New ideas and their applications: double beta decay

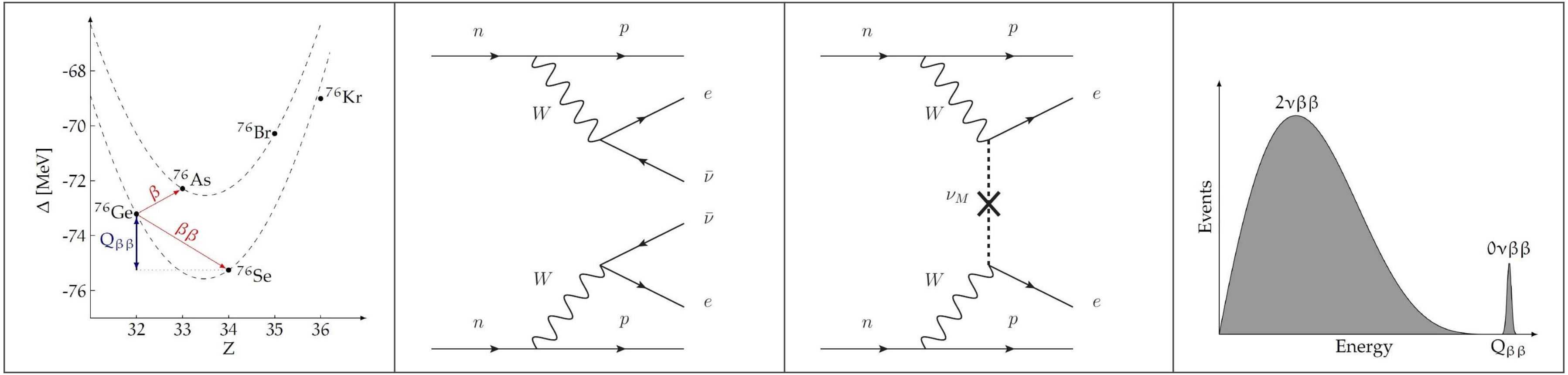
Giovanni Benato

P210 BSM-ν   February 12, 2021

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

Fellini
Fellowship for Innovation at INFN

Expected 0νββ decay signature



ββ decay signature

- Continuum for 2νββ decay
- Peak at $Q_{\beta\beta}$ for 0νββ decay
  ⟹ Energy peak is the only necessary and sufficient signature to claim a discovery
- Additional signatures from signal topology, pulse shape discrimination, multiple channel readout, daughter tagging, …

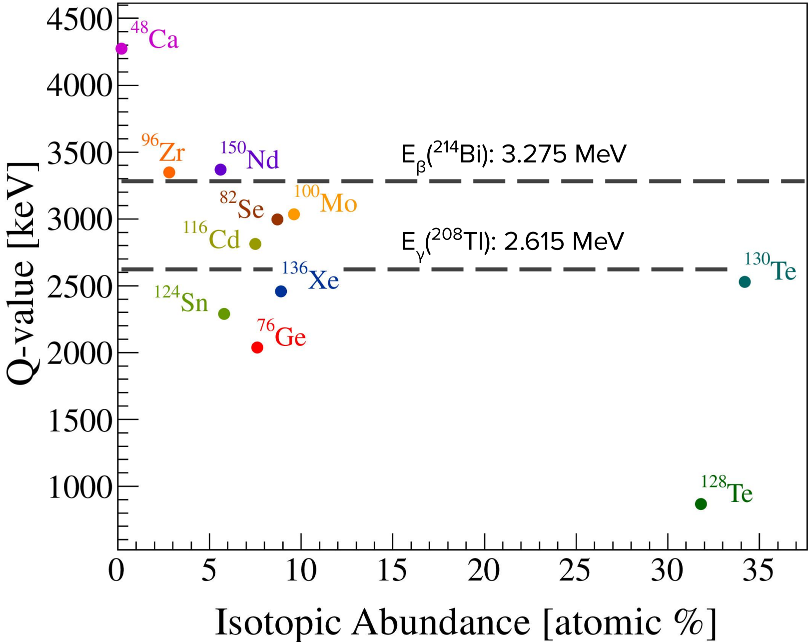
0νββ decay rate

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f|^2 / m_e^2$$

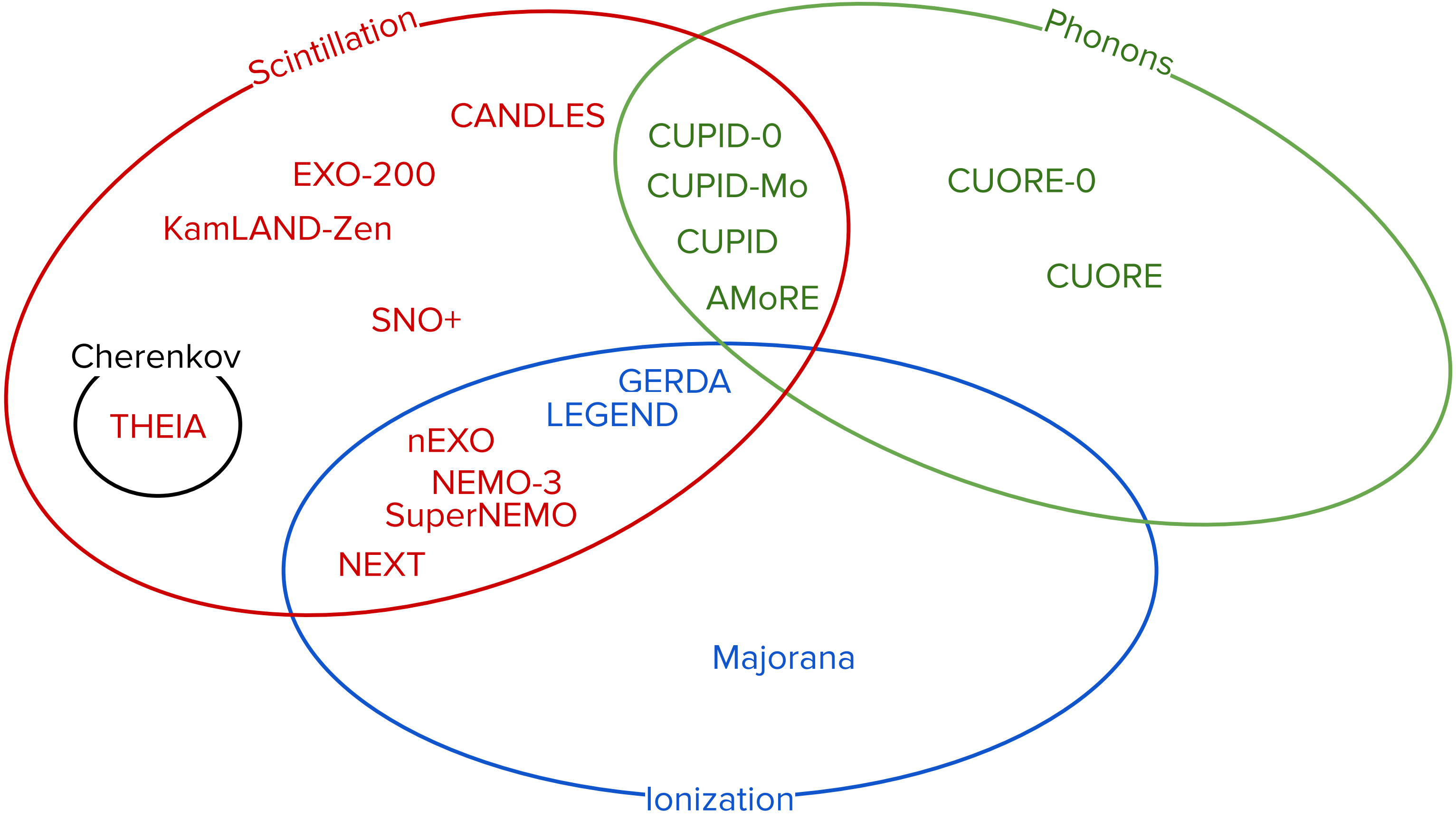
- $T_{1/2}^{0\nu}$ = 0νββ decay half-life
- $G_{0\nu}$ = phase space (known)
- $M_{0\nu}$ = nuclear matrix element (NME)
- f = new physics term

Isotope choice for 0νββ decay experiments

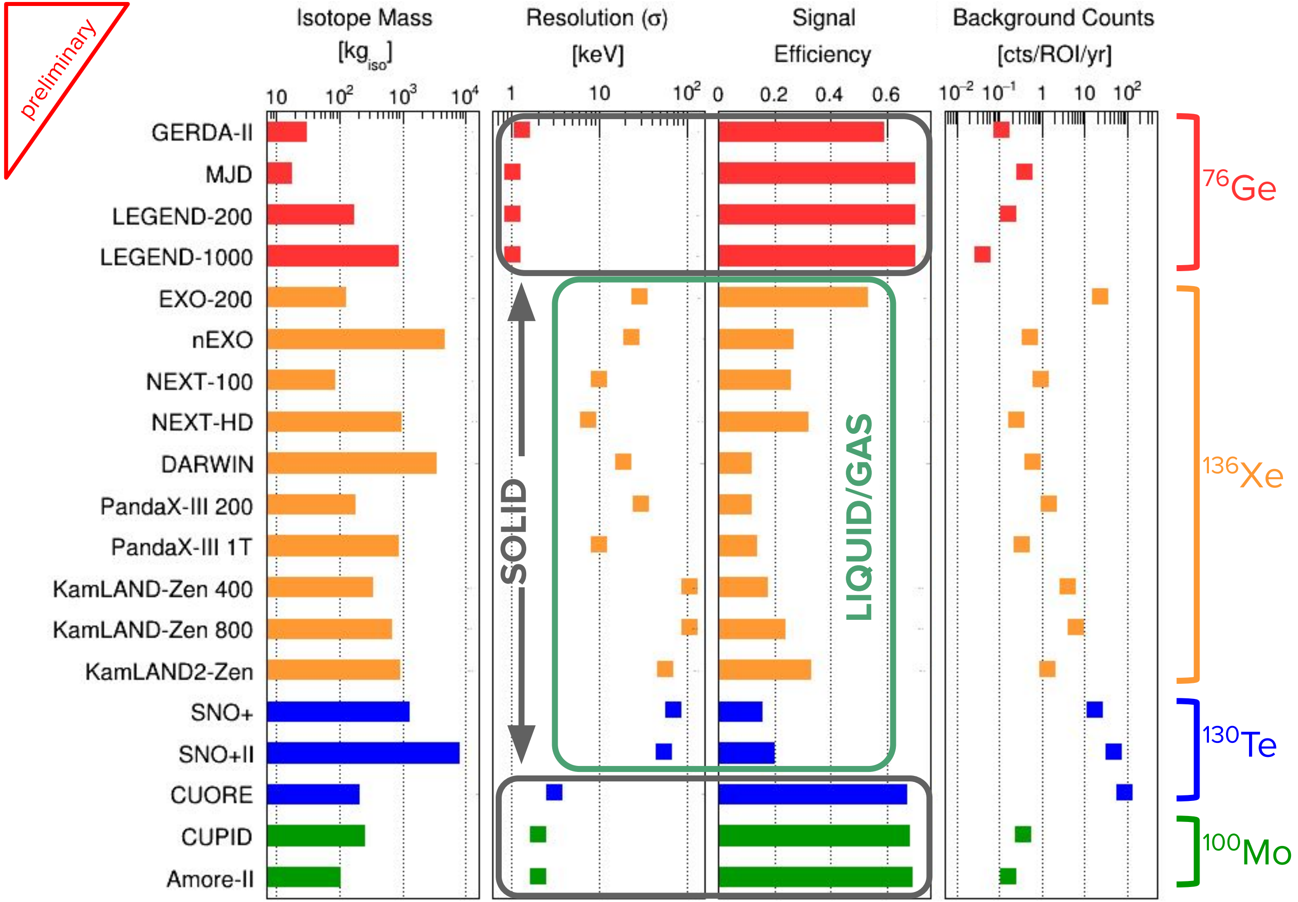
- High isotopic abundance
- Enrichment possible at reasonable cost?
- $Q_{\beta\beta}$ above end point of β or γ radiation?
- Detector technology available?
- Large scale production possible?



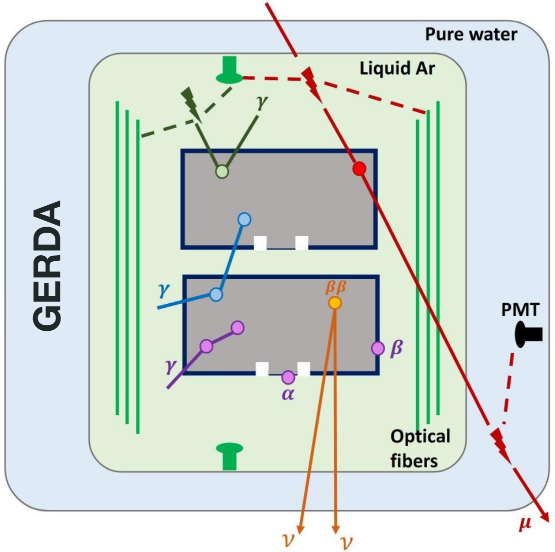
0νββ decay experimental fauna

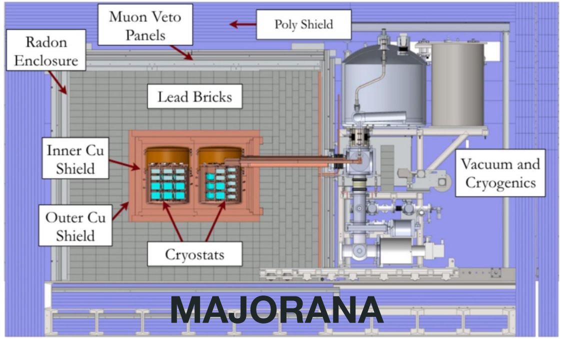


0νββ decay experimental fauna

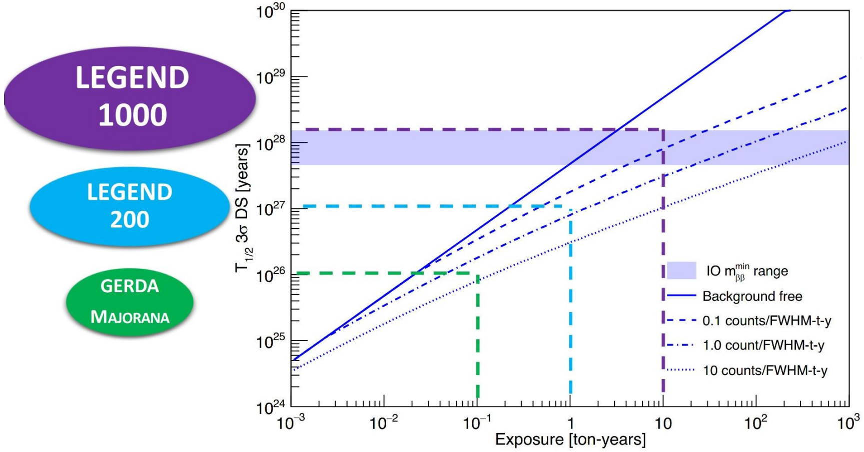


Germanium experiments



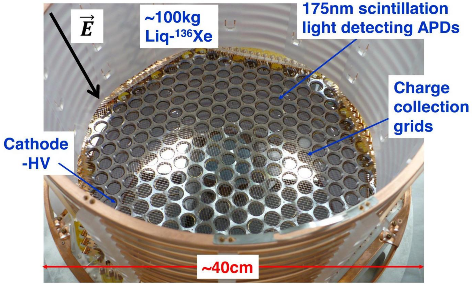


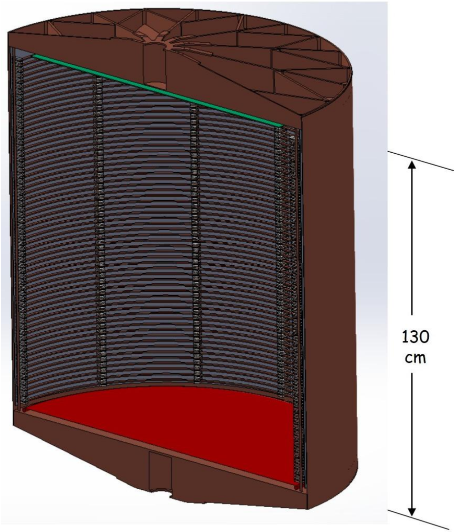
- Low Q-value: 2039 keV
- Highest energy resolution: ~0.1%
- Extremely low bkg: ~$5\cdot10^{-4}$ counts/keV/kg/yr
  → Operating next to linear sensitivity regime
- Best limit:
  $T_{1/2}^{0\nu}(^{76}Ge) > 1.8\cdot10^{26}$ yr @ 90% C.L.
- MAJORANA + GERDA joining for next generation experiment: LEGEND



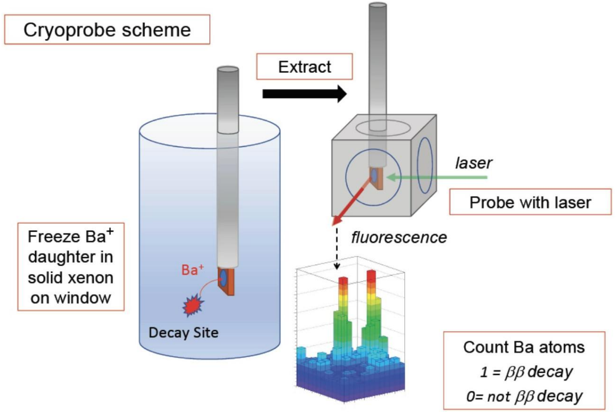
Xenon TPCs

EXO-200 / nEXO

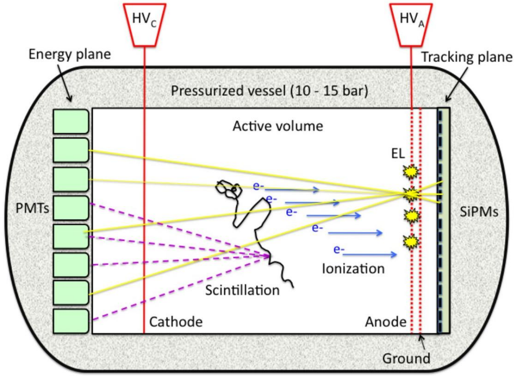


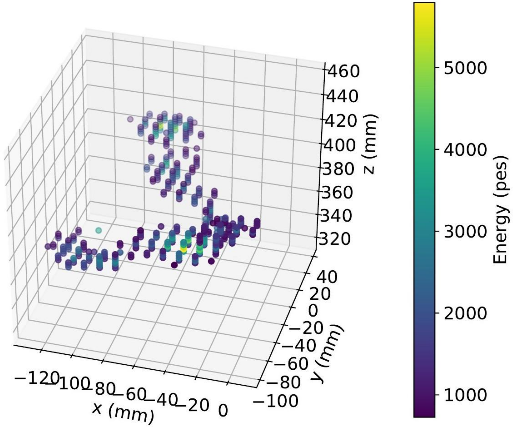


- Liquid TPC
  → Self shielding, easy to scale up
- Gas TPC
  → Energy resolution ~1%
  → Particle tracking
- Double readout: ionization and scintillation
- Best available limit (EXO-200):
  $T_{1/2}^{0\nu}(^{136}\mathrm{Xe}) > 5.0\cdot10^{25}$ yr @ 90% C.L.
- Daughter tagging possible!



NEXT



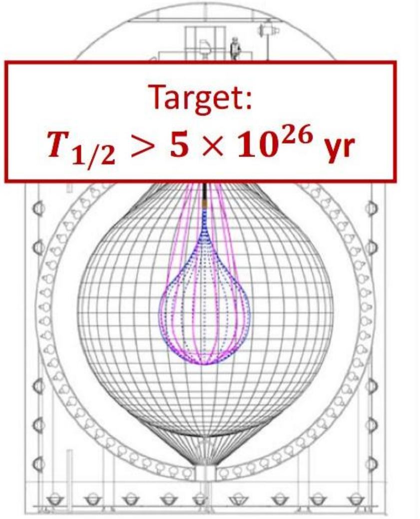


Liquid scintillator experiments

KamLAND-Zen

Current

Target:
$T_{1/2} > 5 \times 10^{26}$ yr



KamLAND-Zen 800

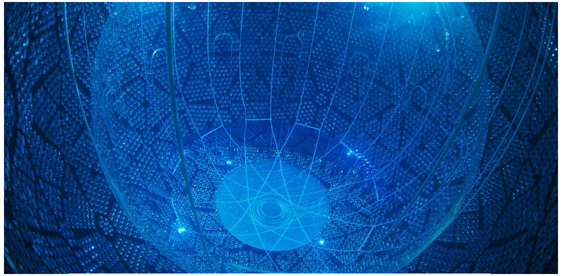
Mini-balloon Radius = 1.90 m

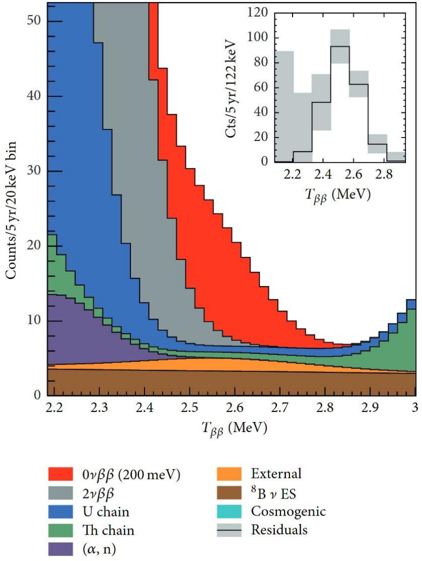
Xenon mass = 745 kg

Started January 2019

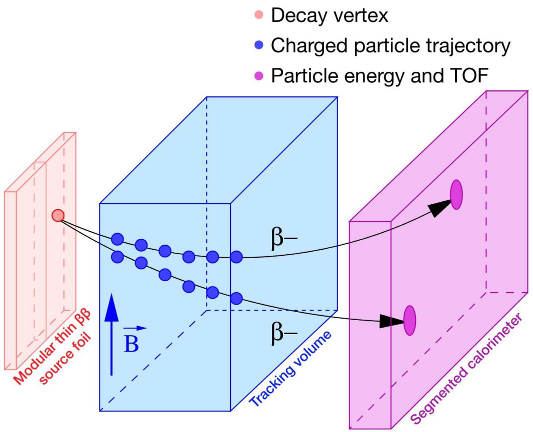
- Readout of scintillation only
  → Energy resolution of few %
  → Particle identification possible
- Very large volume
  → Isotope in central part
  → Highly effective self shielding
- Isotope dissolved in liquid scintillator
  → Easily scalable
- Readout of Cherenkov light possible in future experiments

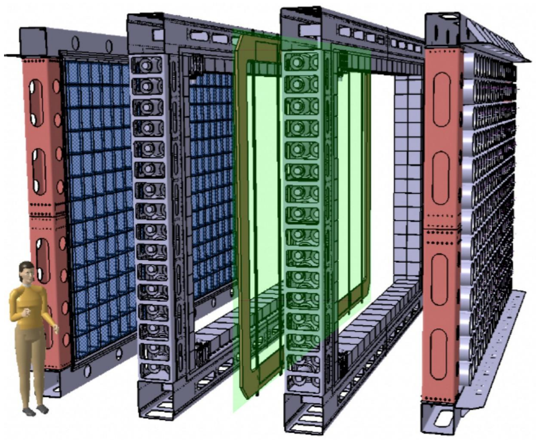
SNO+



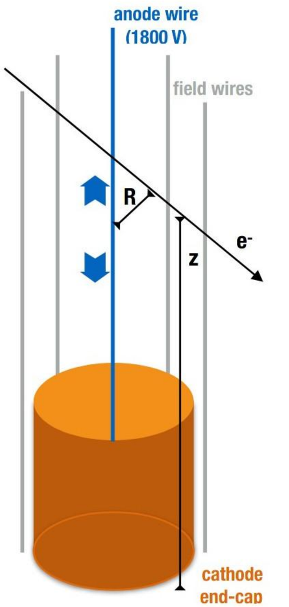


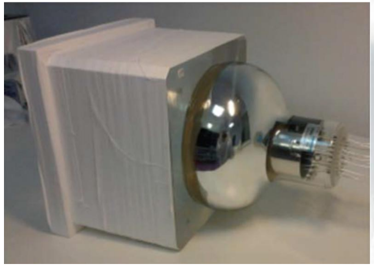
Tracking experiments: SuperNEMO





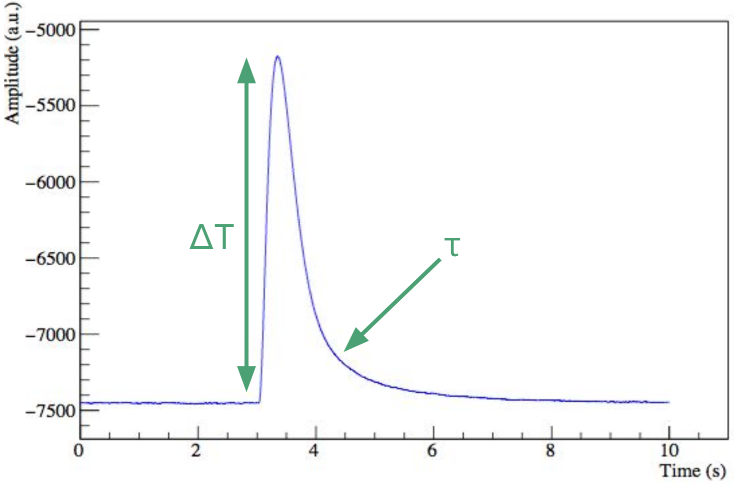
- Measure both energy and momentum
  → Background suppression
  → Single electrons resolved
  → Possible to study 0νββ decay mechanism
- Source ≠ detector
  → Limited isotope mass
  → Any isotope is usable
- Perfect technology for precision measurement of 0νββ and 2νββ decay

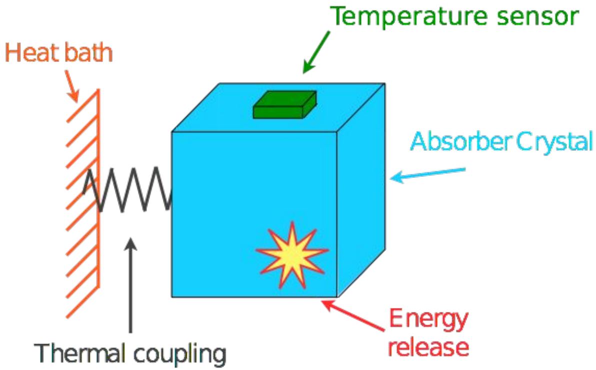




Cryogenic calorimeters a.k.a. bolometers

- Low heat capacity @ T ~ 10 mK
- Excellent energy resolution (**~0.2% FWHM**)
- Detector agnostic to origin of energy deposition
- Detector response of O(1) sec if readout with Neutron Transmutation Doped (NTD) Ge sensors

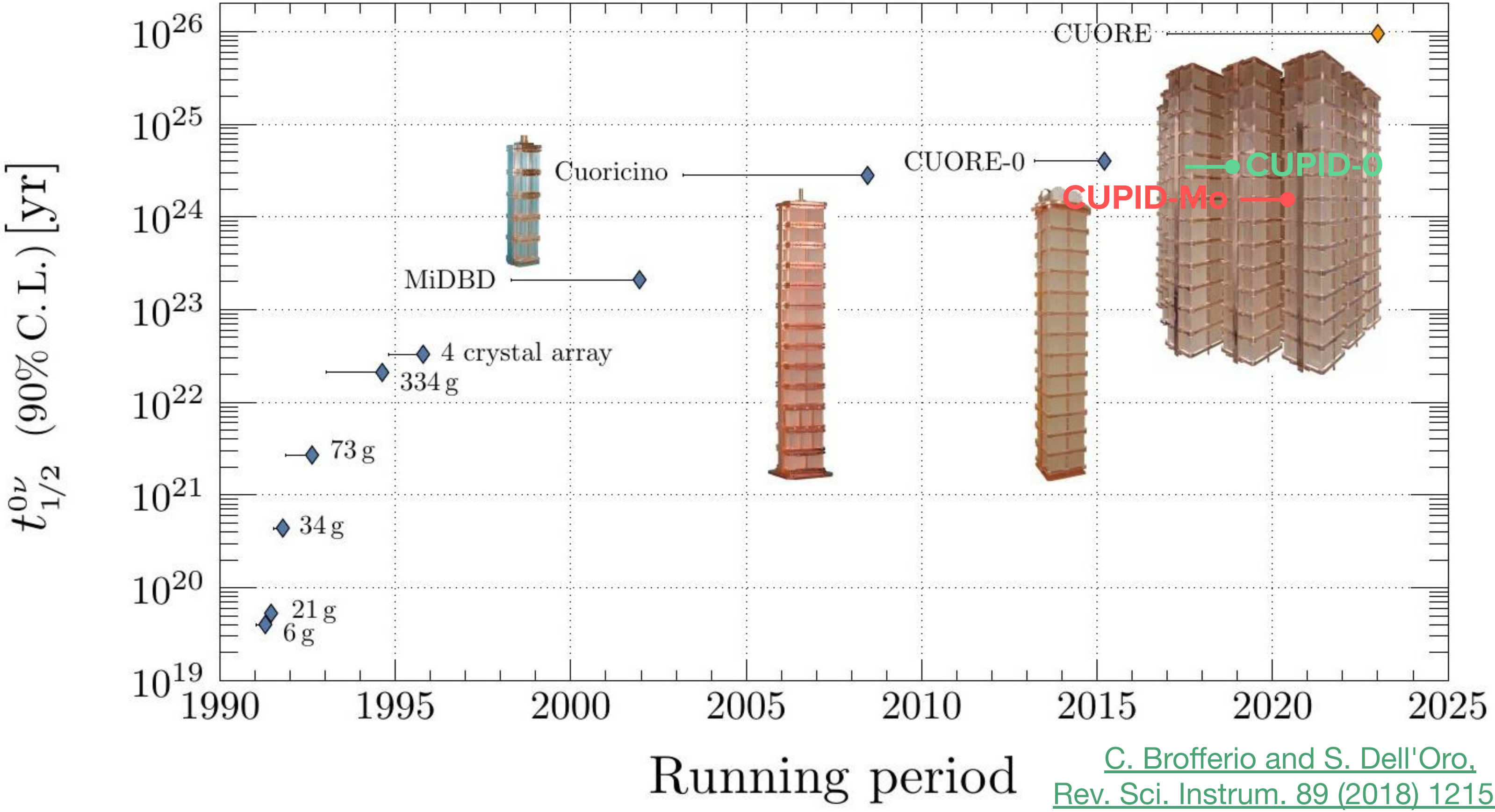




Simplified thermal model

- Crystal heat capacity: C
- Conductivity of coupling to thermal bath: G
- Signal amplitude ∝ $\Delta T = E_{dep}/C$
- Decay constant: $\tau = G/C$

History of bolometric 0νββ decay searches



C. Brofferio and S. Dell'Oro, Rev. Sci. Instrum. 89 (2018) 121502

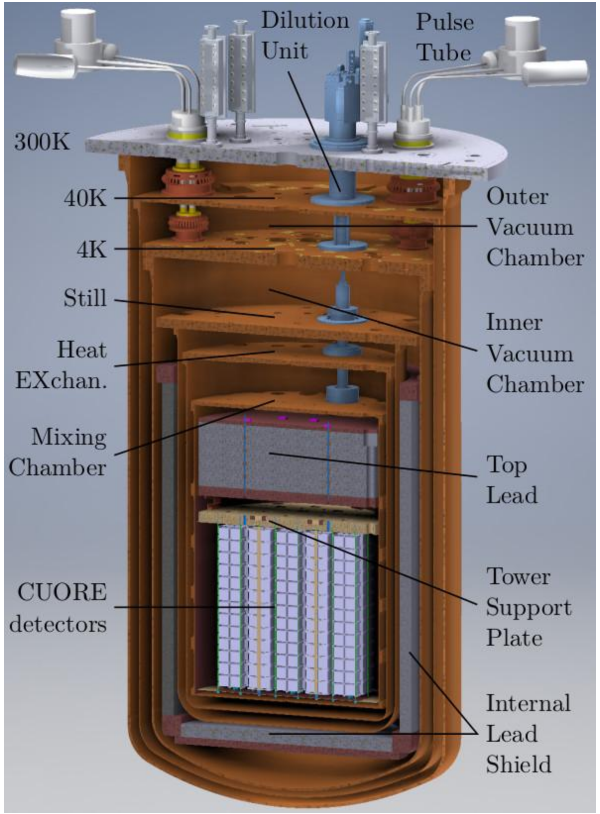
CUORE infrastructure

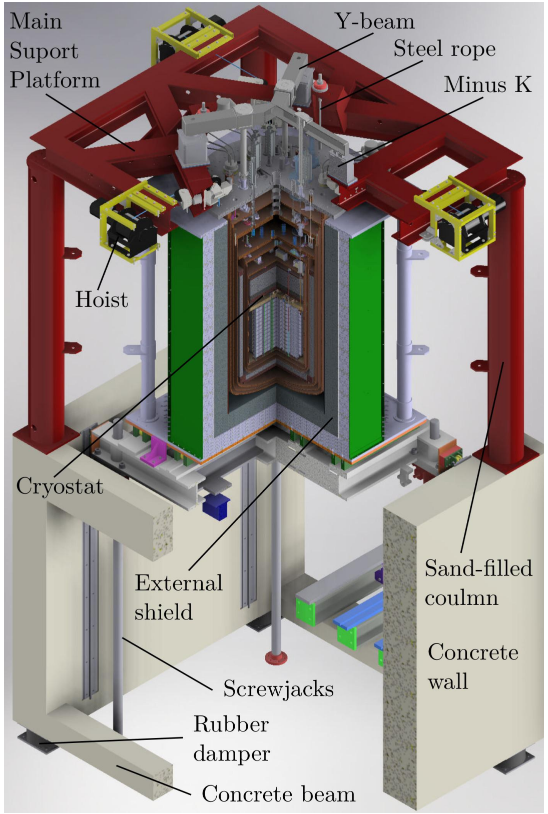
The coldest cubic meter in the known Universe

- Multistage cryogen-free cryostat: nested vessels at decreasing temperature
- Cooling systems: fast cooling system, Pulse Tubes (PTs), and Dilution Unit (DU)
- ~15 tons @ < 4 K
- ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancelling

CUORE (passive) shielding

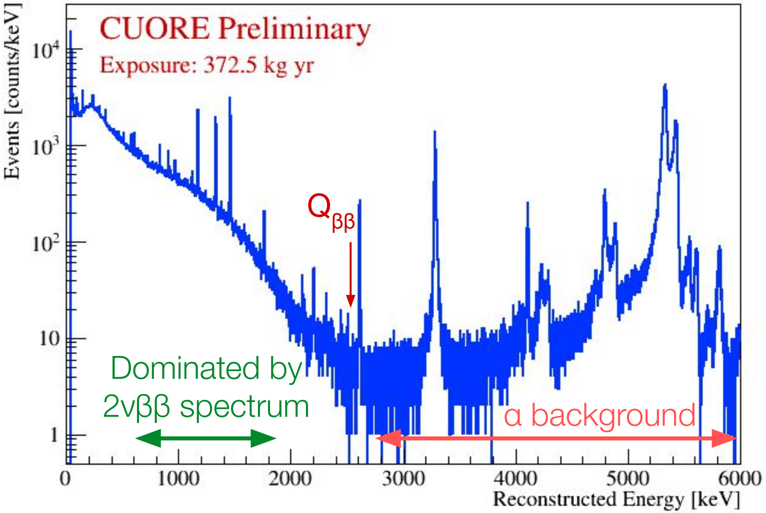
- Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels
- Polyethylene



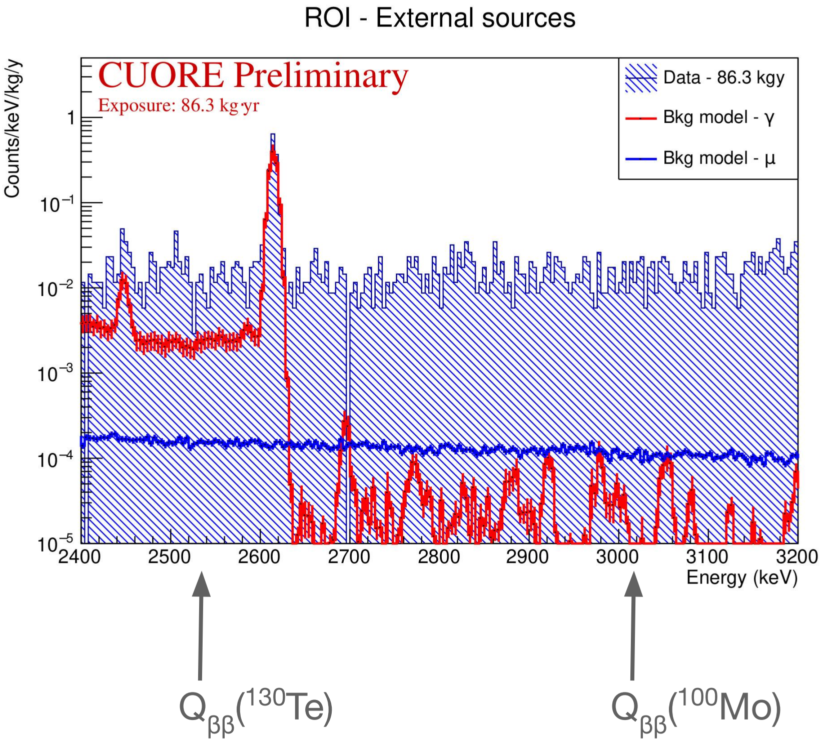


CUORE: the Cryogenic Underground Observatory for Rare Events

- 988 TeO_2 crystals with natural Te composition
→ **742 kg of total mass**, 206 kg of ^{130}Te mass
- Located in Hall A of the Gran Sasso National Lab
- Current limit: **$T^{0\nu}_{1/2}(^{130}Te) > 3.2 \cdot 10^{25}$ yr @ 90% C.I.**
- $Q_{\beta\beta}(^{130}Te) = 2527.5$ keV
→ Above most γ background, below the ^{208}Tl 2.6 MeV line
- TeO_2 crystals do not scintillate
→ no particle discrimination

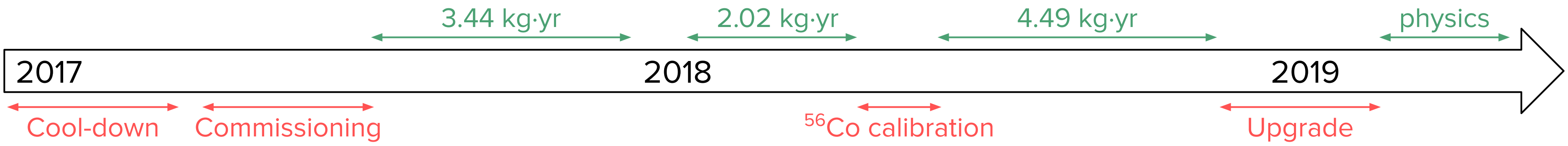


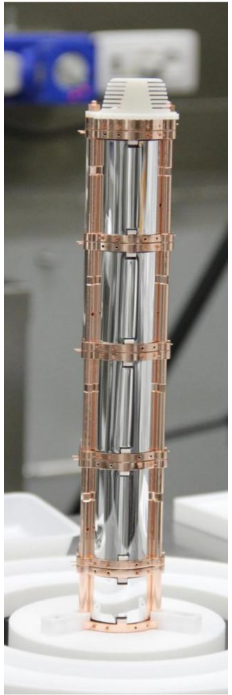
Lessons learned from CUORE



- Most measured background is due to α particles (U/Th close to TeO_2 crystals) → α/β discrimination is required
- A $Q_{\beta\beta}$ > 2.6 MeV would automatically reduce the remaining non-α background by >1 order of magnitude
- Muons are the dominant contribution after α's → active muon veto

Preparing the future: CUPID-0





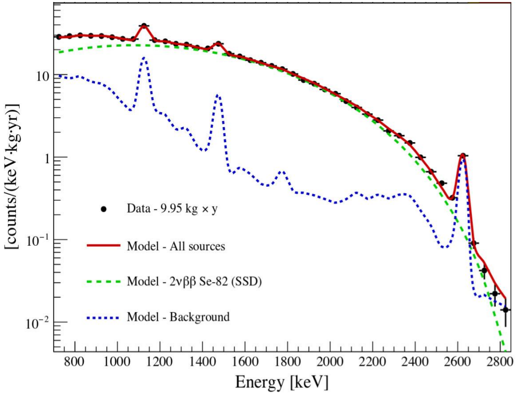
- 26 ZnSe crystals (24 enriched at 95% in ^{82}Se) @ LNGS
- Light detectors: Ge wafer + NTDs → α rejection via PID
- Crystals + LDs encapsulated in copper + reflector foil
- Total Phase-I exposure: 9.95 kg·yr
- Background at $Q_{\beta\beta}$: **$3.5 \cdot 10^{-3}$ counts/keV/kg/yr**

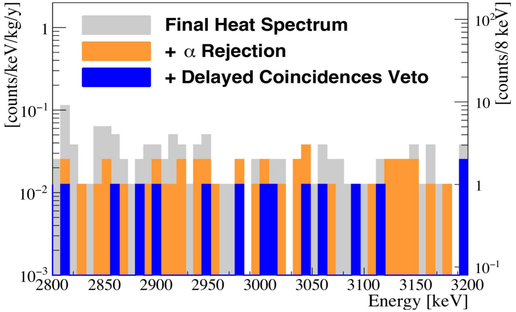
2νββ results

- **$T^{2\nu}_{1/2}(^{82}\mathrm{Se}) = [8.6 \pm 0.03(\mathrm{stat})^{+0.17}_{-0.10}(\mathrm{syst})] \cdot 10^{19}$ yr**
- Tested SSD vs HSD for ^{82}Se → HSD excluded

0νββ results

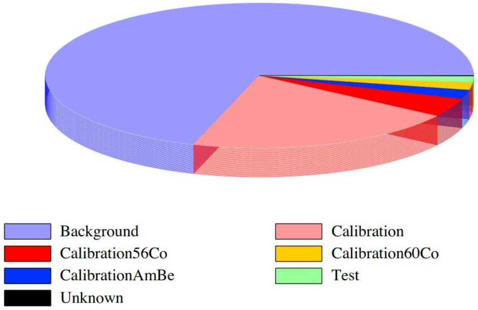
- **$T^{0\nu}_{1/2}(^{82}\mathrm{Se}) > 3.5 \cdot 10^{24}$ yr @ 90% C.I.**

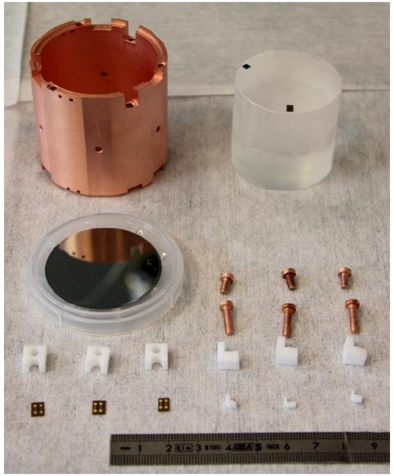


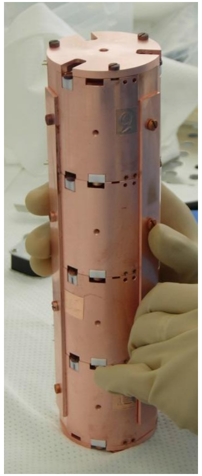


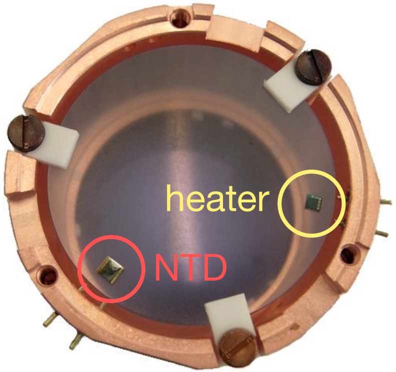
Preparing the future: CUPID-Mo

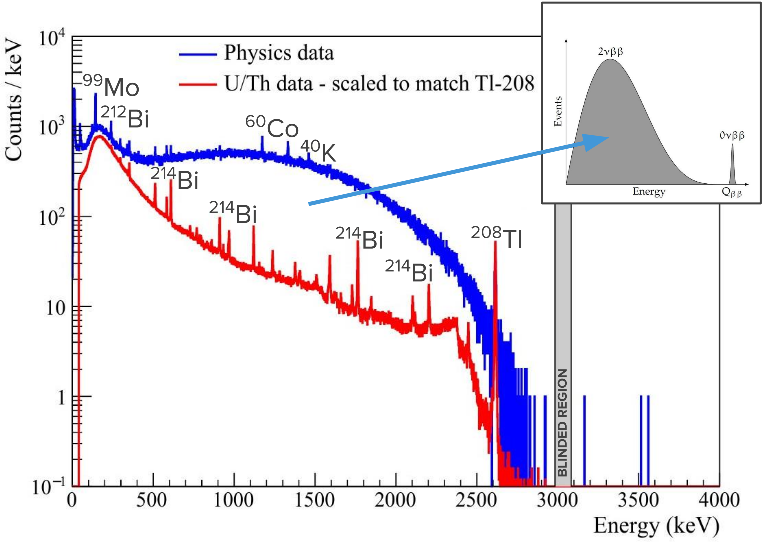
- 20 x 210g Li_2MoO_4 crystals 97% enr. in ^{100}Mo @ LSM
- Ge wafer with SiO anti-reflective coating + NTD as light detector
- Cu frames + reflector foil
- 2.16 kg·yr analyzed exposure
- Dominant 2νββ spectrum
- Most γ lines from external background sources
- Very few counts >3 MeV after PID cut











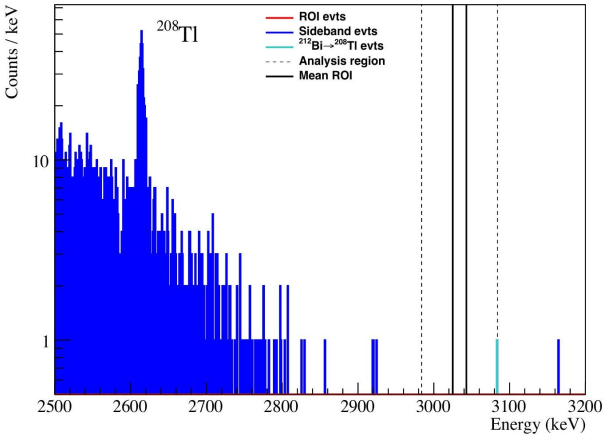
Preparing the future: Cupid-Mo

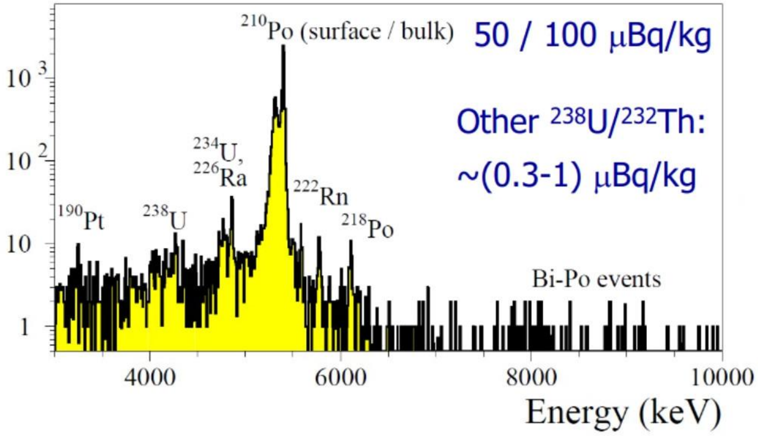
Results

CUPID-Mo, arXiv:2011.13243
(submitted to PRL)

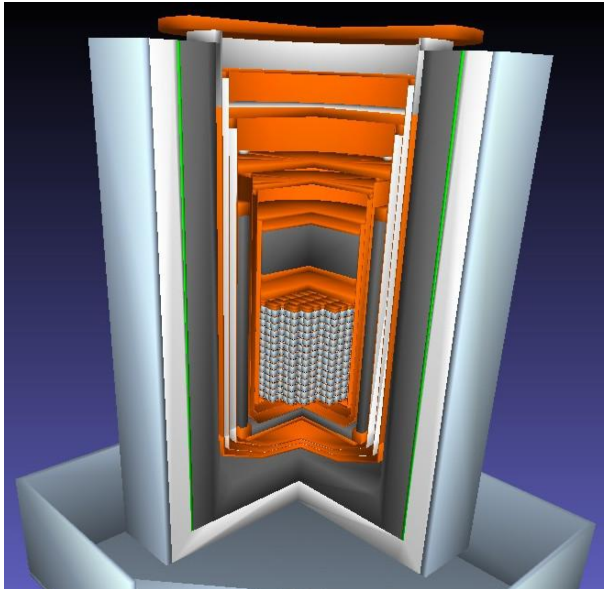
- $\mathbf{T_{1/2}^{0\nu}(^{100}Mo) > 1.5{\cdot}10^{24}}$ **yr** @ 90% C.I. → Best result so far in ^{100}Mo!
- $\mathbf{m_{\beta\beta} < 0.3\text{-}0.5}$ **eV** (depending on NME) → 4th most stringent limit with just 1.19 kg·yr of ^{100}Mo!
- BI O(10^{-3}) counts/keV/kg/yr → Precise evaluation with background model ongoing

CUPID-Mo is a real experiment, not just a demonstrator!



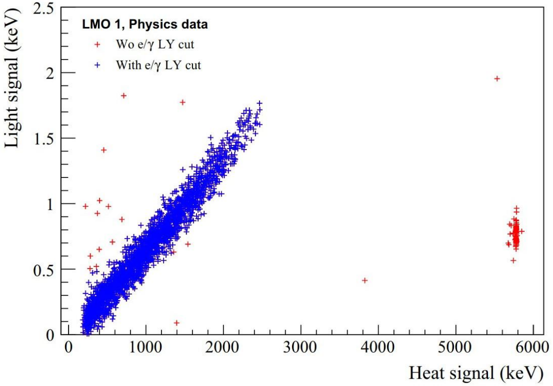


CUPID: Cuore Upgrade with Particle IDentification

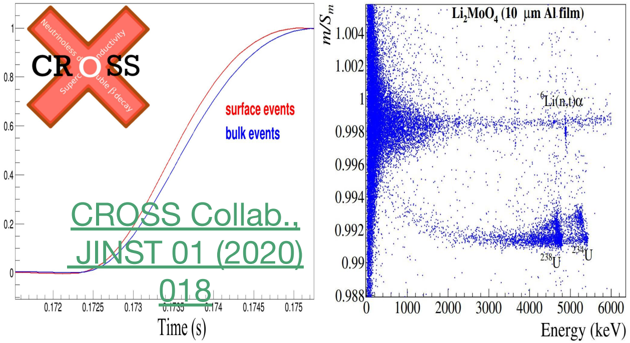


- ~250 kg of $^{enr}Li_2MoO_4$ scintillating crystals
- Goal FWHM: 5 keV at $Q_{\beta\beta}$
- α rejection via PID
- Goal background: 10^{-4} counts/keV/kg/yr
- Discovery sensitivity: $T^{0\nu}_{1/2} = 10^{27}$ yr

PID via scintillation light signal



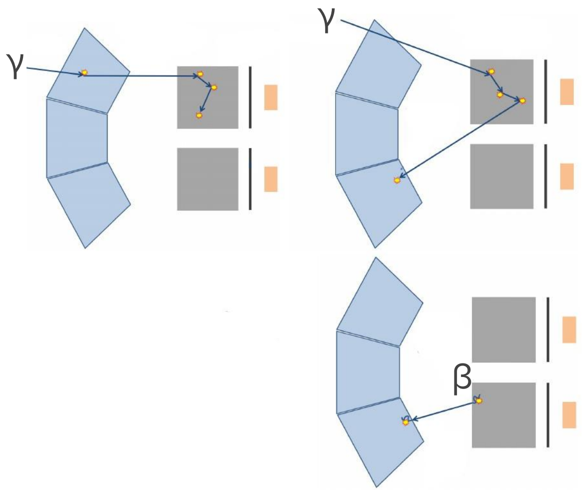
CROSS: pulse shape on heat channel



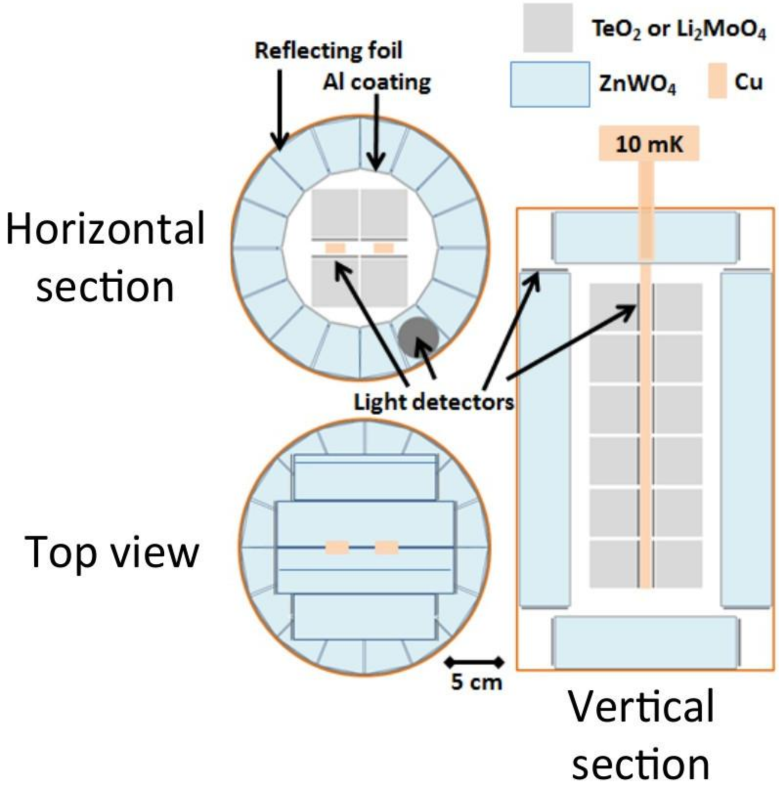
CROSS Collab., JINST 01 (2020) 018

How do we proceed beyond CUPID?

- Increase mass
  → Easy, just need to find money 😜
- Reduce background
  → Active shield, active crystal mounting
  → Faster and more sensitive LDs,
  e.g. TES or Neganov-Luke assisted LDs
- Multi-isotope approach allows confirmation of discovery with same setup



Ongoing ERC: **BINGO**

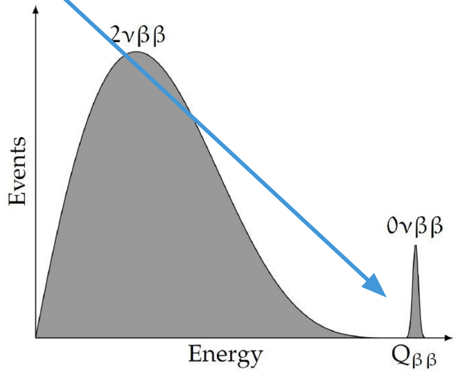


THANK YOU!

Backup: Backgrounds

- $Q_{\beta\beta}$ in the 2-3.5 MeV range for most used isotopes
- Cosmic muons
  ⟹ Operate underground
- Neutrons (muon induced, fission, …)
  ⟹ Neutron absorbers (water, PE, borated PE, …)
- Actinides (^{238}U and ^{232}Th) decay chains + Rn
  - α up to 8 MeV
  - β up to 3.3 MeV
  - γ up to 2.6 MeV

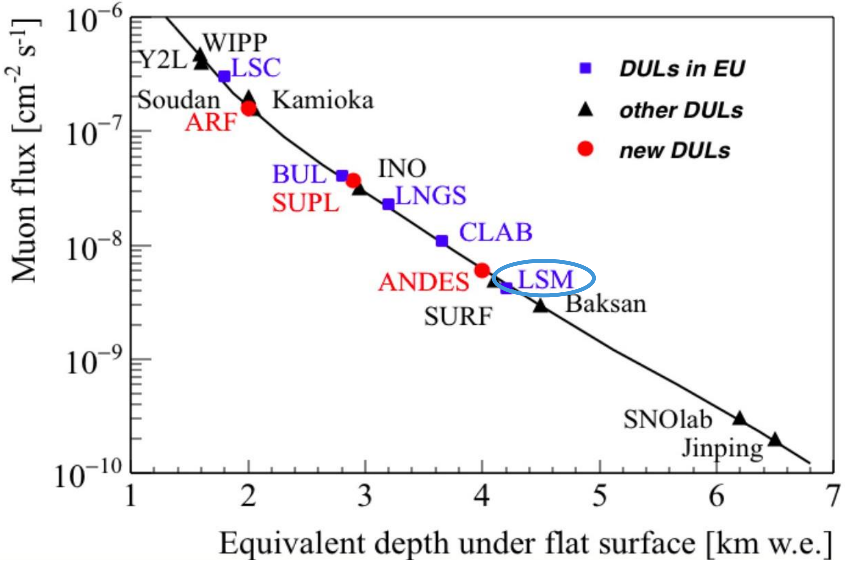
  ⟹ Material selection
  ⟹ Cleaning protocol
  ⟹ Avoid recontamination
  ⟹ Shielding and self-shielding
  ⟹ Event topology
  ⟹ Particle discrimination via pulse shape
- Irreducible 2νββ background
  - Tail of 2νββ spectrum
    ⟹ Energy resolution
  - Pile-up of 2νββ events
    ⟹ Time resolution



Backup: Backgrounds

- $Q_{\beta\beta}$ in the 2-3.5 MeV range for most used isotopes
- Cosmic muons
  ⟹ Operate underground
- Neutrons (muon induced, fission, …)
  ⟹ Neutron absorbers (water, PE, borated PE, …)
- Actinides (^{238}U and ^{232}Th) decay chains + Rn
  - α up to 8 MeV
  - β up to 3.3 MeV
  - γ up to 2.6 MeV

  ⟹ Material selection
  ⟹ Cleaning protocol
  ⟹ Avoid recontamination
  ⟹ Shielding and self-shielding
  ⟹ Event topology
  ⟹ Particle discrimination via pulse shape
- Irreducible 2νββ background
  - Tail of 2νββ spectrum
    ⟹ Energy resolution
  - Pile-up of 2νββ events
    ⟹ Time resolution

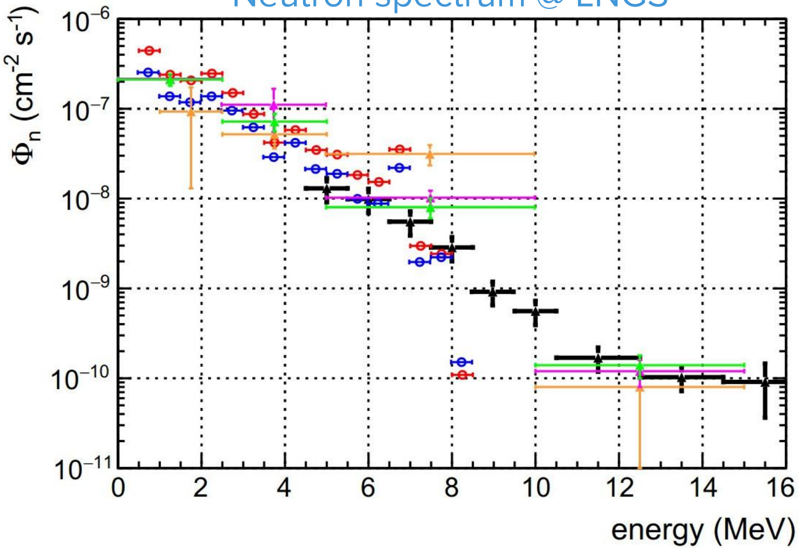


Backup: Backgrounds

- $Q_{\beta\beta}$ in the 2-3.5 MeV range for most used isotopes
- Cosmic muons
  ⟹ Operate underground
- Neutrons (muon induced, fission, …)
  ⟹ Neutron absorbers (water, PE, borated PE, …)
- Actinides (^{238}U and ^{232}Th) decay chains + Rn
  - α up to 8 MeV
  - β up to 3.3 MeV
  - γ up to 2.6 MeV

  ⟹ Material selection
  ⟹ Cleaning protocol
  ⟹ Avoid recontamination
  ⟹ Shielding and self-shielding
  ⟹ Event topology
  ⟹ Particle discrimination via pulse shape
- Irreducible 2νββ background
  - Tail of 2νββ spectrum
    ⟹ Energy resolution
  - Pile-up of 2νββ events
    ⟹ Time resolution

Neutron spectrum @ LNGS

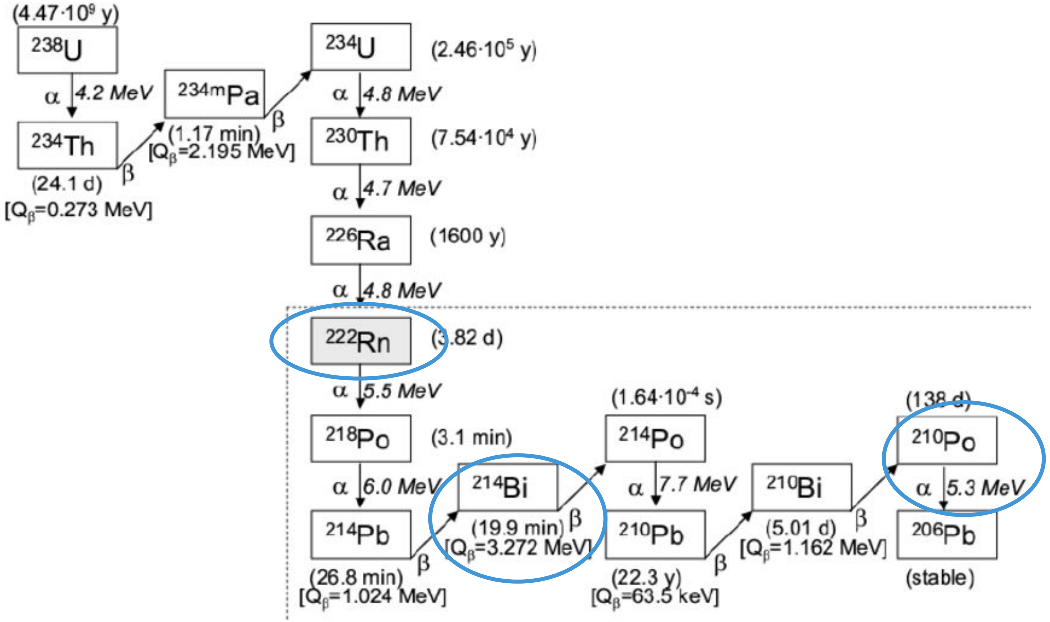


G. Bruno and B. Fulgione, EPJ C79 (2019) 747

Backup: Backgrounds

- $Q_{\beta\beta}$ in the 2-3.5 MeV range for most used isotopes
- Cosmic muons
  ⟹ Operate underground
- Neutrons (muon induced, fission, …)
  ⟹ Neutron absorbers (water, PE, borated PE, …)
- Actinides (^{238}U and ^{232}Th) decay chains + Rn
  - α up to 8 MeV
  - β up to 3.3 MeV
  - γ up to 2.6 MeV

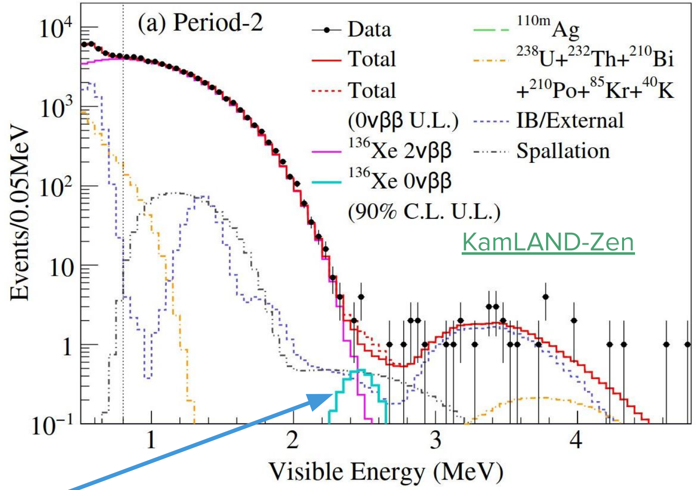
  ⟹ Material selection
  ⟹ Cleaning protocol
  ⟹ Avoid recontamination
  ⟹ Shielding and self-shielding
  ⟹ Event topology
  ⟹ Particle discrimination via pulse shape
- Irreducible 2νββ background
  - Tail of 2νββ spectrum
    ⟹ Energy resolution
  - Pile-up of 2νββ events
    ⟹ Time resolution



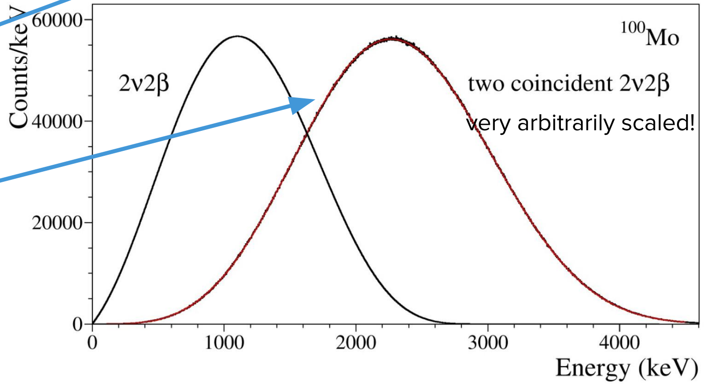
Backup: Backgrounds

- $Q_{\beta\beta}$ in the 2-3.5 MeV range for most used isotopes
- Cosmic muons
  ⟹ Operate underground
- Neutrons (muon induced, fission, …)
  ⟹ Neutron absorbers (water, PE, borated PE, …)
- Actinides (^{238}U and ^{232}Th) decay chains + Rn
  - α up to 8 MeV
  - β up to 3.3 MeV
  - γ up to 2.6 MeV

  ⟹ Material selection
  ⟹ Cleaning protocol
  ⟹ Avoid recontamination
  ⟹ Shielding and self-shielding
  ⟹ Event topology
  ⟹ Particle discrimination via pulse shape
- Irreducible 2νββ background
  - Tail of 2νββ spectrum
    ⟹ Energy resolution
  - Pile-up of 2νββ events
    ⟹ Time resolution

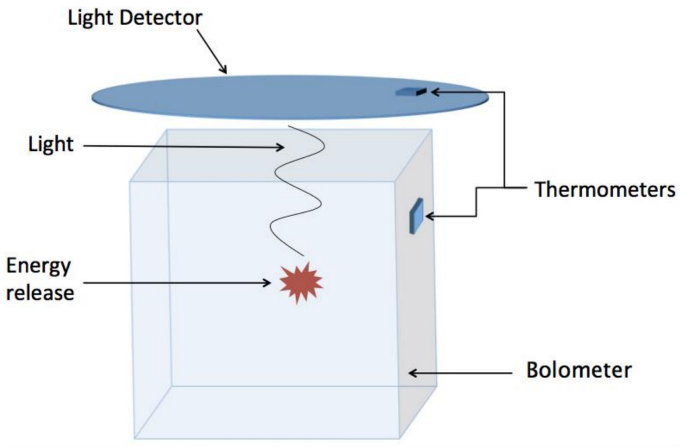


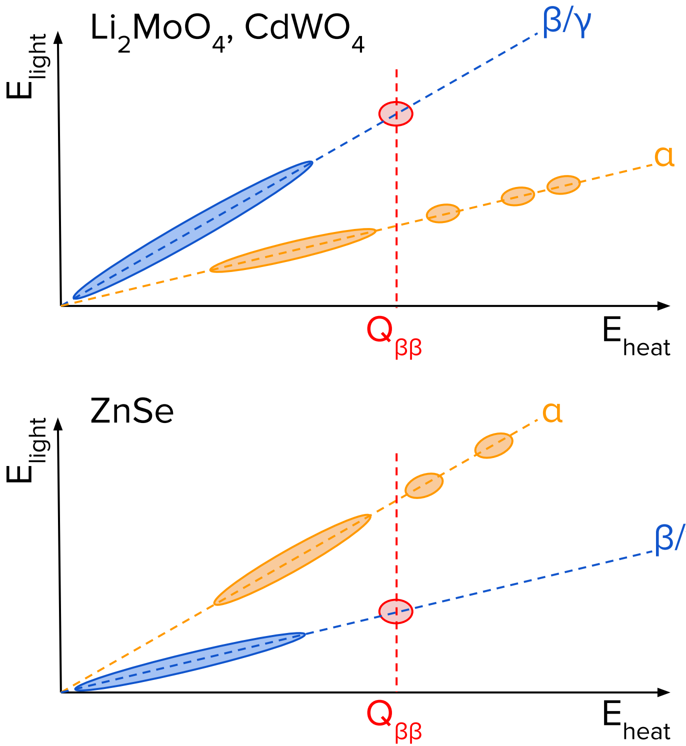
KamLAND-Zen



D. M. Cherniak et al., EPJ C72 (2012) 1989

Backup: Scintillating bolometers





- Main background: surface α events
- Couple main crystal with secondary bolometer reading the scintillation (or Cherenkov) light
- Exploit different light yield (LY) of α vs β/γ to actively suppress background
- Typical light detector: thin Ge wafer coupled to thermometer (NTD, TES, KID, MMC)

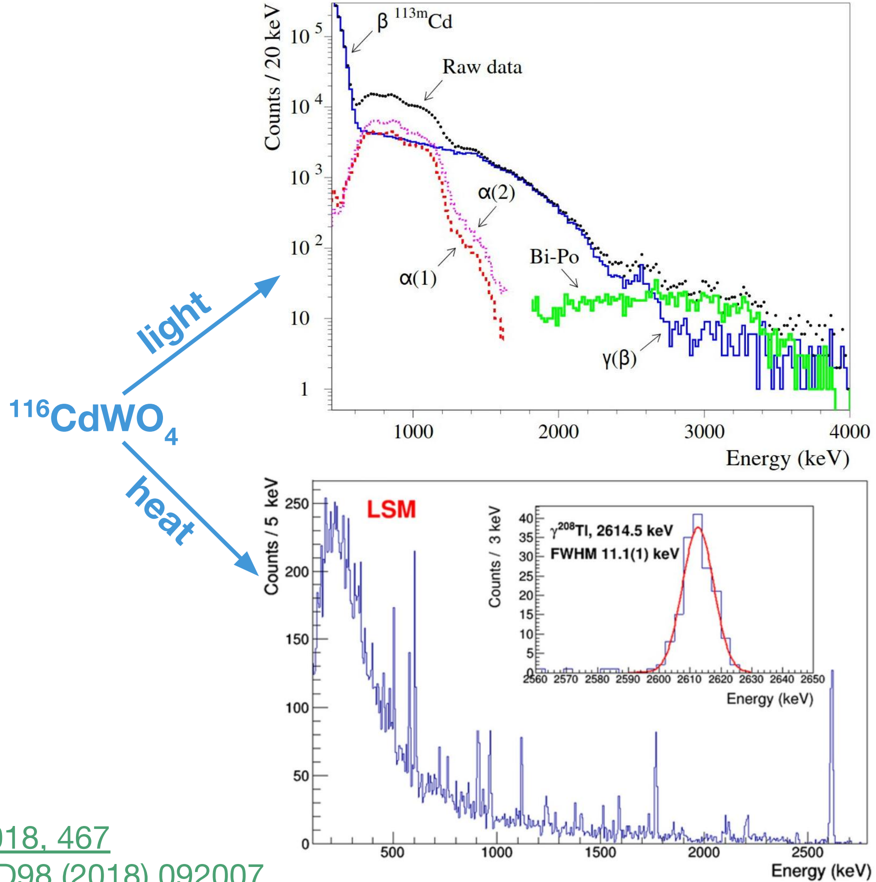
Backup: Scintillating crystals

Scintillation light features

- Typical light yield (LY): O(10) photons/keV
  → Expected energy resolution: few %
- Amount of emitted light is particle dependent
- For some crystals, time profile of scintillation light is particle dependent

Scintillating crystals for 0νββ decay

- Heat to measure energy
- Scintillation light for particle identification (PID)



D. Helis et al., LTD 2018, 467

A. S. Barabash et al, Phys.Rev. D98 (2018) 092007