Double beta decay results from the CUPID-0 experiment

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On behalf of the CUPID-0 collaboration

SEARCHING 0νββ DECAY WITH CRYOGENIC CALORIMETERS

SCIENTIFIC GOAL

Neutrinoless double beta (0νββ) decay is a **portal towards new physics**:

- Lepton number violation (ΔL=2)
- Majorana or Dirac nature
- Insights on neutrino mass

Next generation experiments aim at discovering the 0νββ decay if $m_{\beta\beta} > 10$ meV

CHALLENGES

- Increase the number of observed ββ emitters (>10^{27} nuclei)

  ➡ **$\mathcal{O}$ (10^3 kg)** detector mass & **isotopic enrichment**

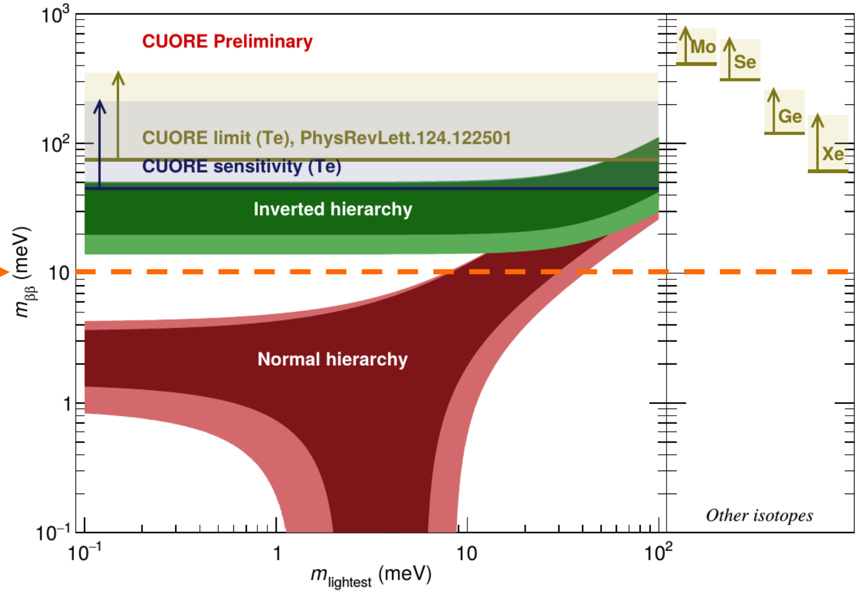
- Background close to zero at the ton × yr exposure scale

  ➡ **Background rejection through particle ID** and improved material selection

- **Energy resolution** of a few keV (FWHM) @ 0νββ Q-value

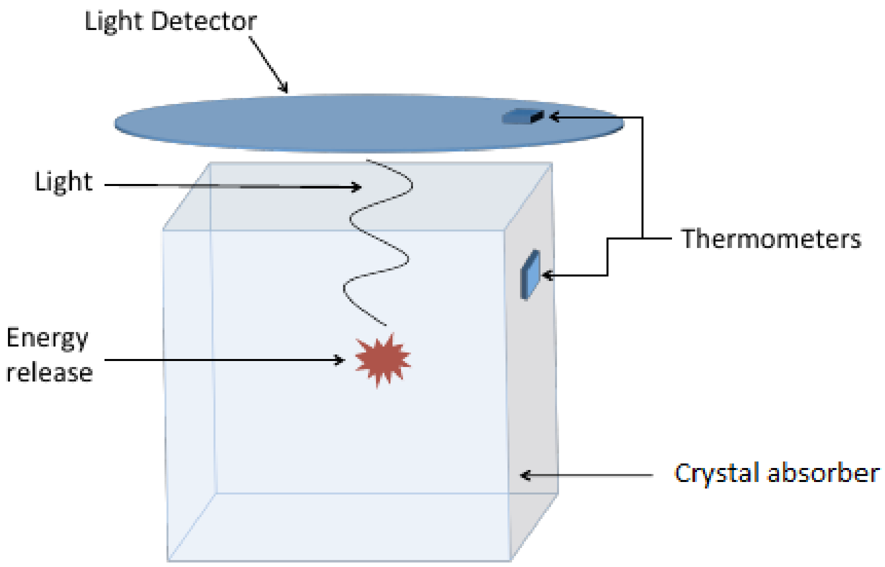
CUORE SENSITIVITY

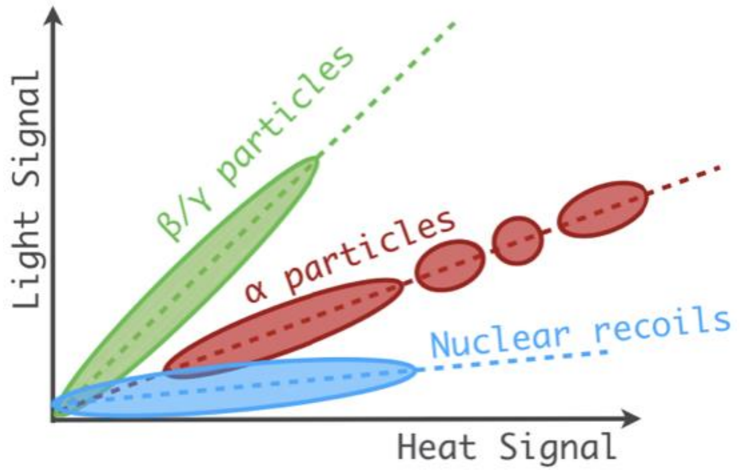
(*see Andrea Giachero's talk*)



SCINTILLATING CRYOGENIC CALORIMETERS

- Calorimeters operated at cryogenic temperature (~10 mK)
- High detection efficiency (source = detector)
- The crystal absorber is an efficient scintillator → the energy is converted into heat & light
- Heat signal → High resolution spectroscopy $\mathcal{O}$(1/1000)
- Light signal → Particle IDentification





CUPID: CUORE UPGRADE WITH PARTICLE IDENTIFICATION

CUPID is a proposed 0νββ next generation experiment (arXiv:1907.09376)

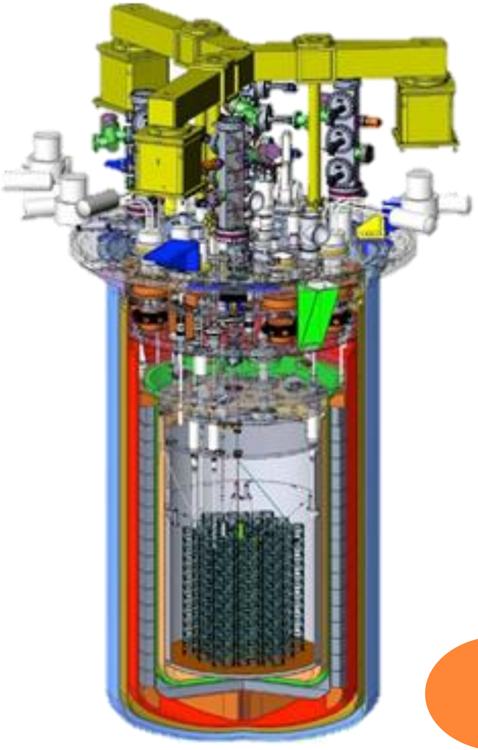
- Array of 1500 $Li_2{}^{100}MoO_4$ **scintillating calorimeters**
- **Enriched to >95%** in ^{100}Mo (250 kg of ^{100}Mo)
- ^{100}Mo Q-value: 3034 keV → β/γ background significantly reduced
- α background rejections thanks to particle ID capability
- An external muon veto will be added

Background <10^{-4} counts/(keV kg yr)

→ 100× reduction with respect to CUORE

CUPID will profit from the CUORE experience in operating a **ton-scale cryogenic experiment** and will be hosted in the same CUORE infrastructure

- **Deep underground** location at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, 1400 m of rock (~3600 m.w.e.)

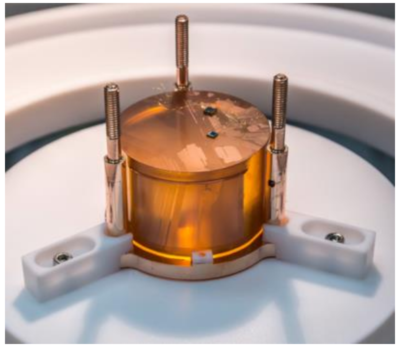


FROM CUORE TO CUPID: CUPID-0

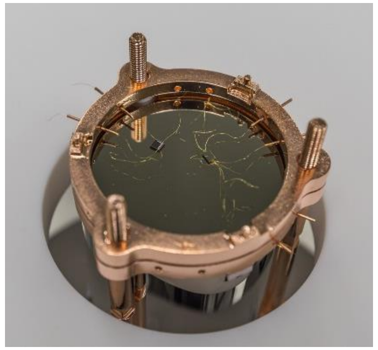
CUPID-0 is the first demonstrator of the new technologies that will be implemented in CUPID and it is also a competitive 0νββ decay search in its own right.

- Array of ZnSe **scintillating calorimeters** for the investigation of ^{82}Se 0νββ decay ($Q_{\beta\beta}$ = 2997.9 ± 0.3 keV).
- 24 ZnSe crystals **enriched to 95%** in ^{82}Se + 2 with natural Se
- Total Mass: 10.5 kg (ZnSe) → 5.17 kg (^{82}Se)
- Ge wafer cryogenic light detectors for **particle ID**
- Reflecting foils to enhance light collection

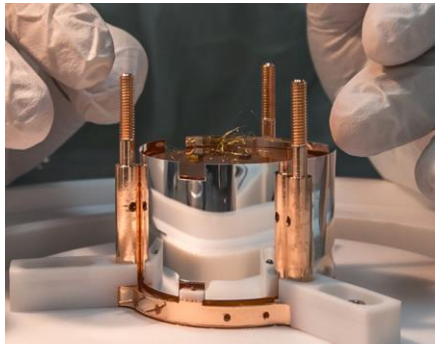
ZnSe crystal



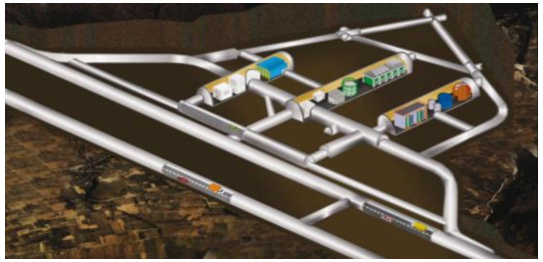
Ge light detector



Reflecting foil



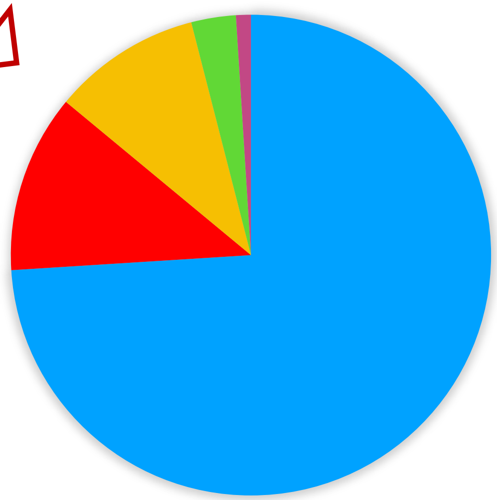
Installed @LNGS in the cryostat previously used for Cuoricino and CUORE-0 experiments



https://cupid-0.lngs.infn.it/

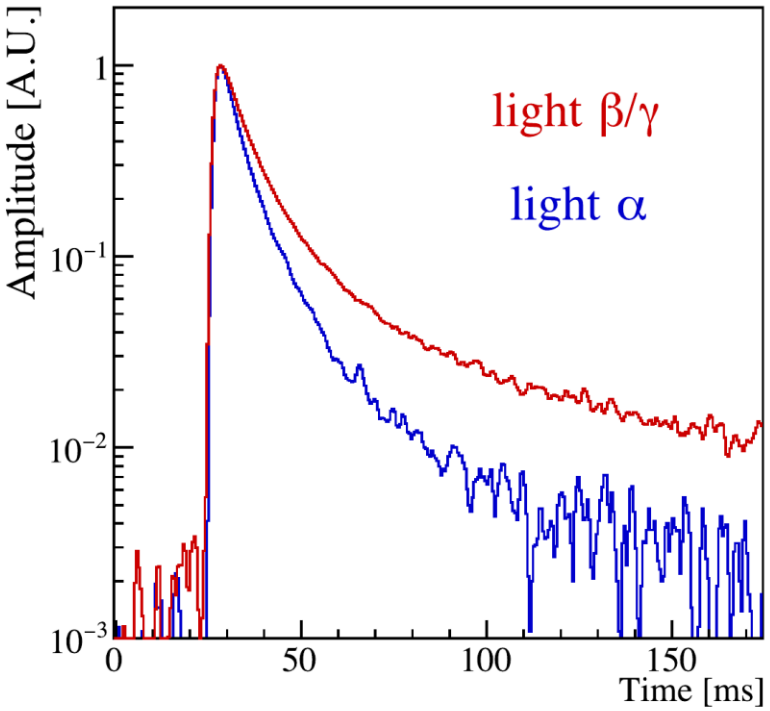
CUPID-0 TIMELINE AND DATA TAKING

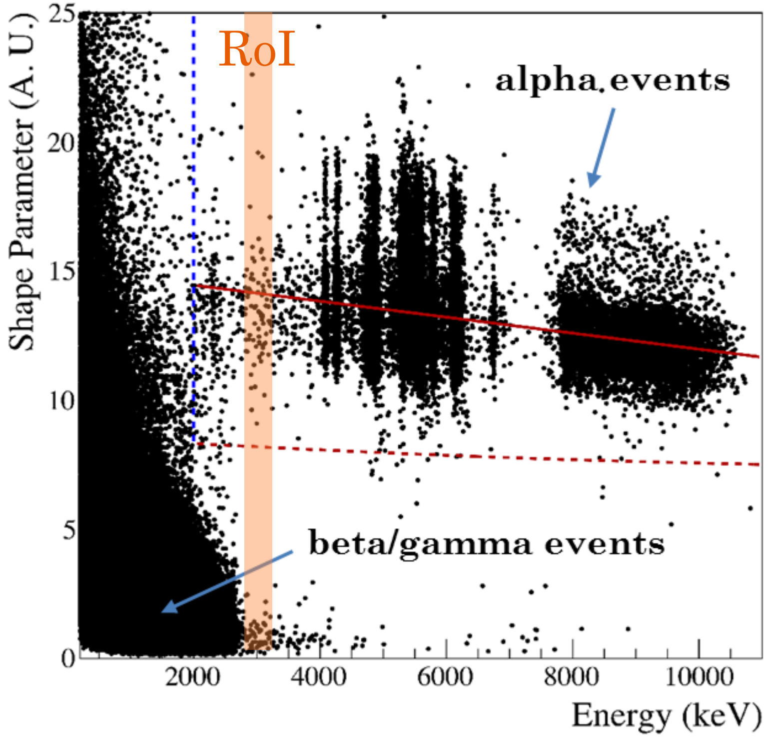
- Data taking started on March 17th, 2017
- Phase I data (presented here) collected between June 2017 and December 2018
- At the end of 2018 detector warm-up and upgrade
- June 2019: Start Phase-II



Particle Identification in CUPID-0

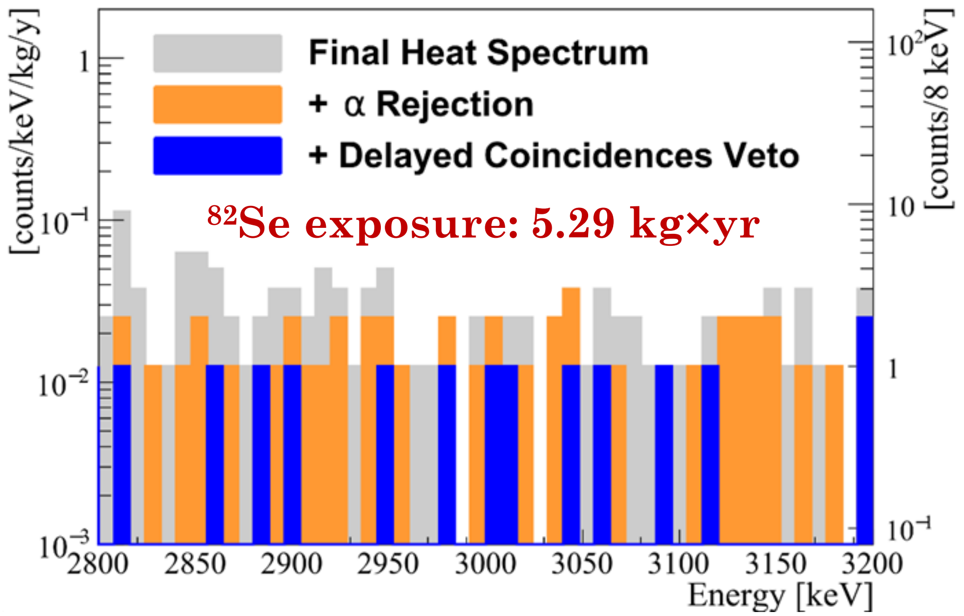
- α and β/γ particle energy deposits feature a different **shape of the light signal**
- A shape parameter (SP) is defined to discriminate α and β/γ events
- > 99.9% of α events (with E > 2 MeV) are separated from β/γ ones





$0\nu\beta\beta$ DECAY SEARCH: RESULTS

Phys. Rev. Lett. **123**, 032501 (2019)



- **Final heat spectrum** (particle only events + anticoincidence cut)

  ⇒ **3.2 × 10^{-2} counts/(keV kg yr)**
- **α rejection** through particle ID

  ⇒ **1.3 × 10^{-2} counts/(keV kg yr)**
- **Delayed-coincidences** to reject ^{208}Tl β/γ events

  ⇒ **3.5 × 10^{-3} counts/(keV kg yr)**

Background index in the range [2.8 – 3.2] MeV:

$$\mathbf{(3.5^{+1.0}_{-0.9}) \cdot 10^{-3}\ cnts/(keV{\cdot}kg{\cdot}yr)}$$

Lowest background achieved with cryogenic calorimeters.

No evidence of $0\nu\beta\beta$ signal

↓

Best half-life limit on ^{82}Se $0\nu\beta\beta$

$$\boldsymbol{T^{0\nu}_{1/2} > 3.5 \cdot 10^{24}\ \text{yr (90\% C.I.)}}$$

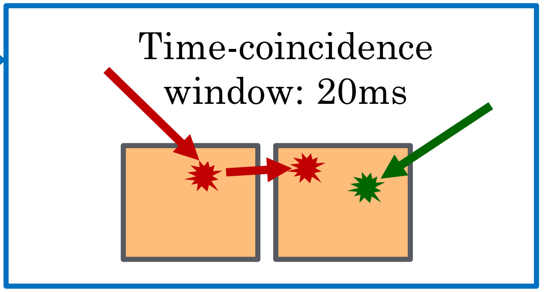
↓

$$\boldsymbol{m_{\beta\beta} < 311 - 638\ meV}$$

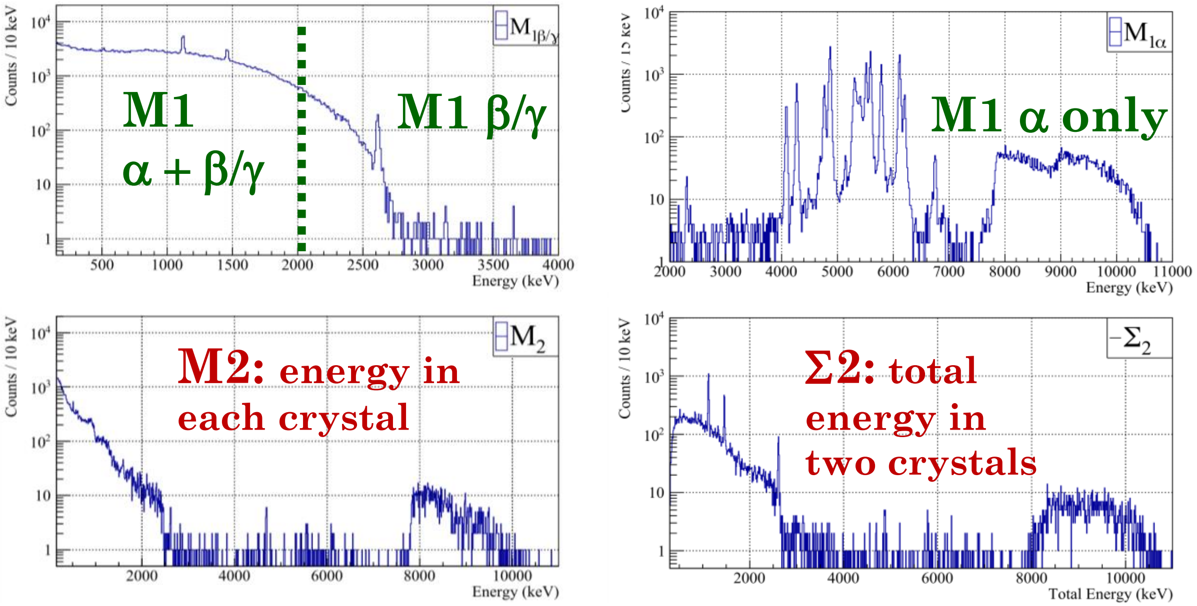
range due to the nuclear matrix element calculations

Background model

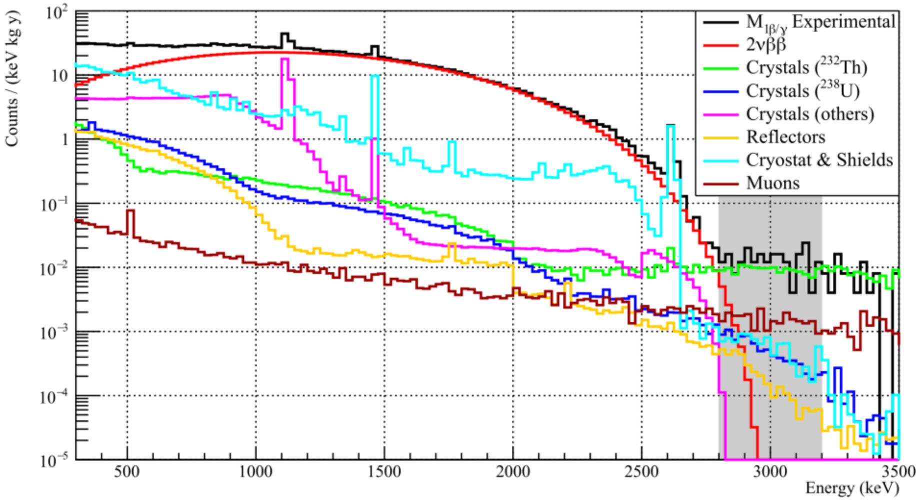
[Eur. Phys. J. C 79, 583 (2019)]



- Experimental data divided according to **multiplicity (M)** and **particle type**



Bayesian fit to the experimental data with a linear combination of **MC simulated spectra** of background sources



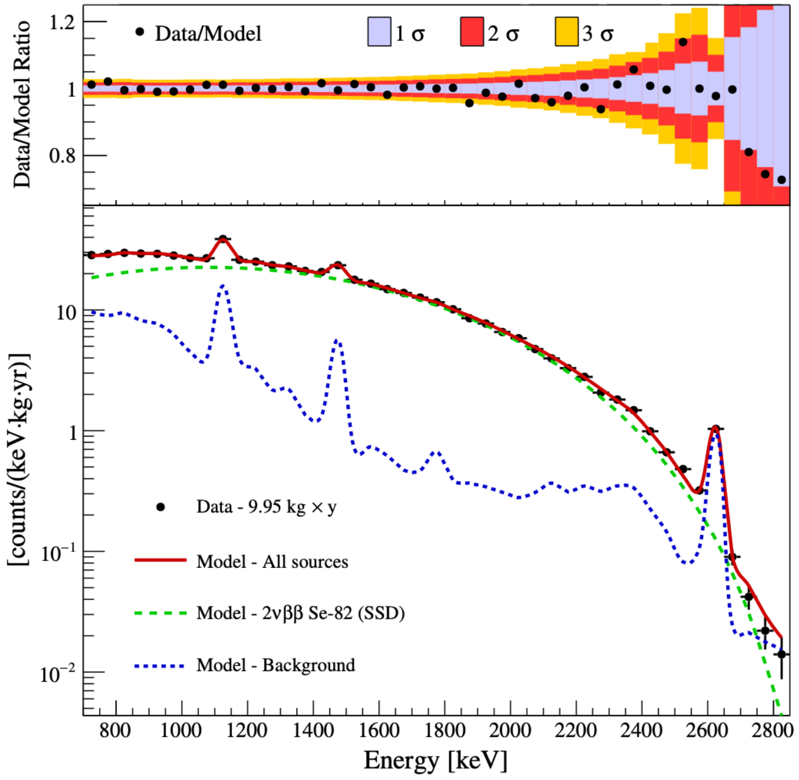
- Comprehension of background in 0νββ RoI
- Measurement of 2νββ decay (see next slides)
- Limit on CPT violation in the ββ decay of ^{82}Se
  → [Phys. Rev. D 100, 092002 (2019)]

MEASUREMENT OF ^{82}SE 2νββ DECAY HALF LIFE

- We obtain the most precise measurement of ^{82}Se 2νββ decay half life:

$$T^{2\nu}_{1/2} = [8.60 \pm 0.03(\text{stat})\,^{+0.19}_{-0.13}(\text{syst})] \times 10^{19} \text{ yr.}$$

Phys. Rev. Lett. 123, 262501 (2019)



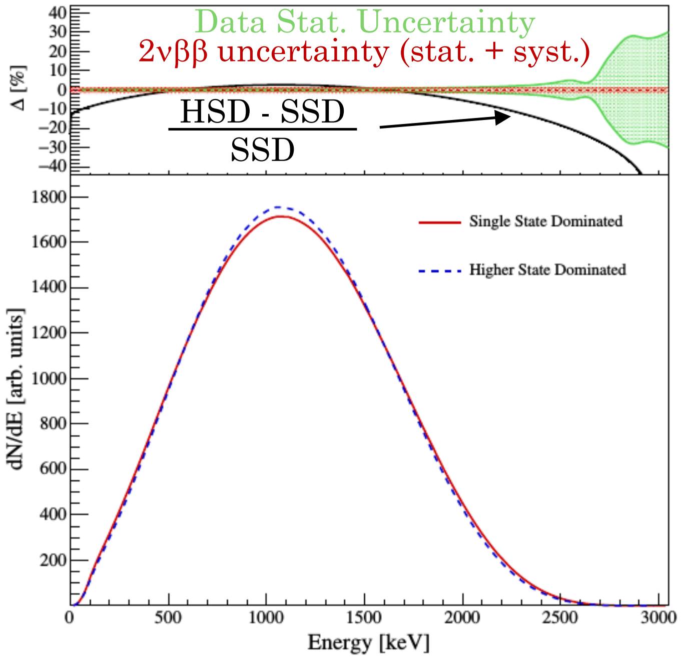
	Systematic Source	$\Delta A_{2\nu}$
Fit	Source localization	$^{+0.36}_{-0.21}\%$
	Reduced sources list	−0.10%
	^{90}Sr/^{90}Y	−1.57%
	Fixed step binning	+0.16%
	Threshold of $\mathcal{M}_{1\beta/\gamma}$	+0.15%
	α identification	−0.01%
	Energy scale	−0.39%
	Prior distributions	+0.04%
	Combined	$^{+0.4}_{-1.6}\%$
	Detector efficiency	±0.5%
	^{82}Se atoms	±1.0%
Model	$2\nu\beta\beta$	±1.0%
Total		$^{+1.6}_{-2.2}\%$

Evidence of Single–State Dominance

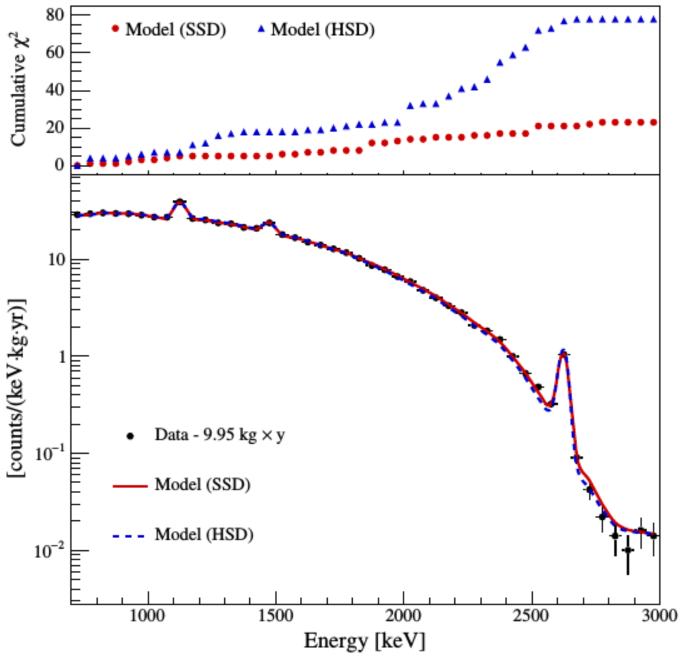
[Phys. Rev. Lett. 123, 262501 (2019)](#)

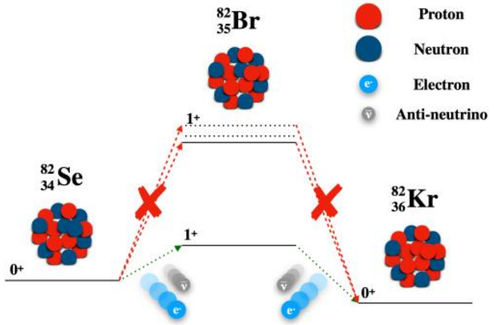
- A precise measurement of the 2νββ spectral shape provides a useful benchmark for nuclear model calculations
- 2νββ is modeled as a sequence of two virtual β decays going through one (**SSD**) or more (**HSD**) states of the (A,Z+1) intermediate nucleus

SSD → single-state dominated
HSD → higher-state dominated



Spectra from [nucleartheory.yale.edu](#) and Jenni Kotila



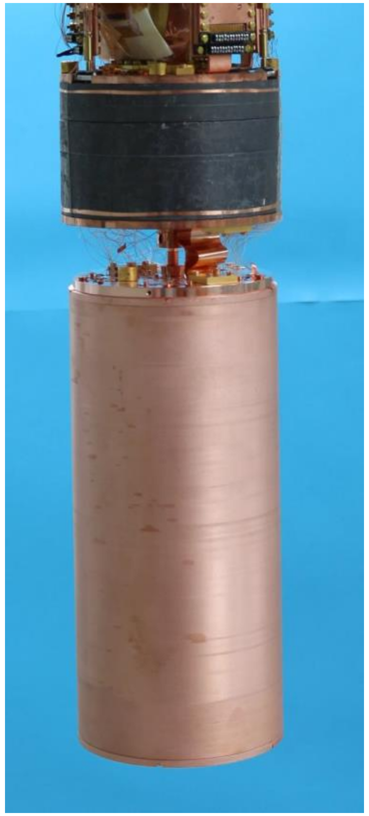


Spectrum	Counts [2 – 3] MeV	t(σ)
Experimental	14830 ± 122	
Model (SSD)	14972 ± 57	1.1
Model (HSD)	14095 ± 56	5.5

We have a strong evidence that the 2νββ decay of ^{82}Se is **Single–State Dominated (SSD)**

CUPID-0 PHASE II

- Muons are main residual background → Installation of μ-veto
- No reflective foil → Measurement of M2 α events from crystal surfaces
- New cleaner Cu shield → Thermalization and additional shielding



Summary and future perspectives

- CUPID-0 is the first ββ-decay experiment based on **scintillating** cryogenic detectors (**highly enriched**)
- It features an **excellent alpha-rejection**, and the **lowest background** among cryogenic calorimeters

- Acquired data allowed to establish the **best half-life limit** on **^{82}Se 0νββ** decay:

$$T_{1/2}^{0\nu} > 3.5 \cdot 10^{24}\ yr\ (90\%\ \text{C.I.})$$

and the **most precise measurement of ^{82}Se 2νββ** decay half-life:

$$T_{1/2}^{2\nu} = [8.60 \pm 0.03(\text{stat})\ ^{+0.19}_{-0.13}(\text{syst})] \times 10^{19}\ \text{yr}.$$

- CUPID-0 Phase II → better understanding of background sources (data release within 2020)

CUORE, CUPID-0, and CUPID-Mo provide the most stringent limits on 0νββ, and the most precise measurements of 2νββ **on three different isotopes**.

Solid foundations for the CUPID experiment!