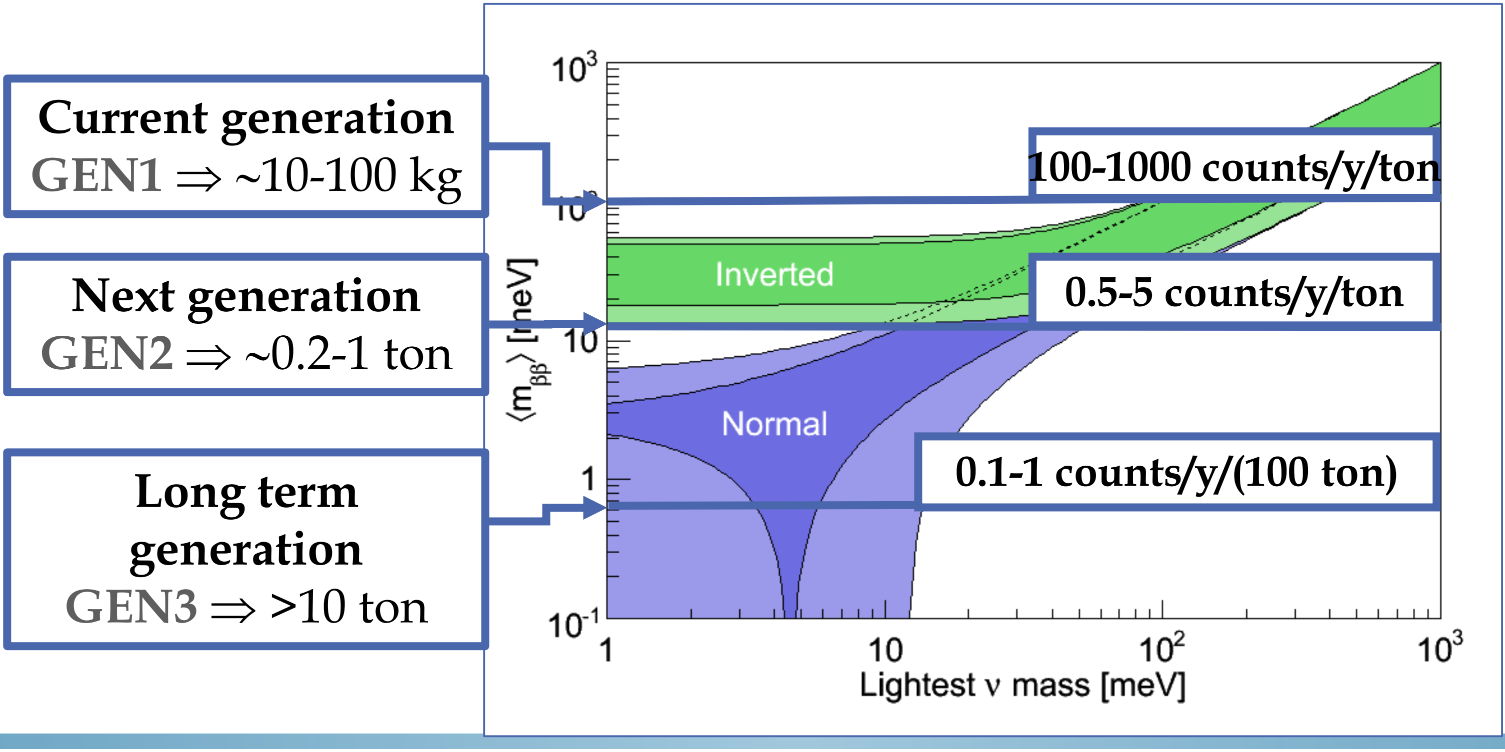
Background index: ***counts/(keV× kg×y):***

- **b ~ 10^{-1}** in « classical » source=detector experiments
- **b ~ 10^{-2} - 10^{-3}** in current source=detector and in classical external-source experiments
- **b ~ 10^{-4}** in future experiments (minimum request to cover inverted hierarchy)



Observation challenge for 0νββ:

- New physics beyond the Standard model
- Majorana nature of neutrino
- Answer about origin of matter/antimatter asymmetry in the Universe
- Definition of absolute scale of neutrinos mass:



Current generation
GEN1 ⇒ ~10-100 kg

Next generation
GEN2 ⇒ ~0.2-1 ton

Long term generation
GEN3 ⇒ >10 ton

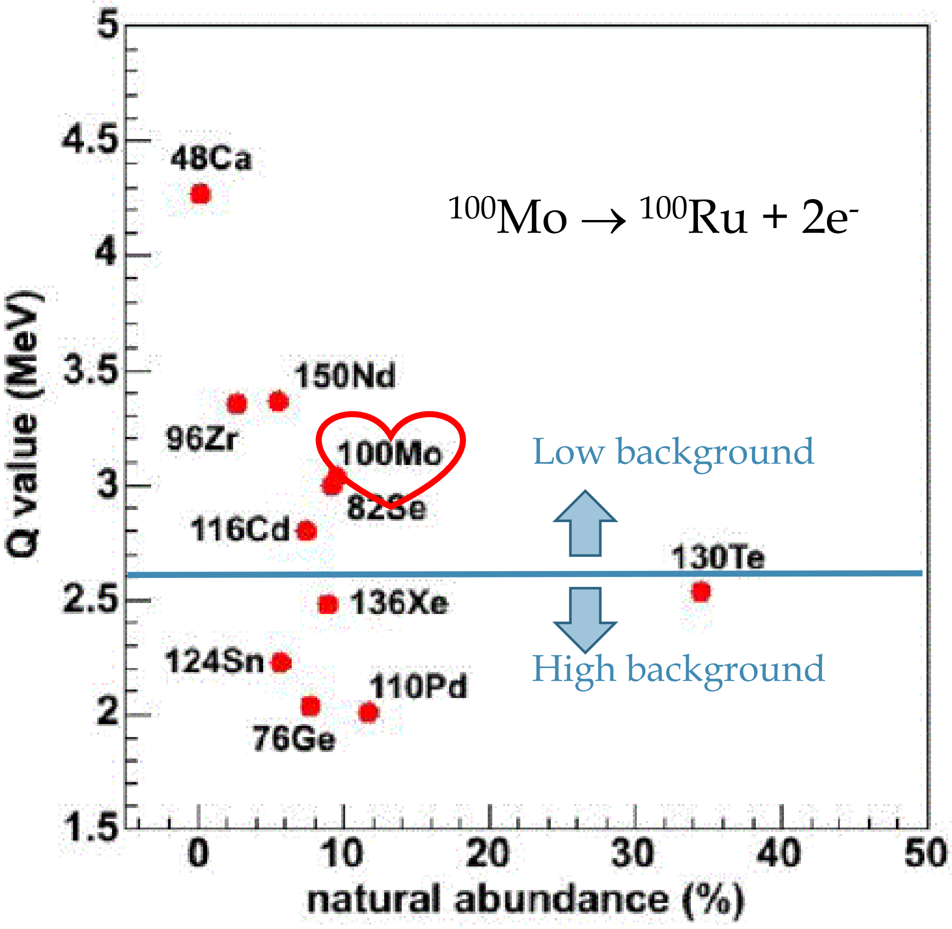
100-1000 counts/y/ton

0.5-5 counts/y/ton

0.1-1 counts/y/(100 ton)

Isotope selection: why ^{100}Mo?

- **There is no "perfect" isotope, but…**
- High energy of decay: $Q_{2\beta}$= 3034 keV > 2615 keV
- Isotopic abundance = 9.7 %
- Possibility of enrichment in a large amount (enrichable by gas centrifugation)
- Favorable theoretical predictions
- High detection efficiency using molybdate crystal
- Very high energy resolution and powerful particle discrimination(cryogenic scintillating bolometers)



Molibdenum-based crystals

- Crystals succesfully tested as scintillating bolometers:

- **$CaMoO_4$**
- $CdMoO_4$
- $PbMoO_4$
- $SrMoO_4$
- **$ZnMoO_4$**
- **Li_2MoO_4**

AMoRE
Drawbacks:
- Necessity of ^{48}Ca depletion
- Radiopurity (difficult to purify Ca from U, Th, Ra)

LUMINEU
Initial choice (2012): $ZnMoO_4$
First tests on large Li_2MoO_4 crystals: spring 2014

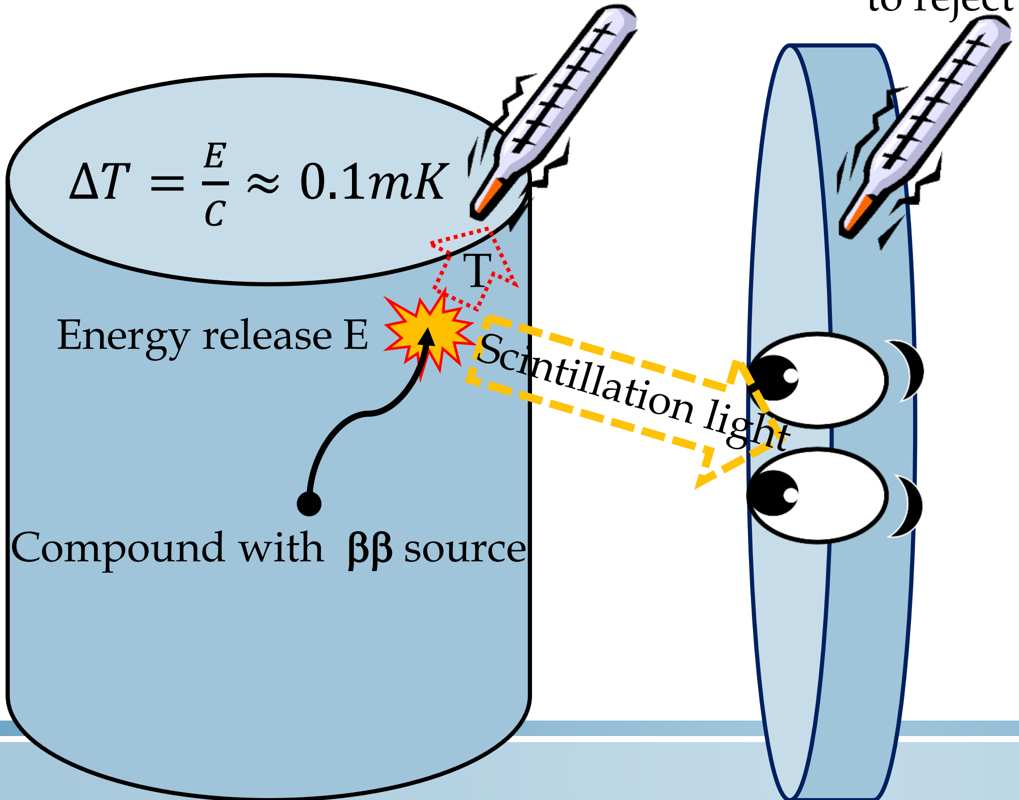
Selection of Li_2MoO_4 for a pilot experiment (March 2016)

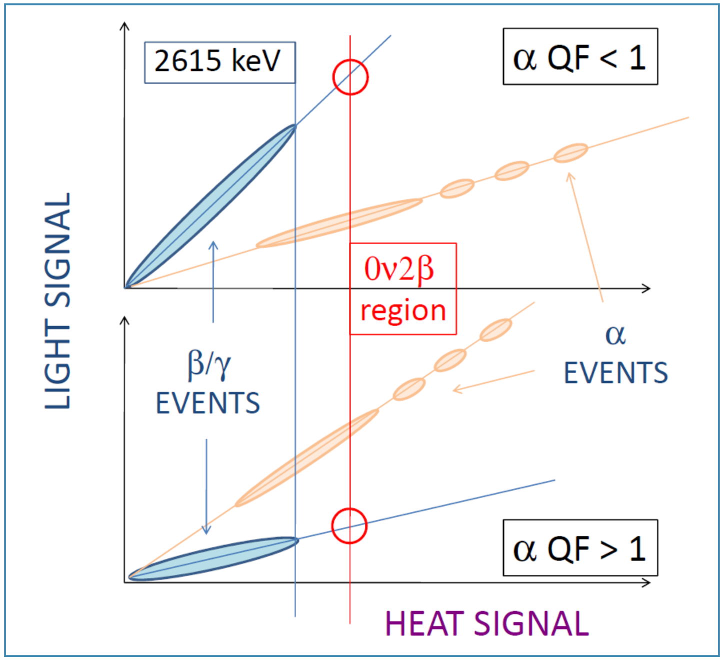
Pros:
- Better bolometric performance
- Easy crystallization / excellent quality
- Outstanding radiopurity

Cons:
- Hygroscopic material
- ^{40}K is natural contaminant
- Lower light yield (~0.8 keV/MeV)

Scintillating bolometers

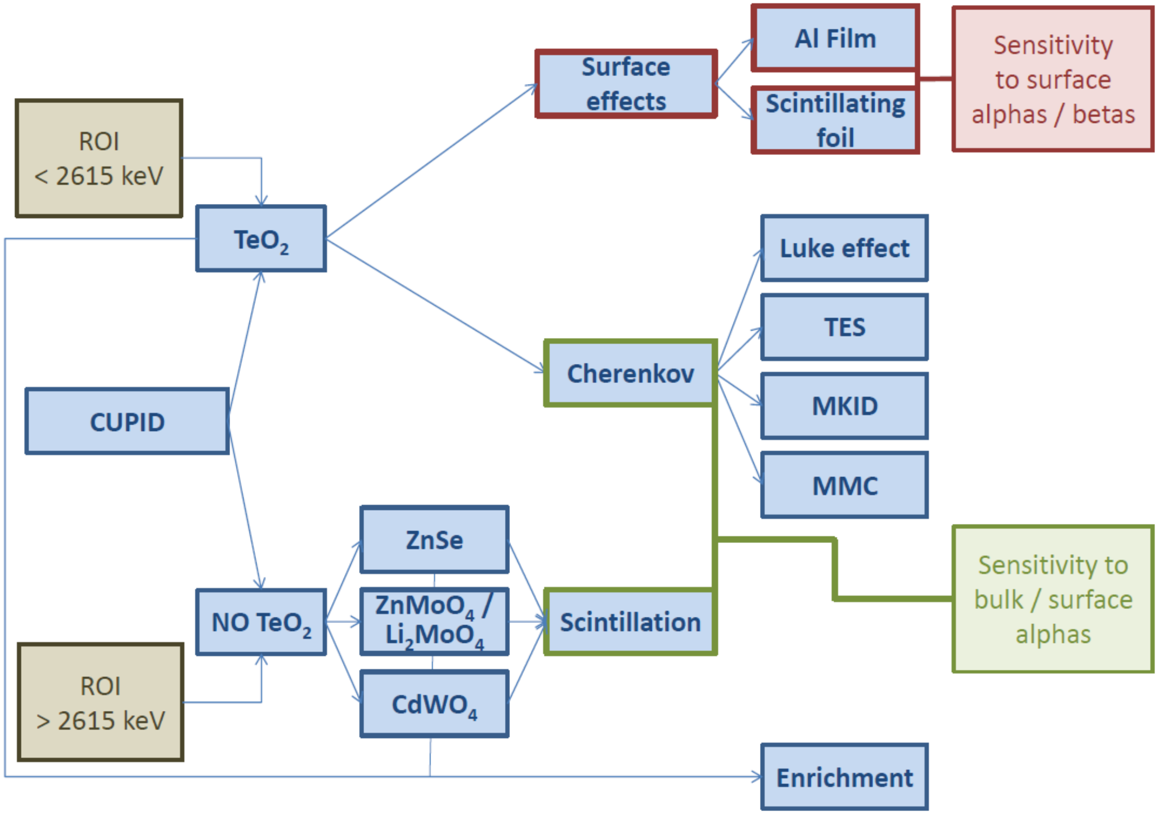
- The nuclear **energy** is measured as a **temperature increase** in a crystal
- **Thermometer provides** phonon signal
- Typical signal sizes: **0.1 mK / MeV**, converted to about **0.1-0.5 mV / MeV**
- High energy resolution: **5-7 keV (0.2%)**
- High registration efficiency: **(70% - 90%)**
- Flash of light is produced by the absorption of a particle
- Different particles produce different amount of light
- Powerful particle discrimination - potential to reject background





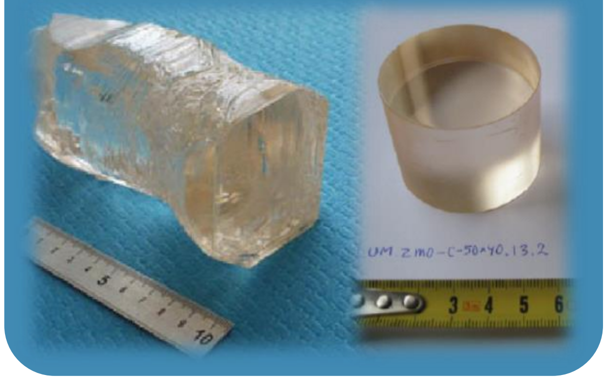
CUPID (CUORE Upgrade with Particle IDentification)

- **Follow-up to CUORE with background improved by a factor 100**
- Reduce/control background from materials and from muon /neutrons
- Improve detector technology to get rid of α/surface background



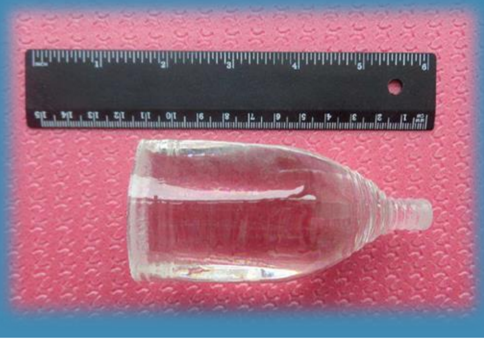
From LUMINEU to CUPID-Mo

Tests of $ZnMoO_4$, natural and enriched. (from 2008)

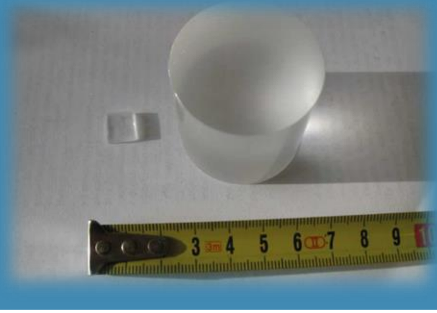


Tests of Li_2MoO_4

First crystals - 2010



$Li_2{}^{100}MoO_4$: production of first enriched crystal in 2015



Suspended tower in LSM to compare $ZnMoO_4$ and $Li_2{}^{100}MoO_4$ to choose best (2015-2016)

Two suspended towers, 4 enriched $Li_2{}^{100}MoO_4$ crystals winter 2016 – spring 2015

Test of technology

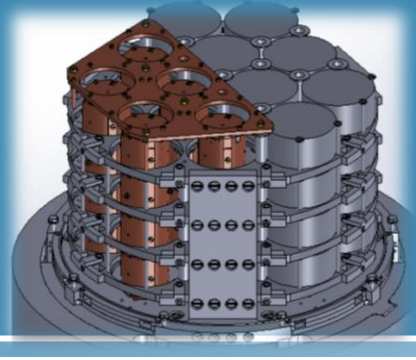
and background

evaluation

for the future

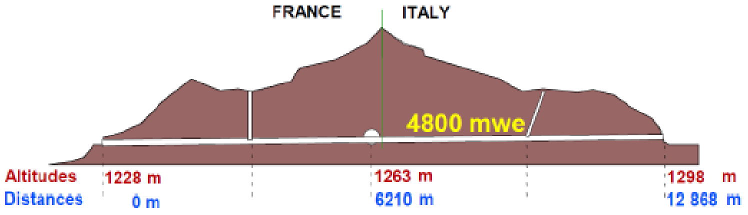
demonstrator

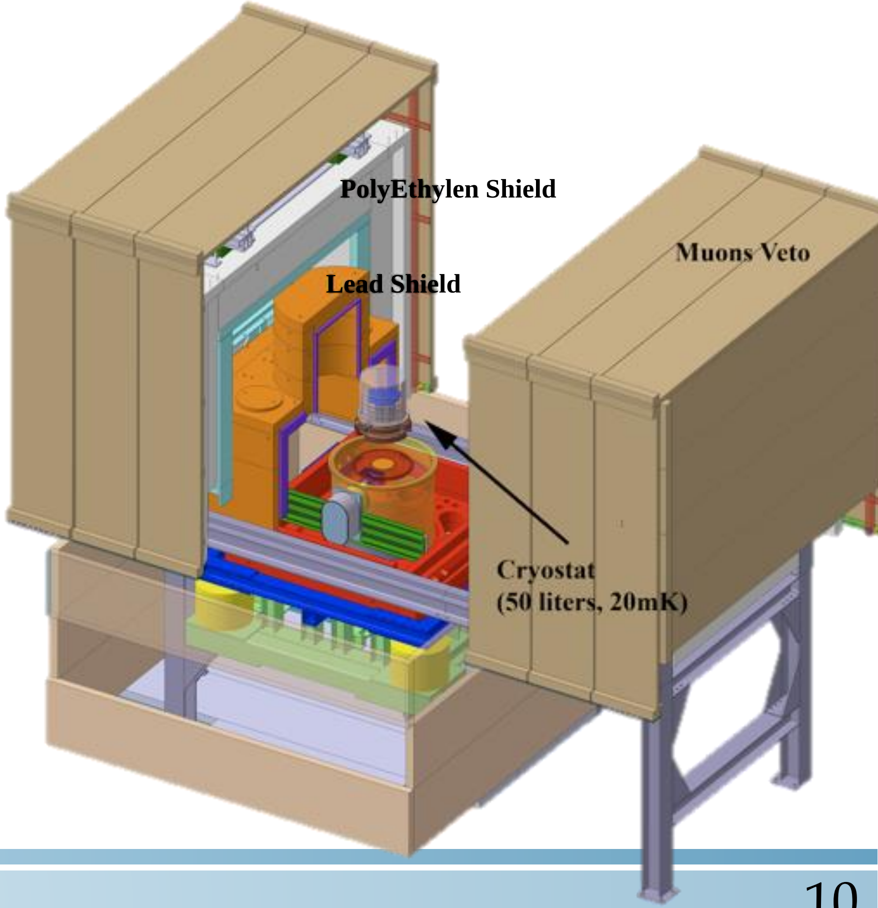
20 enriched crystals: autumn 2017. Prove of 0-background experiment concept



LSM underground laboratory

- **Laboratoire Souterrain de Modane (LSM)**
  - Frejus tunnel
  - 1.7 km rock overburden (~4.8 km w.e.)
  - cosmic μ reduction= 10–8(1/m2h)
  - Deradonized air flow (~30 mBq/m3)
- **EDELWEISS set-up:**
  - Clean room
  - Copper cryostat
  - Low radioactivity lead (min. 20 cm)
  - Polyethylene (min. 50 cm)
  - Monitoring of μ / n / Ra
  - Muon veto

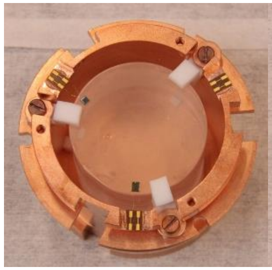




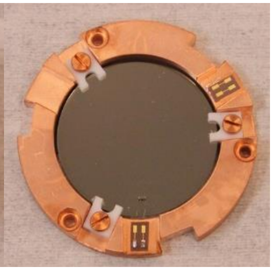
Two suspended towers

T1

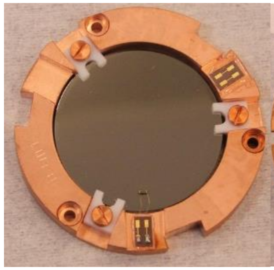
LMO1b



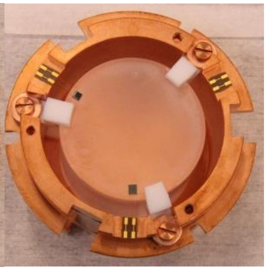
Ge LD



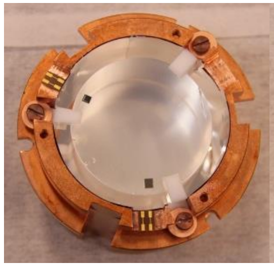
Ge LD



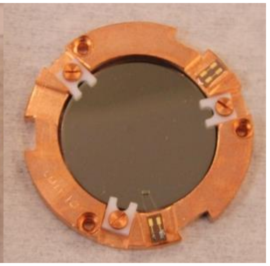
LMO1t



LMO2b

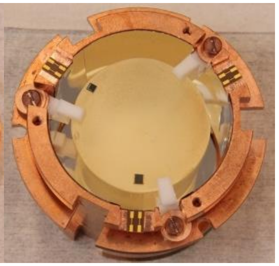


Ge LD



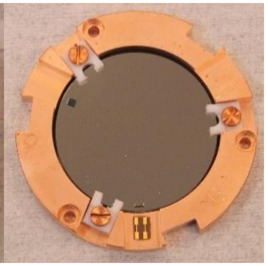
Ge LD

CWO-NAT

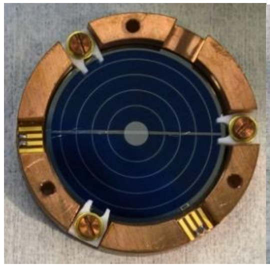


LMO2t

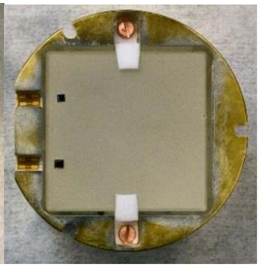
Ge LD

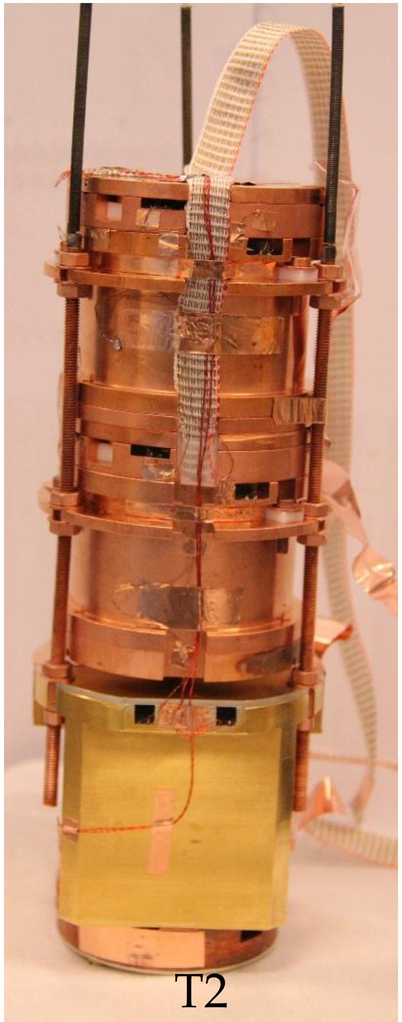


Ge-NL LD



TeO_2





T2

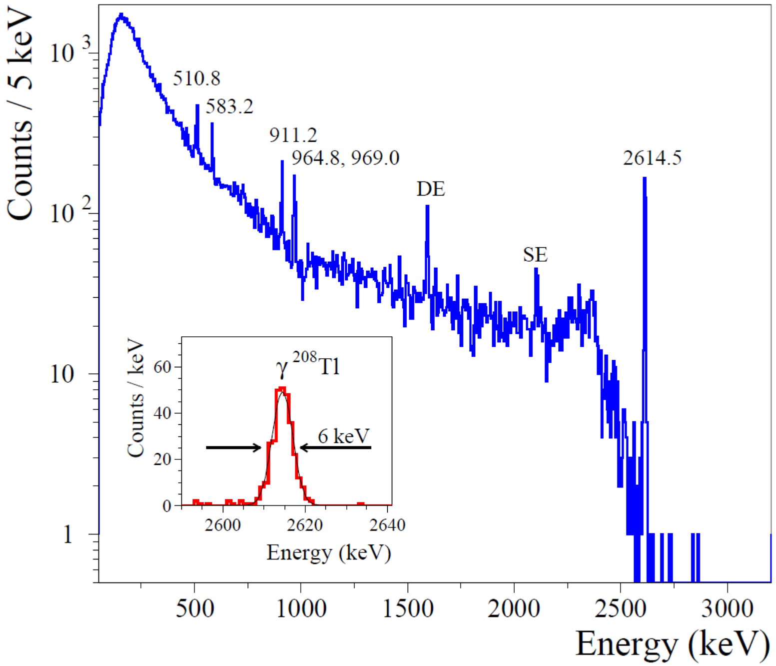
Test of technology for demonstrator with 20 crystals and R&D detectors with another compounds for 2β-decay research

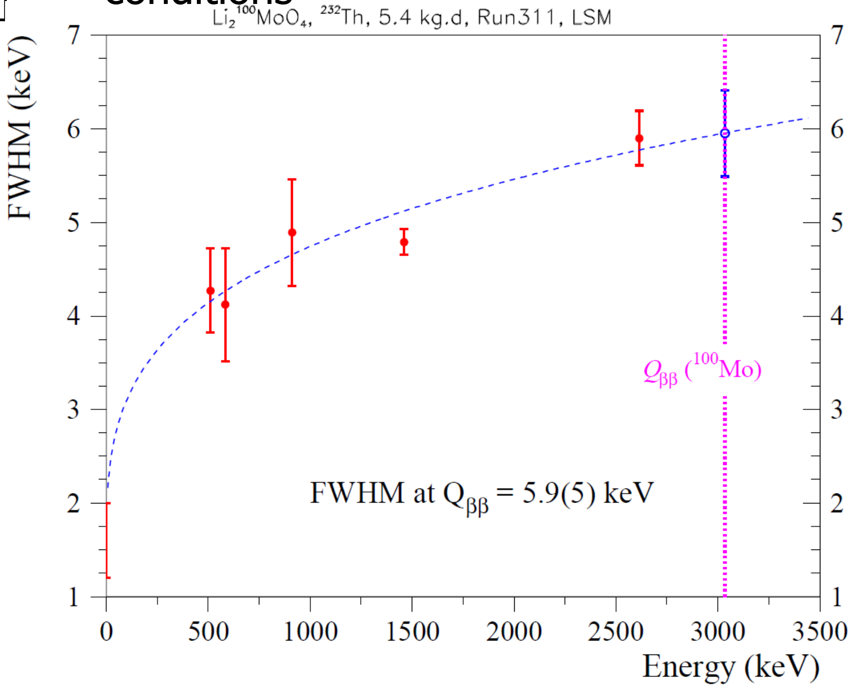
Performance of 4 enriched crystals

Crystal ID	Signal, nV/keV	FWHM , keV at energy, keV		
		0	1461	2615
1t	40	~1.0	4.0(2)	5.8(6)
1b	47	~1.2	4.7(2)	5.7(6)
2t	50	~2.4	4.1(5)	5.5(5)
2b	48	~2.0	5.1(4)	5.7(6)
Total	~46	~1.6	4.8(1)	5.0(3)

Enriched $Li_2{}^{100}MoO_4$ crystals demonstrate high performance:

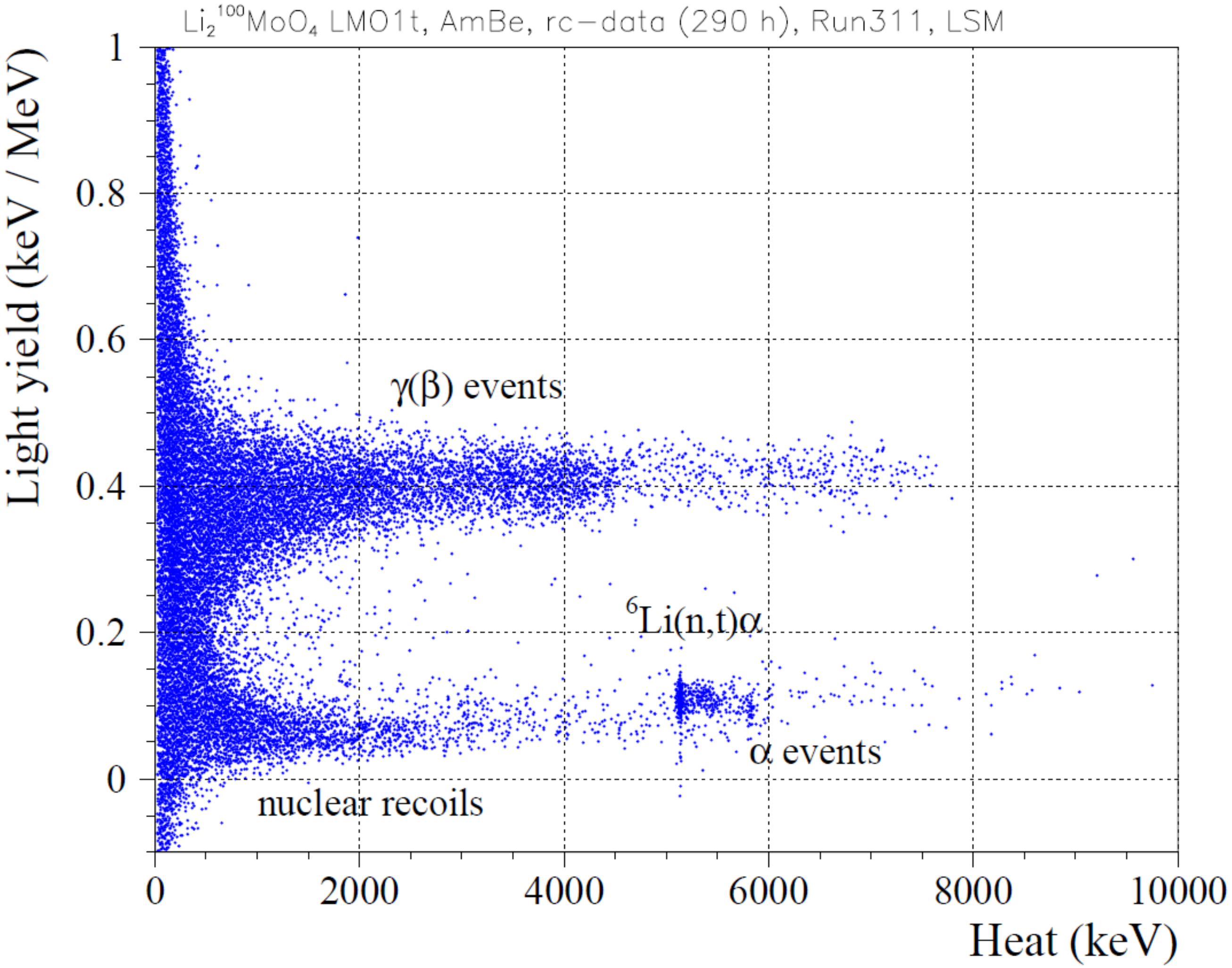
- ~50 nV/keV sensitivity
- 1-2 keV FWHM noise
- ~6 keV FWHM at 2615 keV ⇒ FWHM = 6 keV at $Q_{\beta\beta}$ at not optimal conditions





FWHM at $Q_{\beta\beta}$ = 5.9(5) keV

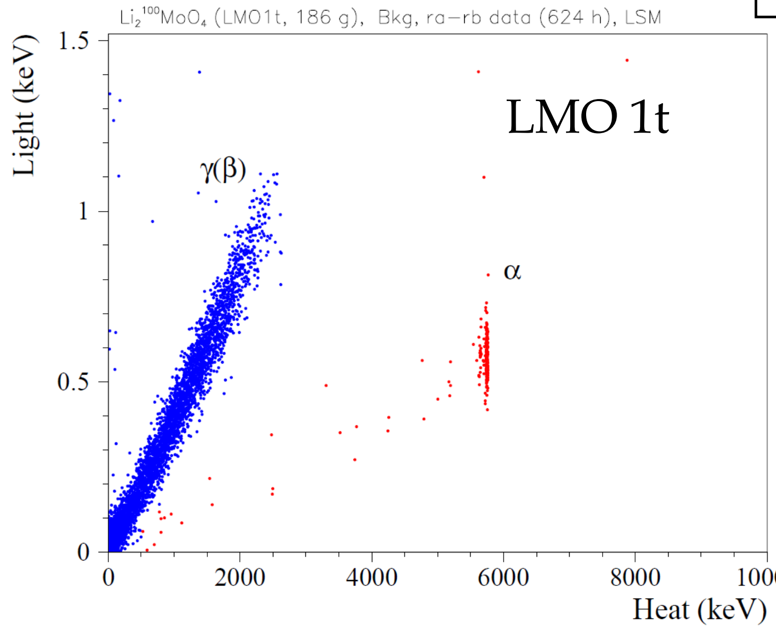
Neutron calibration: alpha discrimination

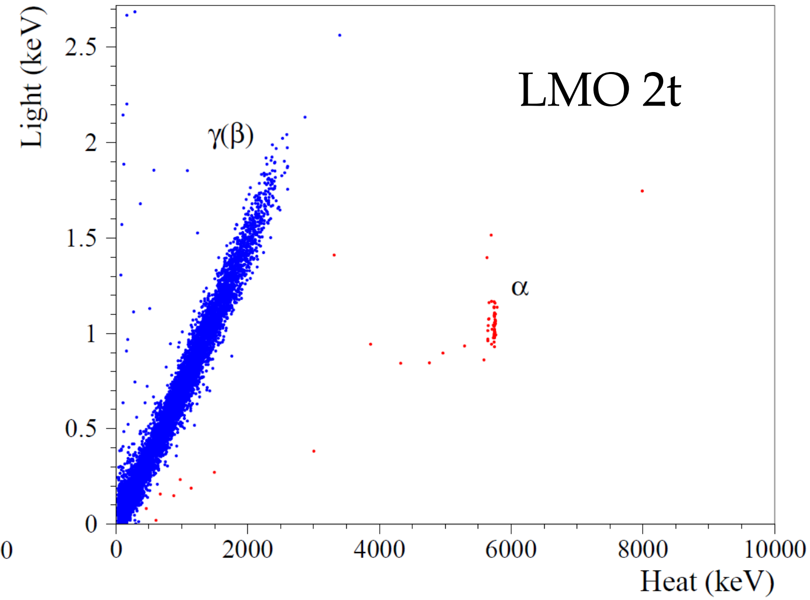


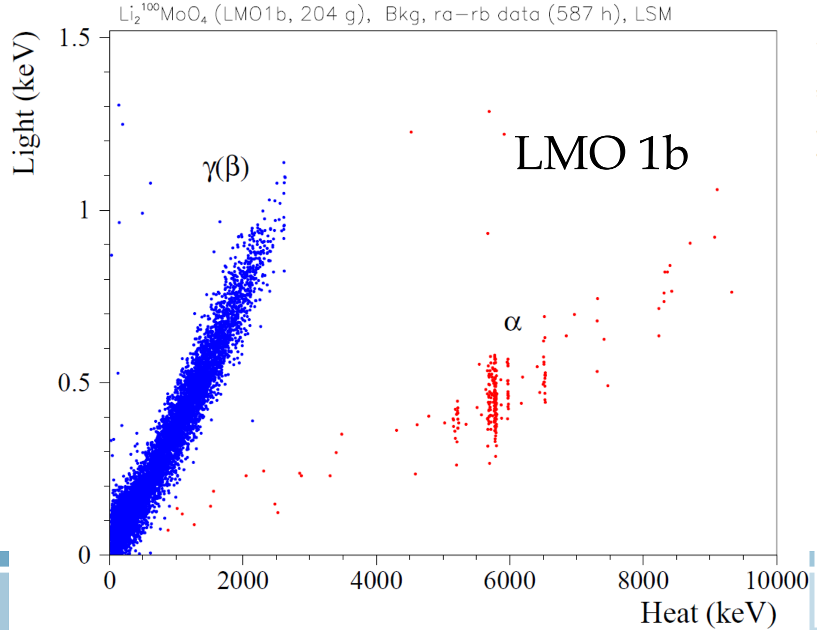
- γ(β) [2.5-2.7 MeV] / α+t [5.0-5.5 MeV] **Discrimination Power = 9.5(5)**

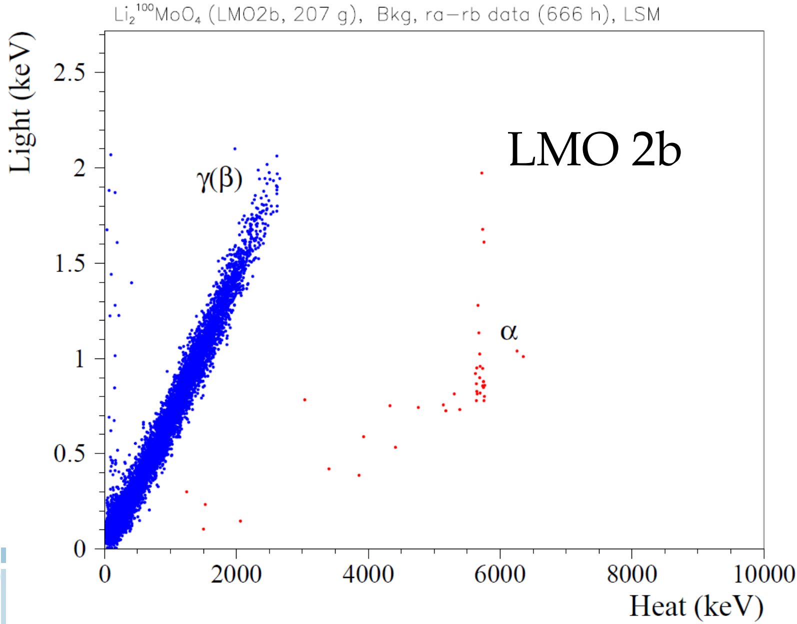
Background: ~600h

For all LMO's: α's in 2.7-3.9 MeV~0.2 cnts/yr/kg/keV
High bulk and surface purity

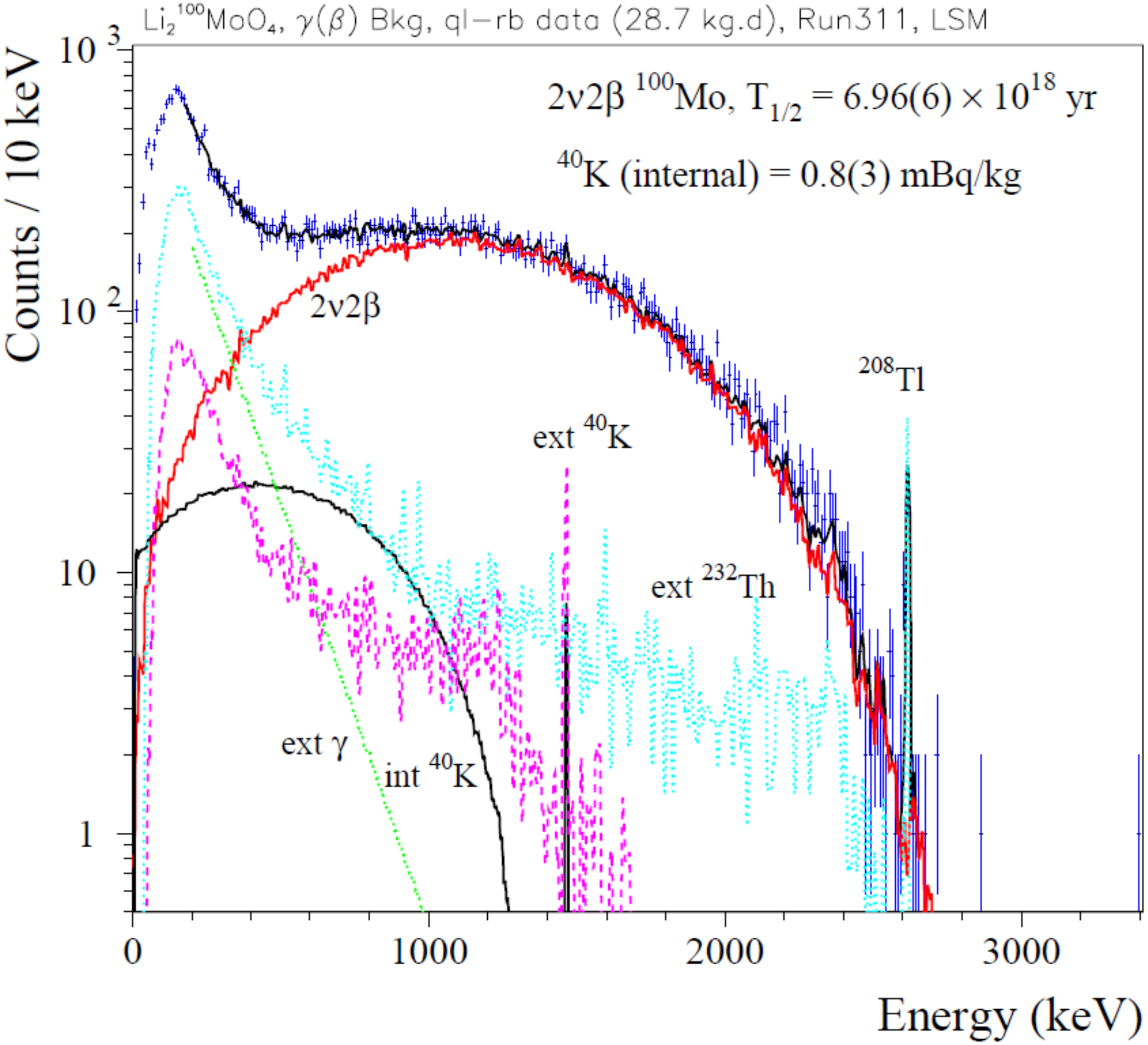








Double beta decay of ^{100}Mo



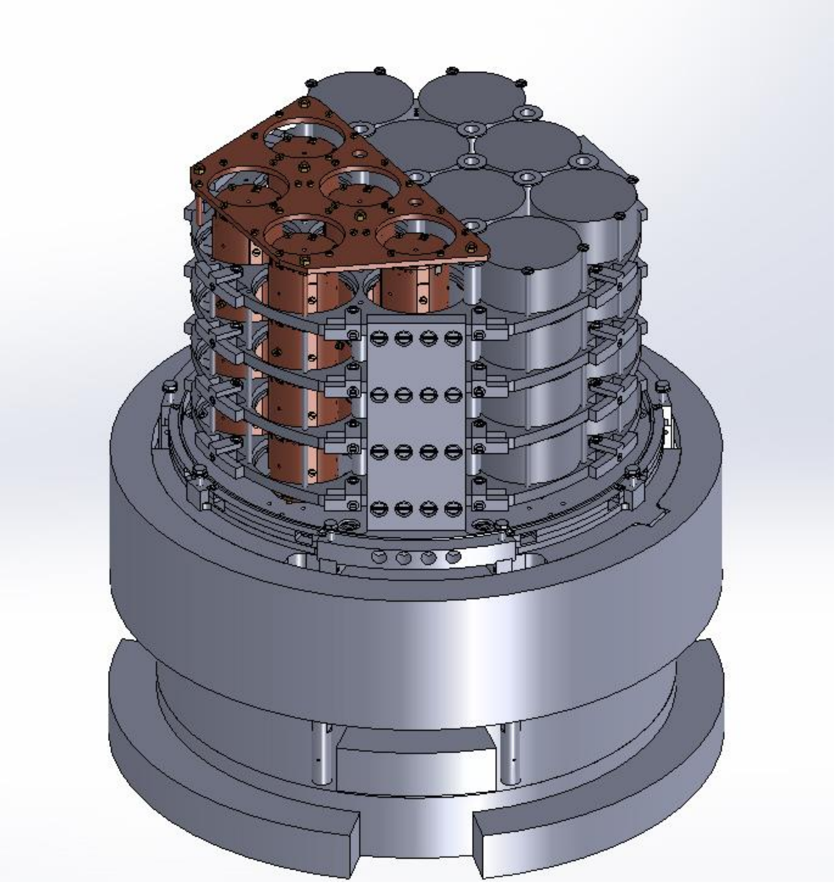
Investigation of ^{100}Mo 2ν2β:

- Exposure: 28 kg×d
- Enrichment: 96.9% of ^{100}Mo
- eff_{PSD}: 97%
- Fit: 160-2650 keV ⇒ Effect = 24320±229 decays
- **$T_{1/2}$ = [6.96±0.06] × 10^{18} yr**

Sensitivity to ^{100}Mo 0ν2β:

- $Q_{\beta\beta}$(^{100}Mo): 3034 keV
- ROI: 10 keV window @ $Q_{\beta\beta}$
- $\text{eff}_{0\nu2\beta}$: 70% in ROI
- BI: 0.05 cnts/yr/kg/keV ⇒ Bkg: 0.04 counts
- Effect: 0 counts ⇒ limS: 2.4 counts at 90% CL
- **lim$T_{1/2}$ = 5×10^{22} yr @ 90% CL**

CUPID-Mo experiment



- Detectors of the 1st batch of 20 crystals will be assembled and operated in LSM **coexisting with EDELWEISS low-mass WIMP search.**

20-detector demonstrator schedule:

- **June-July 2017** – underground test of a single 4-detector tower
- **November 2017 – half 2018** – long underground run, first results of background model and sensitivity will come out.

- In calculating the sensitivity (90% C.L.), we will assume:
- **b = 1 x 10^{-3}** counts/keV/kg/y
- **8 keV** energy window
- **78%** efficiency

Configuration	Half life limit [90% c.l.]	$M_{\beta\beta}$ [meV]
20 crystal [20×0.5 cr.×y]	1.4×10^{24}	240 – 670
20 crystal [20×1.5 cr.×y]	4.2×10^{24}	140 – 390
40 crystal [40×3 cr.×y]	1.7×10^{25}	70 – 200

Conclusions and perspectives

- Properties of neutrino: mass scale, Dirac or Majorana – answer to this question is important for development of new theories
- Cryogenic scintillating bolometers are promising detectors for high-sensitivity searches for 0νββ decay
- Detectors, developed in the framework of the LUMINEU project, show excellent performance: a few keV energy resolution, 20 sigma α/β particle discrimination power at the $Q_{2\beta}$value of ^{100}Mo
- $Li_2{}^{100}MoO_4$ crystals are perspective material for 0νββ decay research, also can be used as neutron detectors with high energy resolution
- Operation of four $Li_2{}^{100}MoO_4$ scintillating bolometers array was highly successful
- Goal of Cupid-Mo demonstrator: long run with 20 $Li_2{}^{100}MoO_4$ crystals to prove “zero-background” concept for future ton-scale experiment

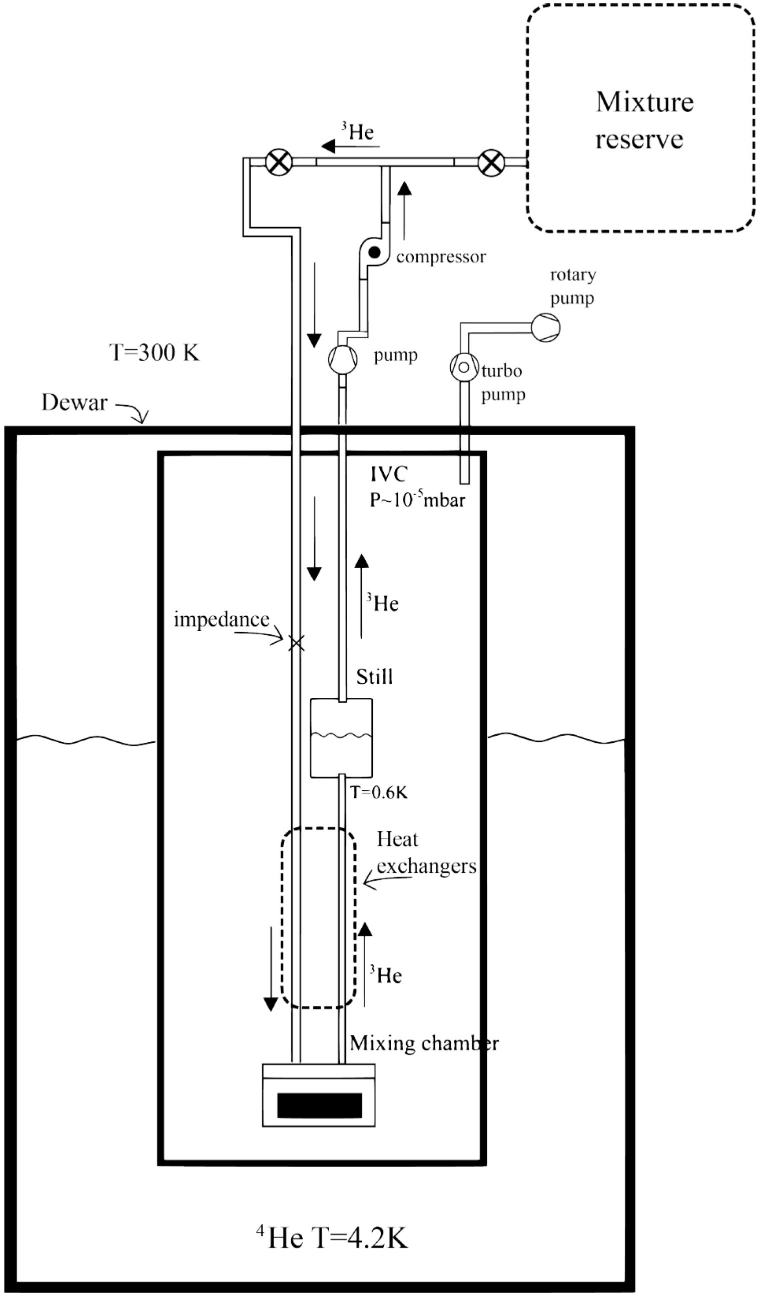
Thanks for your attention!

In physics, you don't have to go around making trouble for yourself - nature does it for you.
Frank Wilczek

Backups

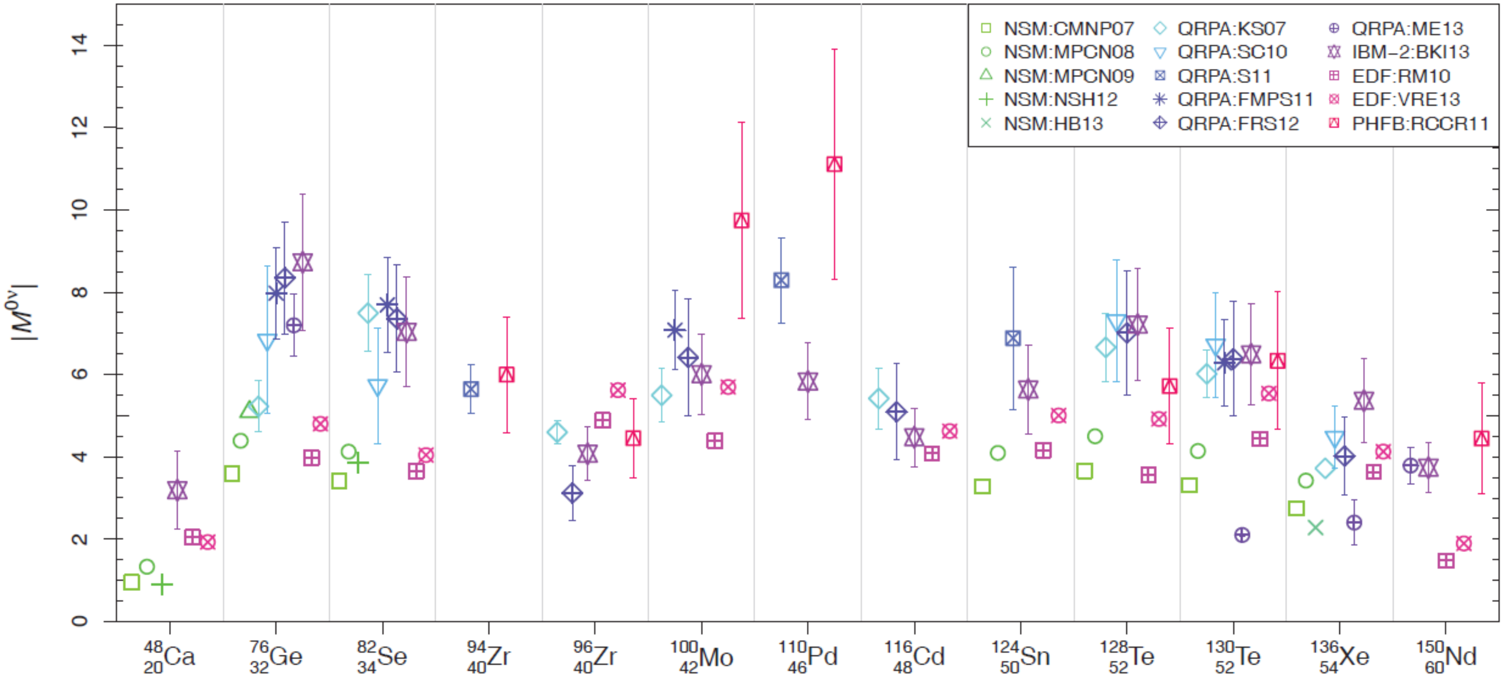
Duilution refrigerators

- Complicated system
- It has to be wholly isolated from the environment: vacuum chamber
- To cool down below the LHe temperature (≈ 4K) the cryostat uses a mixture of two isotopes of helium: 3He and 4He.
- Two ways to pre-cool:
  - Wet: LHe bath which provides the first cooling stage at 4.2 K.
  - Dry: pulse tube cooler using heat-exchange gas

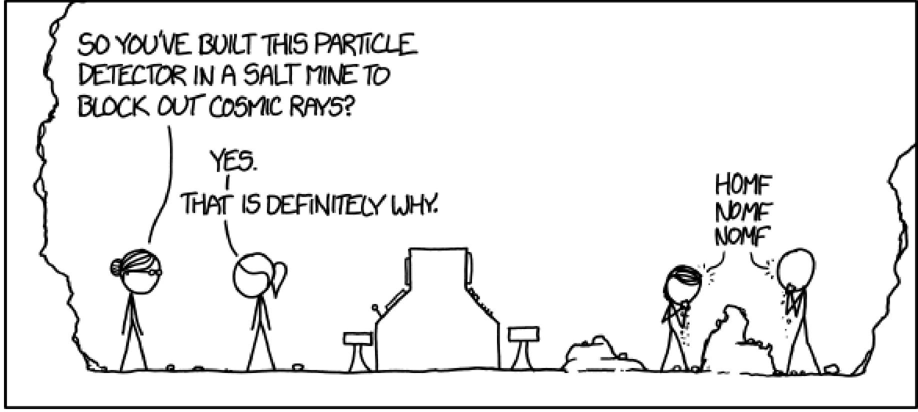


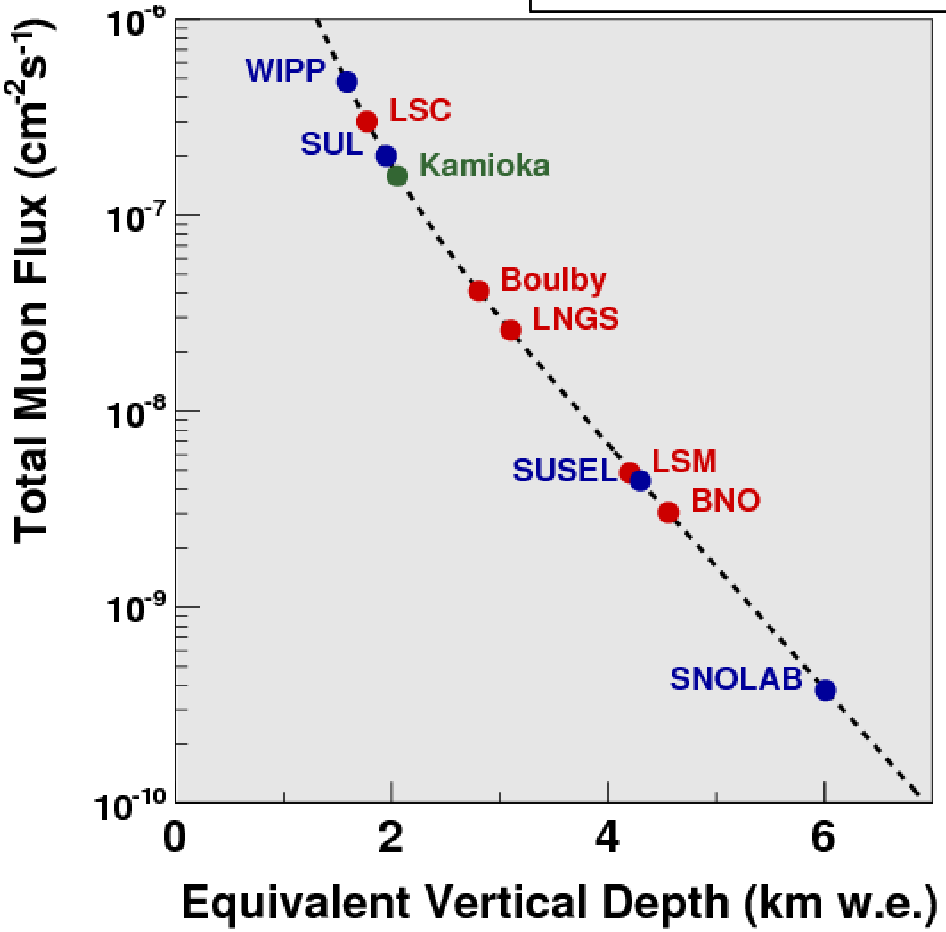
Uncertainty in predictions: Nuclear Matrix Elements

- Complicated nuclear many-body problem
- Cannot be measured independently
- Different methods have been used for the calculation of neutrinoless double-β decay NMEs:



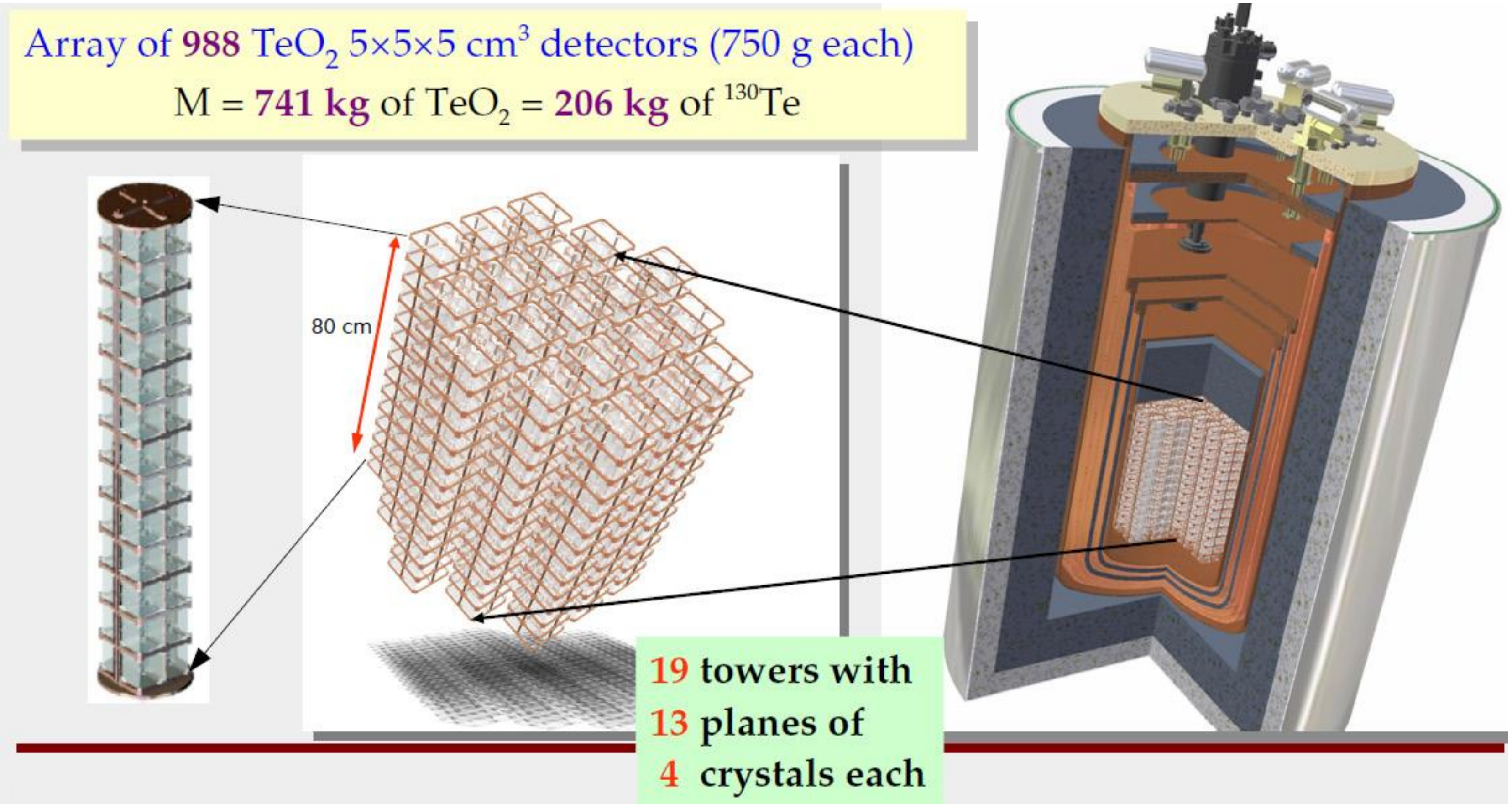
Going underground





CUORE (Cryogenic Underground Observatory for Rare Events)

- Operation already started.



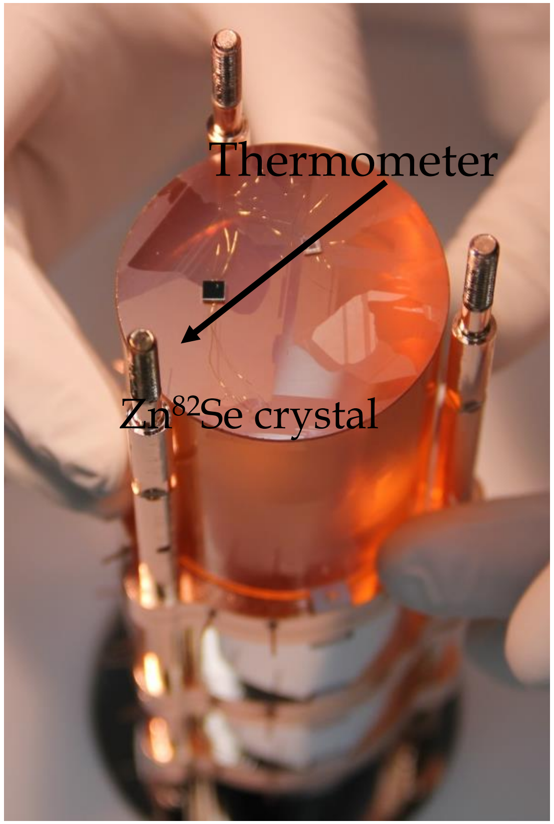
Array of **988** TeO_2 $5\times5\times5$ cm^3 detectors (750 g each)

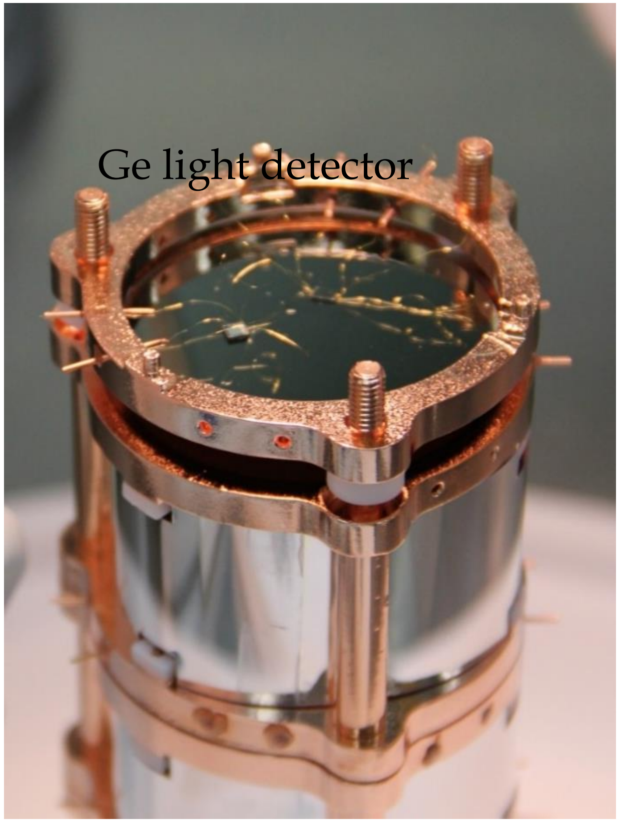
M = **741 kg** of TeO_2 = **206 kg** of ^{130}Te

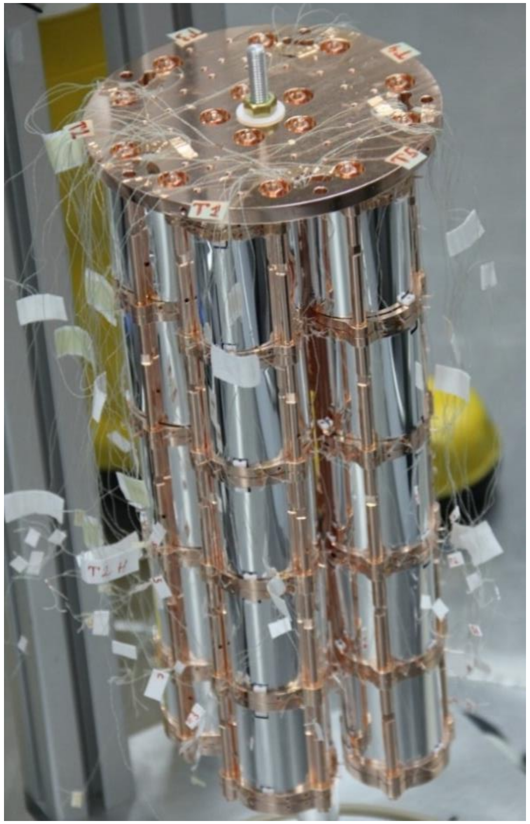
19 towers with
13 planes of
4 crystals each

CUPID-0/Se experiment: CUORE Upgrade with Particle IDentification

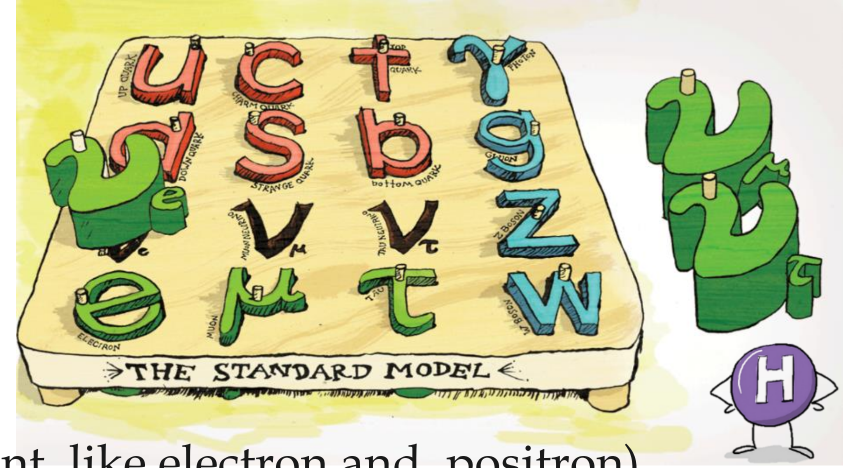
- Search for 0nbb decay of 82Se with Zn82Se scintillating bolometers
- Data taking with 26 enriched detectors is ongoing
- Expected 1 yr sensitivity is T1/2 ~ 1025 yr



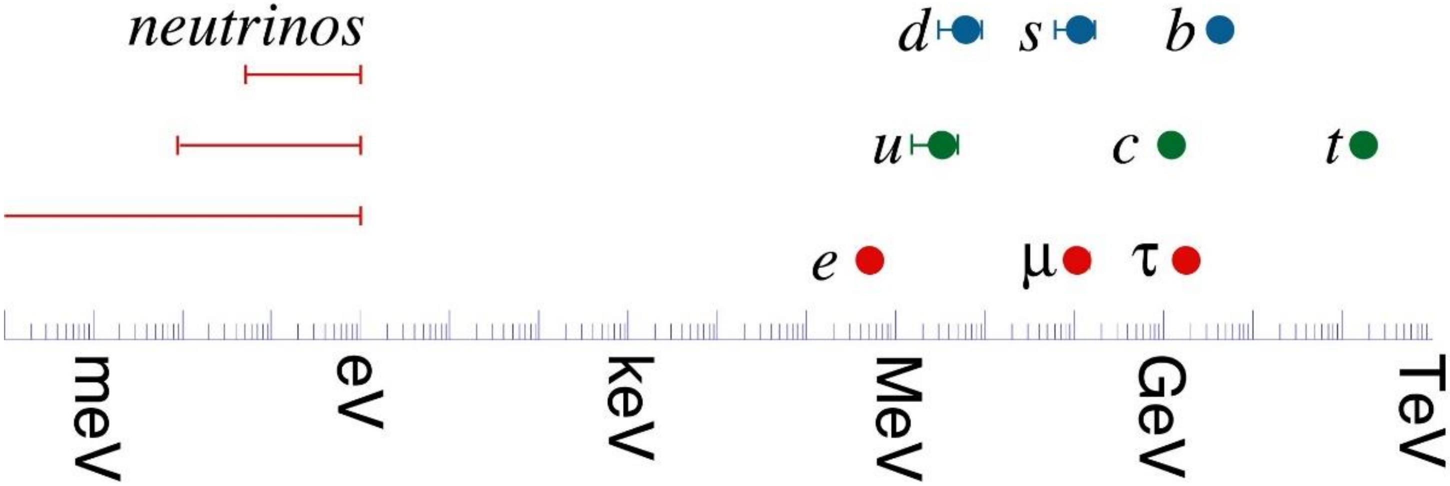


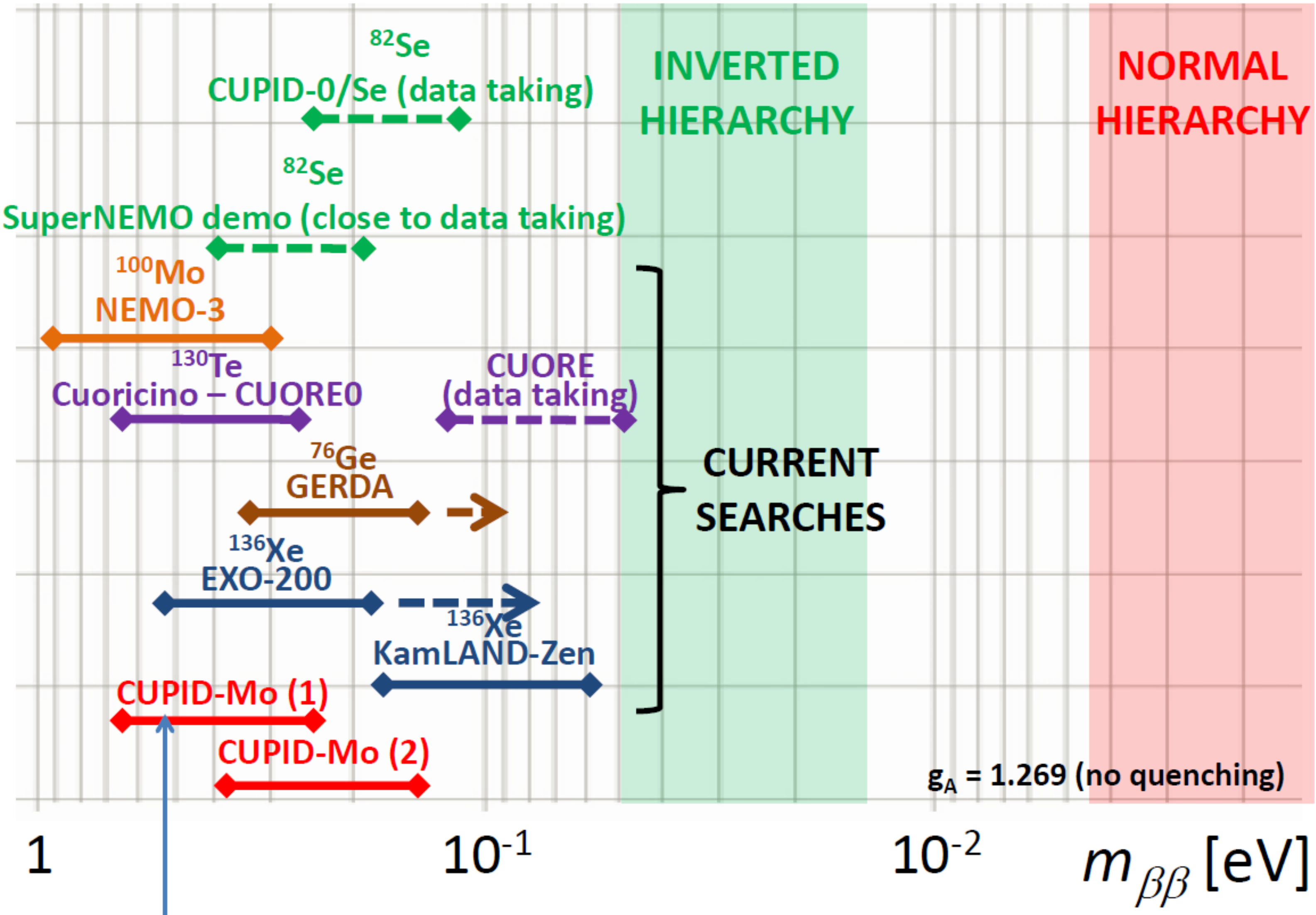


Neutrinos properties: a door to new physics



- **Nature of neutrino**:
  - **Dirac** (particle and anti-particle are different, like electron and positron)
  - **Majorana** (particle and anti-particle cannot be distinguished)
- **Neutrino oscillations**: neutrinos do have masses (in SM they are considered to be massless), but scale is not defined





This can be achieved in **2018 !**

Pulse-shape parameter