Experimental sensitivities to 0νββ decay

(plus a list of experimental approaches not covered by the talks after mine)

Giovanni Benato

Int 26-2a Workshop

Seattle, July 21-24, 2026

Detector technologies

Readout channel	Energy resolution	Particle identification	Event topology	Applicable to multiple isotopes
Ionization	0.1–1%	In gas or pixelated detectors	Yes	Not really
Phonons	~0.2%	Nope	Maybe in the future	Yes
Scintillation	Few %	α vs β/γ	In liquid and gases	Yes
Cherenkov	Forget about it	Visible only for β's	Maybe	Yes

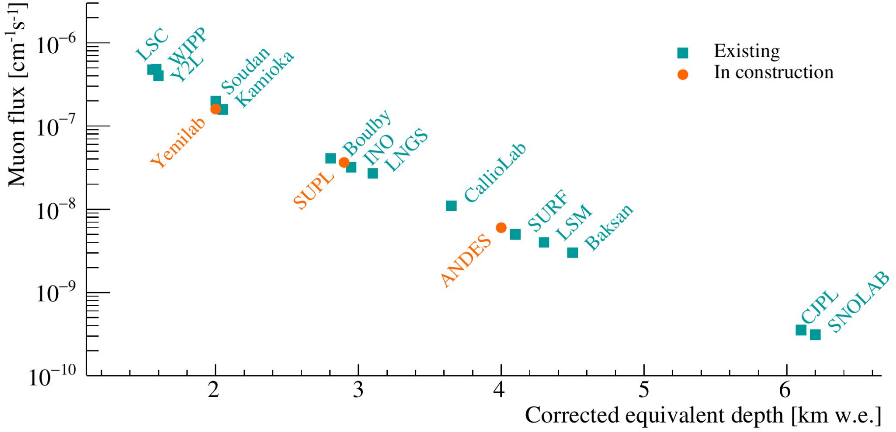
Detector technologies

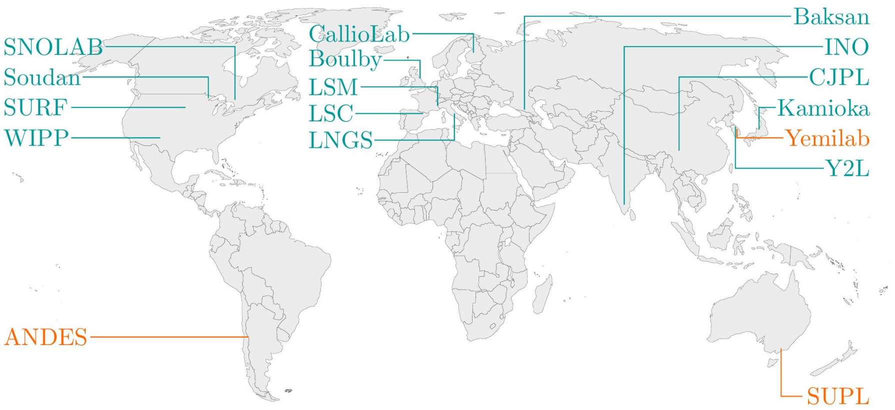
Detector type	Description	Typical isotope mass	Containment efficiency	Pros and cons
Solid state granular	Crystal containing ββ isotope	O(0.1–1) kg (single crystal)	70–95%	+ Scalable + High resolution - Many crystals required
Monolithic liquid or gaseous	Material=isotope or isotope dissolved in liquid	O(100–1000) kg	100%	+ Single detector + Self shielding - Poor resolution
Composite	Foil with isotope + tracker	O(10) kg	~50%	+ Ultra-low background + Multiple isotopes - Very hard to scale

Backgrounds

- Short list of background significant for all $0\nu\beta\beta$ decay experiments
  - Cosmic muons and related secondaries
  - Natural radioactivity (actinides decay chains)
  - Anthropogenic radioactivity
  - Neutrons
- Additional background significant for specific experiments
  - Pile-up of $2\nu\beta\beta$ decay events for detectors with slow response

Backgrounds: cosmic-ray induced

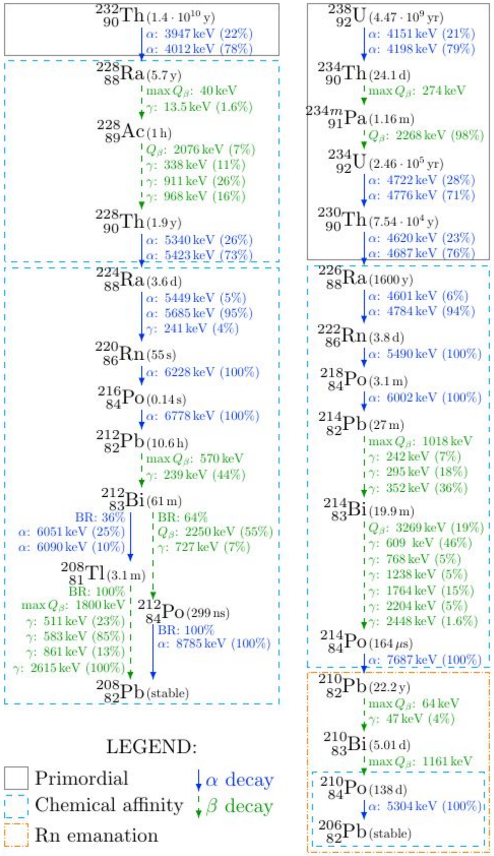




- Factor 10 suppression on muon flux every ~1.5 km of water equivalent
- Muon energies up to TeV scale
  →Muon veto through Cerenkov on water tank or plastic scintillator panes
- Spallation processes inducing activation of radioactive nuclei
  →Store all materials underground
  →Assemble detectors underground
  →In-situ activation relevant for large scintillation experiments

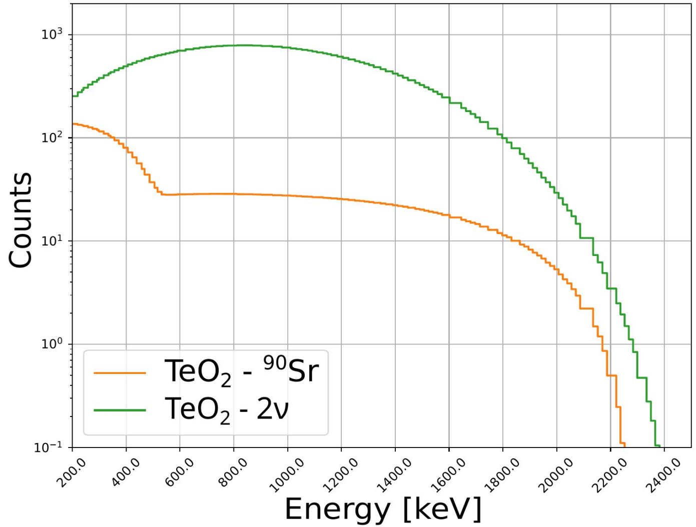
Backgrounds: actinide decay chains

- ^{238}U and ^{232}Th ubiquitous in all materials
  - α from 4 to 9 MeV
  - β up to 3.3 MeV (but most are below 2 MeV)
  - γ up to 2.6 MeV
  - Various summations possible
- Passive suppression
  - Select the most radiopure materials (ICP-MS, Ge screening, α detector screening, neutron activation analysis)
  - Clean all surfaces and avoid any recontamination!
- Active suppression
  - Particle discrimination to suppress α's
  - For granular detectors, multiplicity analysis to suppress coincident γ's, Compton + full absorption, and pair production
  - Event topology inside single detector (crystal)



Backgrounds: anthropogenic radioactivity

Isotope	Half-life	Q_β [keV]	Detected	Notes
^{88}Y	107 d	3008	No	Several γ lines
^{90}Sr	28.8 y	546	No	
^{90}Y	64 h	2279	No	Pure β emitter
^{110m}Ag	250 d	3008	Yes	Several γ lines
^{134}Cs	2 y	2059	No	Several γ lines
^{144}Ce	285 d	319	No	
^{144}Pr	17.3 m	2997	No	Pure β emitter



- Radioactive isotopes resulting from nuclear accidents or nuclear weapon tests
- Most worrisome isotopes are β emitters with (relatively) long half-life values and large Q_β
- Actual relevance depends on the history of employed detector materials and detector technology
- Can be problematic for precision measurements of 2νββ spectra!

Backgrounds: neutrons

Radioactivity-induced neutrons

- Possible production mechanisms:
  - Spontaneous ^{235}U fission in rock or concrete
  - (α,n) reaction induced by ^{238}U and ^{232}Th chains in rock/concrete
- Energies up to ~10 MeV
- Suppression techniques:
  - 20-30 cm of polyethylene + boron-rich passive shield
  - >1 m of water
  - Embed nuclei with high neutron-capture cross section in detector (e.g. ^{6}Li)

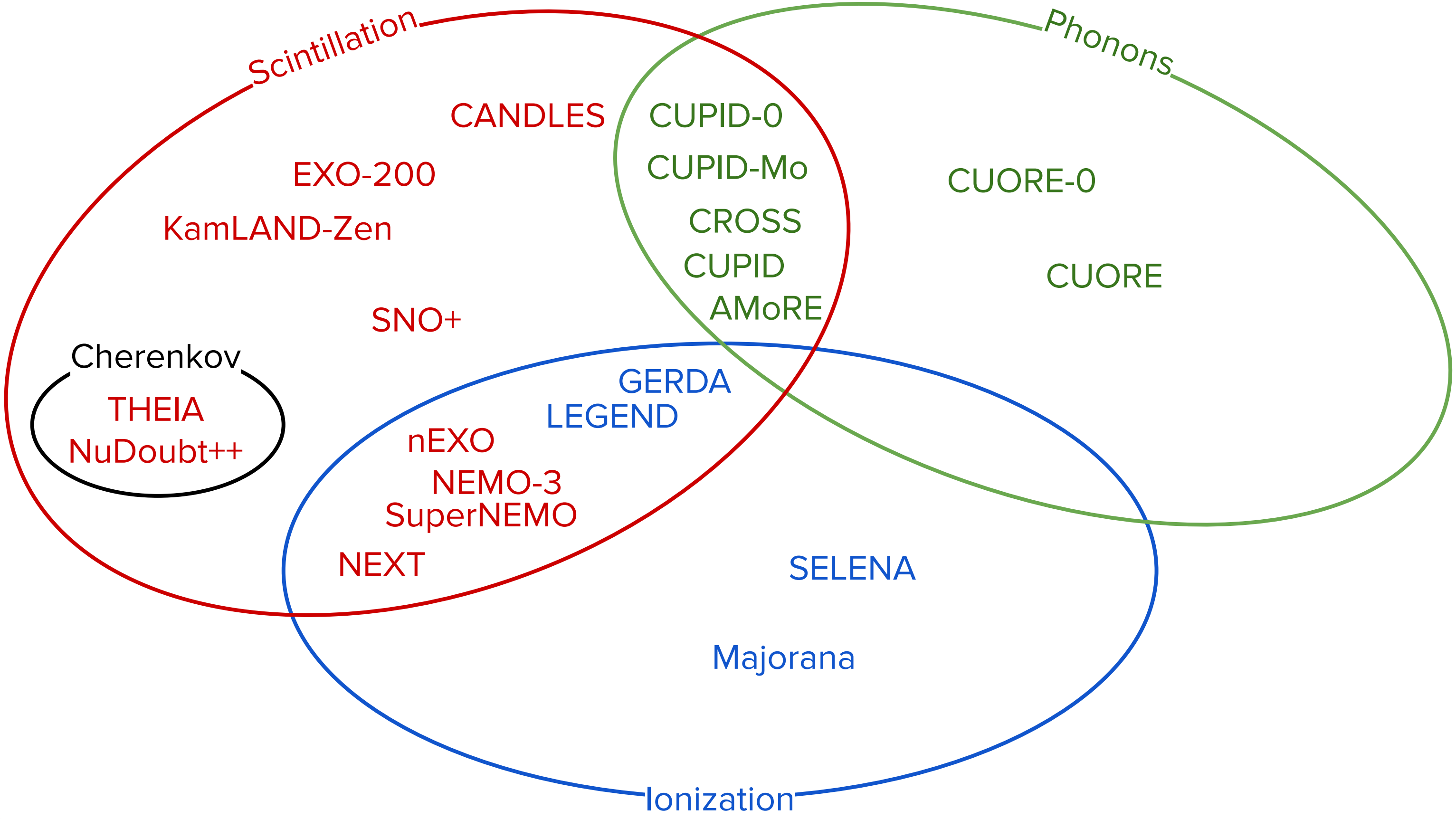
Spallation-induced neutrons

- Energies up to several GeV
- Much lower flux
- Can yield (n,γ) reactions in active or passive detector materials
- Subdominant so far

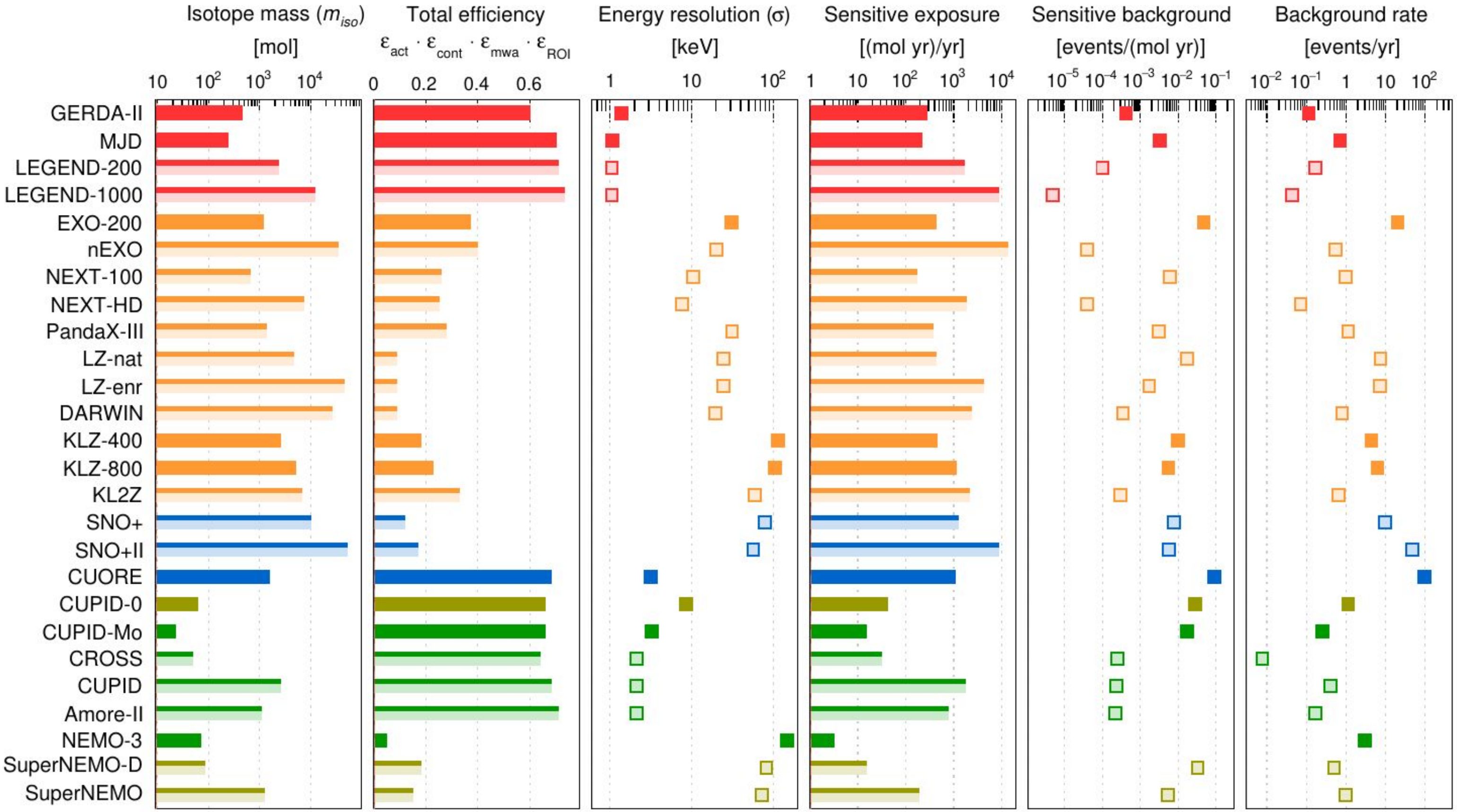
Efficiencies

- **Containment**: what fraction of ββ decay events is fully contained in the detector?
  - Ranges from ~75% to 100%, depending on detector size and material
  - Uncertainty evaluated with MC simulations
- **Active volume**: what fraction of ββ decay events releases energy in the detector active volume?
  - Ranges from 90% to 100% depending on detector technology
  - Uncertainty strongly depends on detector technology and prior characterization
- **Isotopic abundance**: what number of ββ isotopes are present in the detector?
  - Uncertainty usually at per-mile level
- **Trigger + event reconstruction**: what fraction of signal events are properly reconstructed?
  - Close to 100% at $Q_{\beta\beta}$, possible large uncertainty near threshold (for precision spectral analyses)
- **Event selection**: what fraction of events is identified as signal?
  - Includes anti-coincidence, pulse-shape discrimination, event topology, …
  - Usually, uncertainties at the percent level

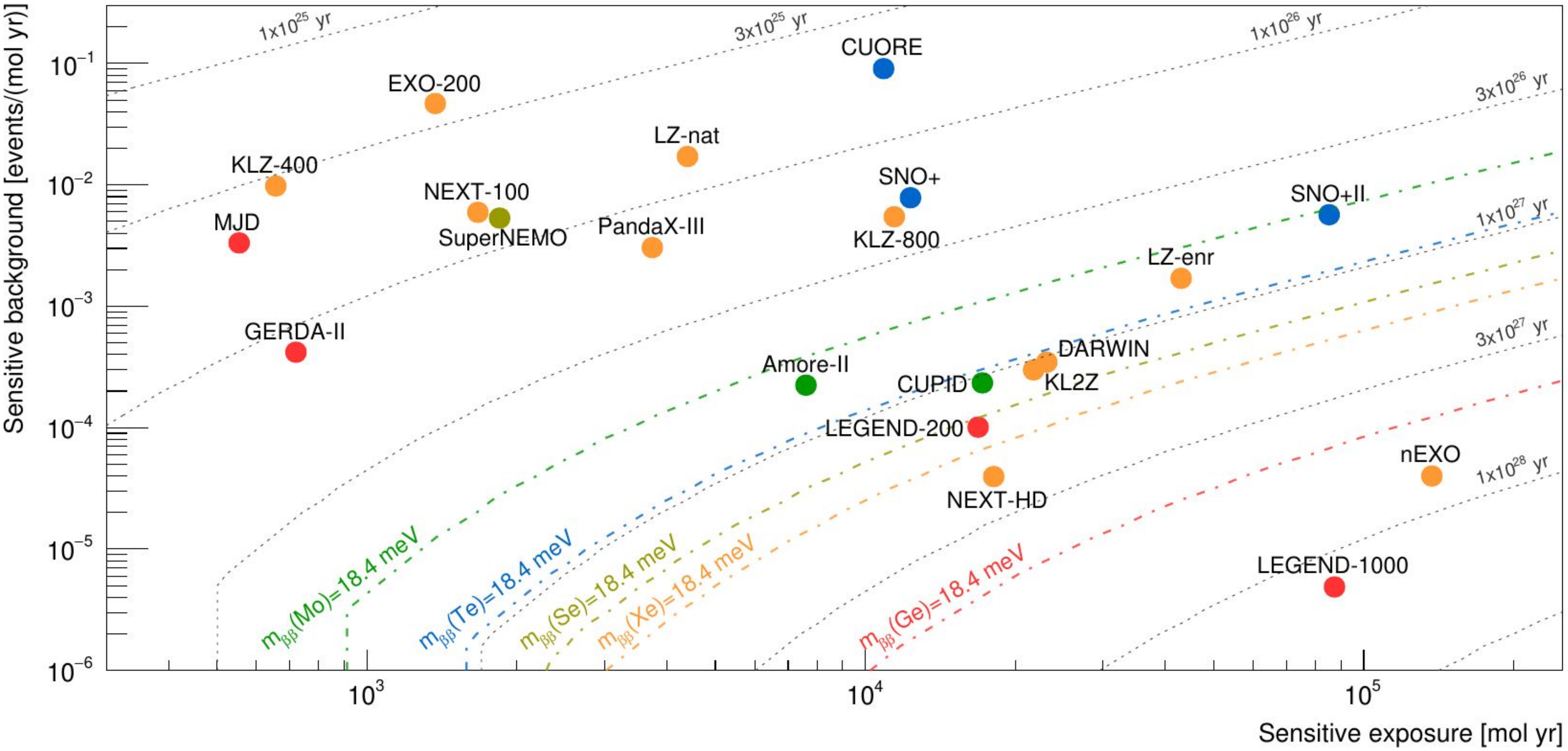
Experimental fauna



Experimental fauna (as of 2023)



Experimental fauna (as of 2023)



Sensitivity to 0νββ decay

0νββ decay signature

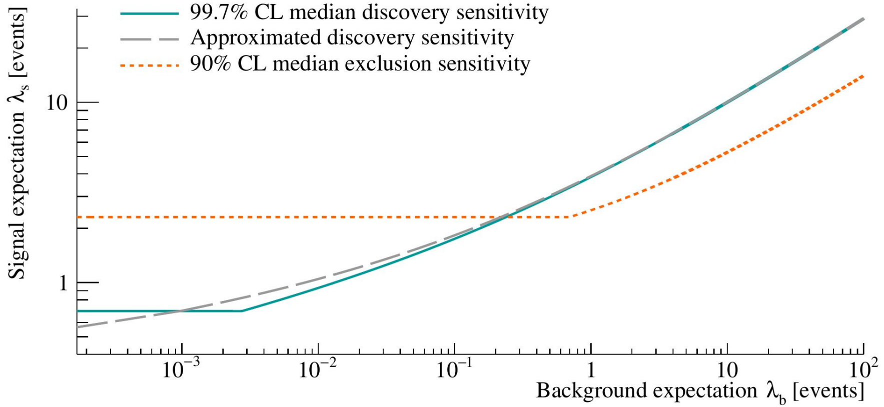
- Peak at $Q_{\beta\beta}$ in sum-energy spectrum
- Homogeneous distribution in time and space
- Localized energy distribution of 1–10 mm in solid or liquid
- Uncorrelated to any other physical process

Background signatures

- Significantly different energy distribution
- Can have non-uniform distribution in space and/or time
- Spatial distribution of energy release can be much smaller or larger than 1–10 mm

Sensitivity

- Experiments typically perform a multi-variate analysis (Energy + space / time / pulse shape)
- Can be approximated with multi-variate cut combined with counting analysis
- What counts, is the expected number of signal and background events in some N-dimensional region of interest

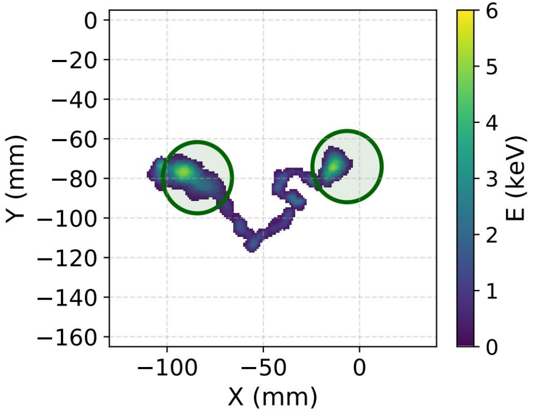


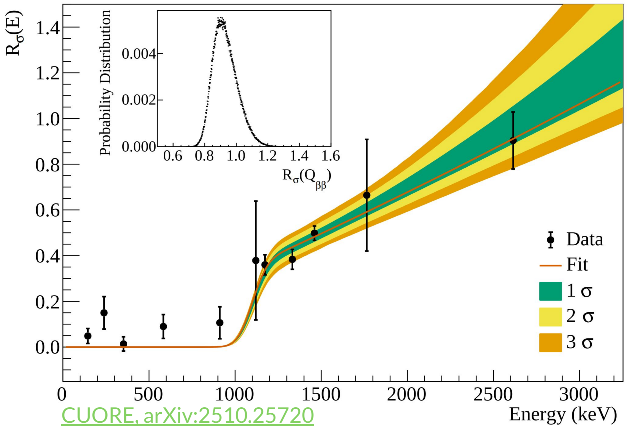
What is not captured in this picture

- Experiments with poor resolution (scintillation only) heavily depend on background modeling
  →Very good for limit setting thanks to scalability, less suitable for discovery
- If experiment X sees a significant excess at $Q_{\beta\beta}$, ~~nobody~~ I won't believe until I see the event topology
  →Single electron tracks or Bragg peak necessary as smoking gun
  →Daughter isotope tagging (e.g. barium tagging) not sufficient, as it could be caused by $2\nu\beta\beta$ decay, too
- Sensitivity to $0\nu\beta\beta$ decay uncorrelated to sensitivity to nuclear models via cross-check of $2\nu\beta\beta$ NME

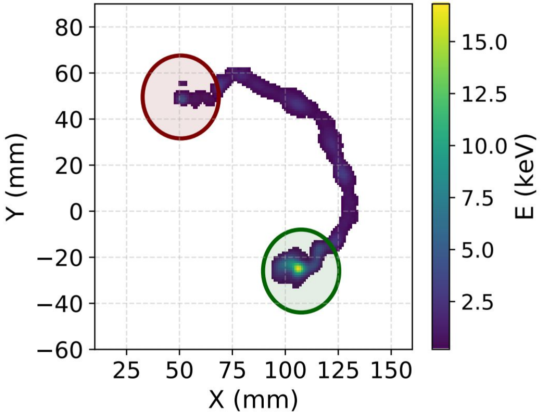
My personal wish list for future experiments

- Particle identification
  →0νββ events ought to be produced by electrons!
- Event topology
  →Electron Bragg peaks should be visible
- Energy resolution of bolometric experiments should be pushed beyond current limitations
  →Why do we have an energy-dependent resolution when we expect it to be flat?





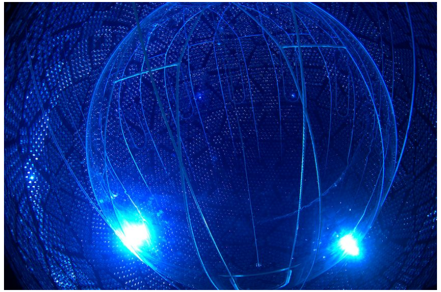
CUORE, arXiv:2510.25720

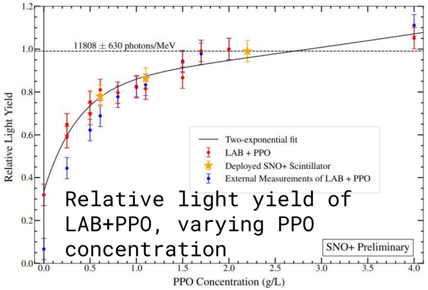


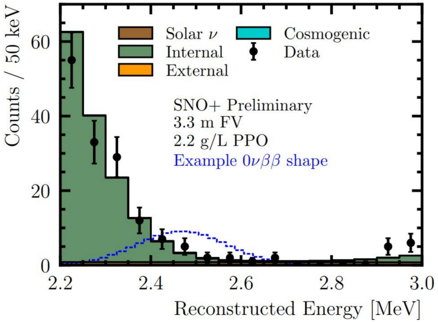
NEXT, JHEP 09 (2023) 190

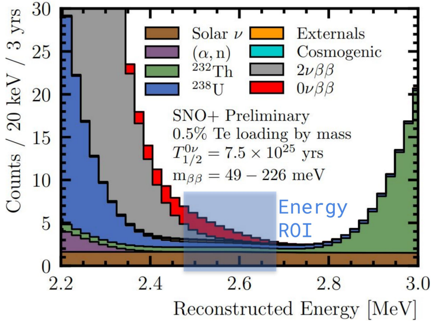
SNO+

- Te-loaded liquid scintillator inside water Cherenkov detector
- Water phase
  - Optical calibration + detector commissioning
  - Measured external γ background
- Partial scintillator phase:
  - Measured light yield
  - Measured U and Th contamination levels
- Scintillator phase
  - Measured scintillator attenuation + backgrounds
- Te loading
  - Expected in 2027 @0.5% →3.9 tonnes
  - Up to 1.5% loading should be feasible



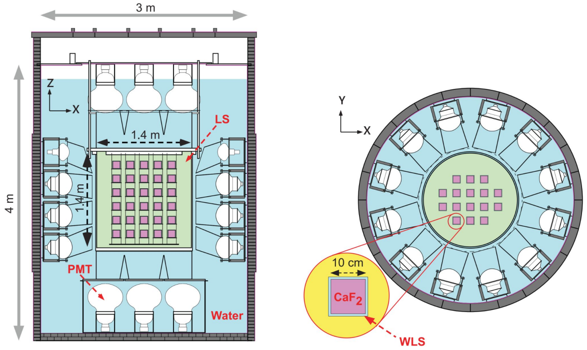


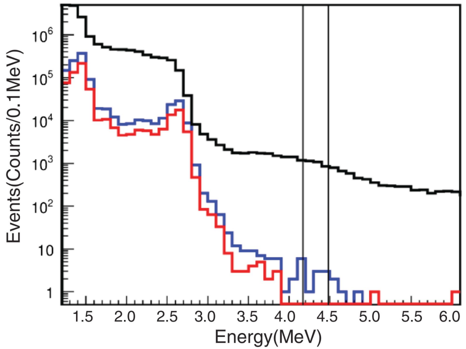


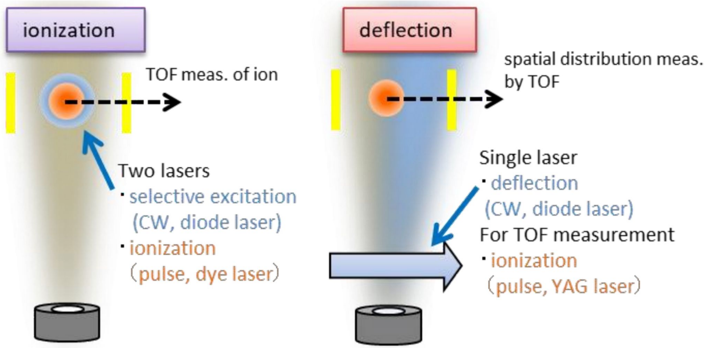


CANDLES

- $^{48}CaF_2$ scintillating crystals in liquid scintillator (LS)
  - High Q-value (4.27 MeV) but low natural abundance (0.187%)
  - Background suppression via LS veto and particle discrimination
- Can laser isotope separation grant 50% enrichment and be scalable?
  - Ionization: 90% enrichment, poor duty cycle
  - Deflection: 5.5% enrichment, 20% collection efficiency
- Once enrichment is achieved, we might as well turn it into a bolometric experiment!

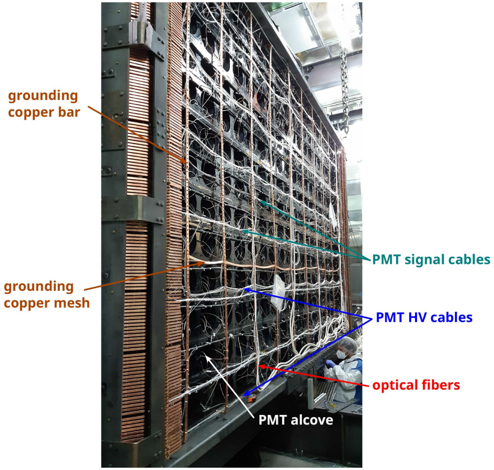






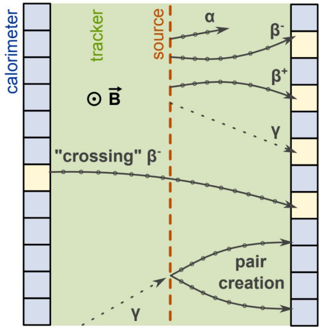
CANDLES, Phys.Rev.D 103 (2021) 9, 092008; CANDLES, J.Phys.Conf.Ser. 2147 (2022) 1, 012012

SuperNEMO



- Hybrid design: source foil + gas tracker + plastic scintillator calorimete
  - Poor energy resolution
  - Space and time resolution grants great background suppression
  - Very hard to scale →Will probably stop with 6.11 kg of ^{82}Se
  - Single electron tracking →Sensitive to decay mechanism!
- Currently operating at Modane

Topological signature of events

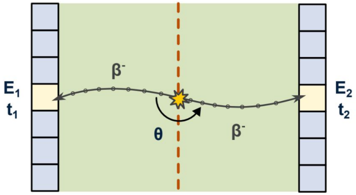


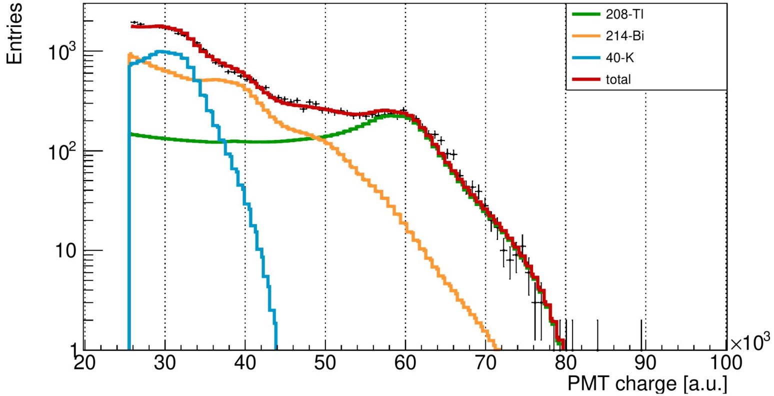
Full kinematic of ββ events

Individual electron energy

Angular correlation

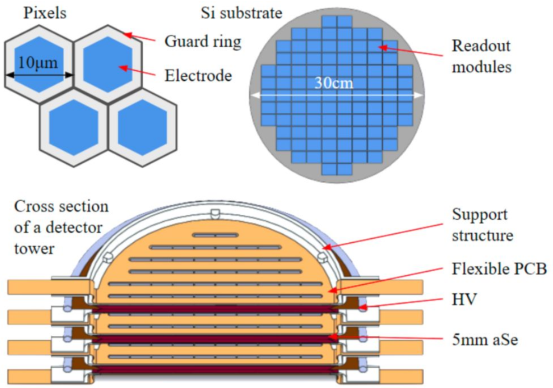
Total electron energy



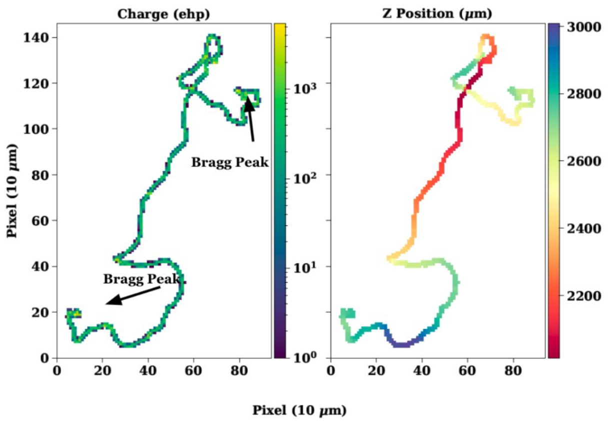


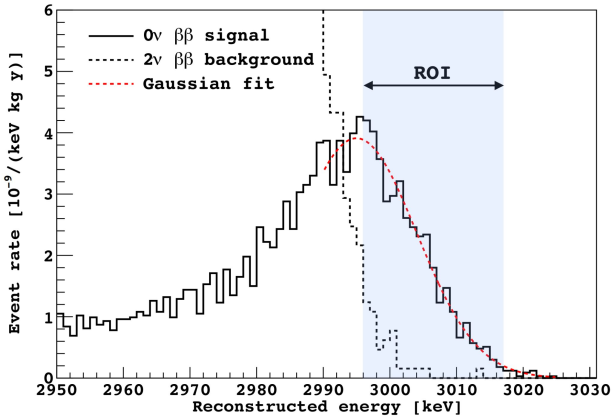
SuperNEMO, JINST 20 (2025) 11, T11003

SELENA



SELENA, PoS TAUP2023 (2024) 163

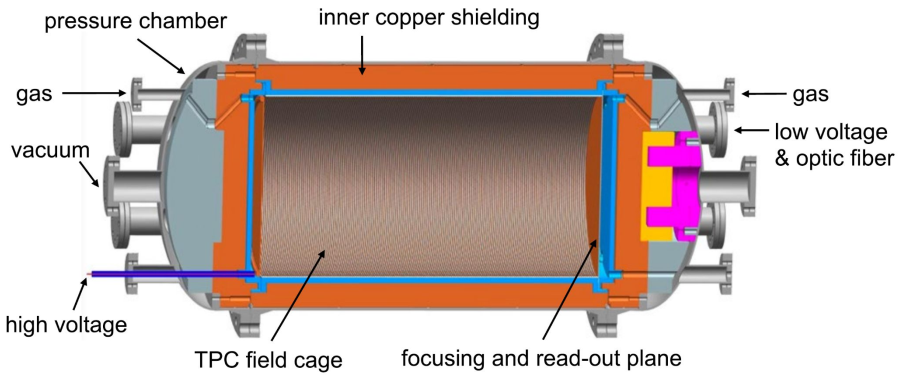


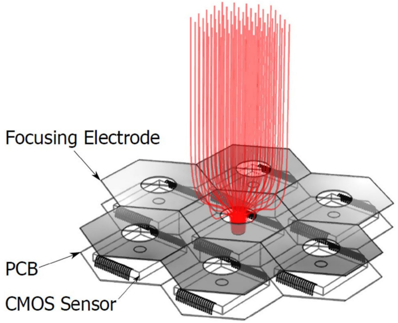


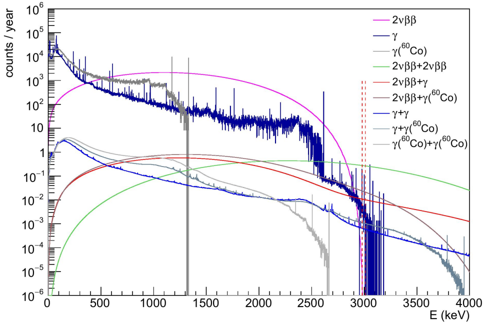
- 5 mm thick amorphous ^{82}Se deposited on CMOS
  - Rolling-shutter readout (like DAMIC)
  - Scaling granted by industrial capabilities
- Background suppression via pixelated readout
  - Identify ββ events via double Bragg peak search
  - Identify events from U and Th chain via delayed coincidences
  - Expected resolution (FWHM): ~1.1% @$Q_{\beta\beta}$

NνDEX

- High-pressure $^{82}SeF_6$ gas TPC
  - Electronegative gas → No amplification
  - Single ionization readout
- Topmetal silicon sensor
  - CMOS sensor with focusing electrode
  - 30 e^- noise →Amplification-free readout
- Main background: 2νββ pileup
  - Full-length drift time: 7 sec
  - Solution: read scintillation on HV plane
- NνDEX-100 to be installed @CJPL in 2027
- For more info, google "NνDEX experiment for double beta decay"

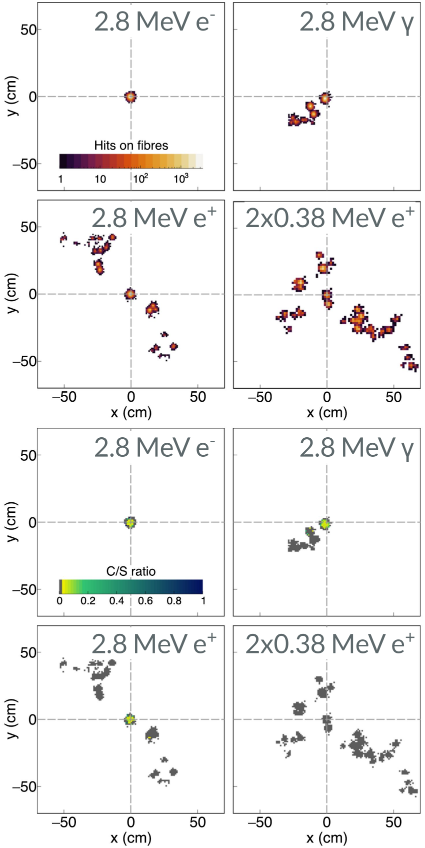






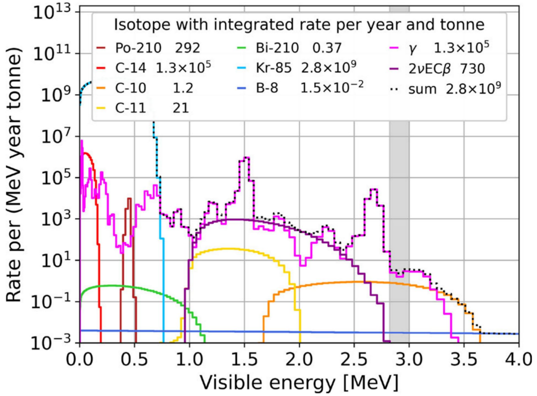
NνDEX, Nucl. Sci. Tech. 35 (2024) 3

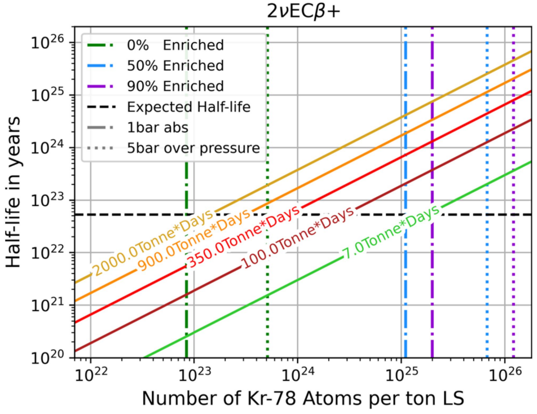
NuDoubt^{++}



- Search for $\beta^+\beta^+$, β^+EC, ECEC decays
  - Allow to validate nuclear models!
  - 0ν mode could be resonantly enhanced
- Slow hybrid scintillator
  - Delay scintillation using solvents
  - Cherenkov/scintillation ratio for particle discrimination
- Opaque scintillator + fiber readout
  - Can dissolve isotope to high concentration
  - Same setup for ^{78}Kr and ^{124}Xe?

Isotope	Q [MeV]	f_{iso} [%]
^{78}Kr	2.881	0.4
^{106}Cd	2.775	1.3
^{124}Xe	2.857	0.1





NuDoubt++, Eur.Phys.J.C 85 (2025) 2, 121

Questions?


No, I don't look like Javi Menendez!
As long as we don't find 0νββ decay, we're just splitting hairs
I bet you a beer NuDoubt++ won't see anything
No s***, it's opaque!