CUPID-1T and the future neutrinoless double beta decay experiments

Pía Loaiza

Laboratoire de Physique des 2 infinis Irène Joliot-Curie

université PARIS-SACLAY

GDR DUPhy, October 2022

Neutrinoless double beta decay in a nutshell

$(A,Z) \rightarrow (A, Z+2) + e^- + e^-$

Considering light neutrino exchange:

$$\frac{1}{\tau_{1/2}^{0v}} = |m_{\beta\beta}|^2 \, |M^{0v}|^2 \, G^{0v}(Q, Z)$$

M^{0v} : nuclear matrix element

$G^{0v}(Q, Z)$: known phase-space factor

$$m_{\beta\beta} = |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha} m_2 + |U_{e3}|^2 e^{2i\beta} m_3$$

Effective Majorana mass

U: PMNS matrix

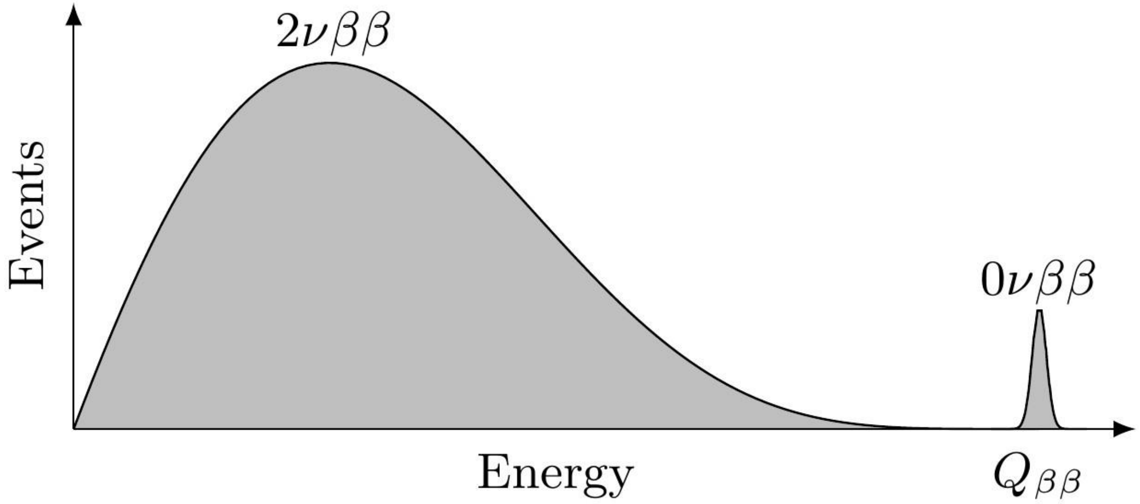
α, β : Majorana phases

If inverted hierarchy: $m_3 << m_1 << m_2$

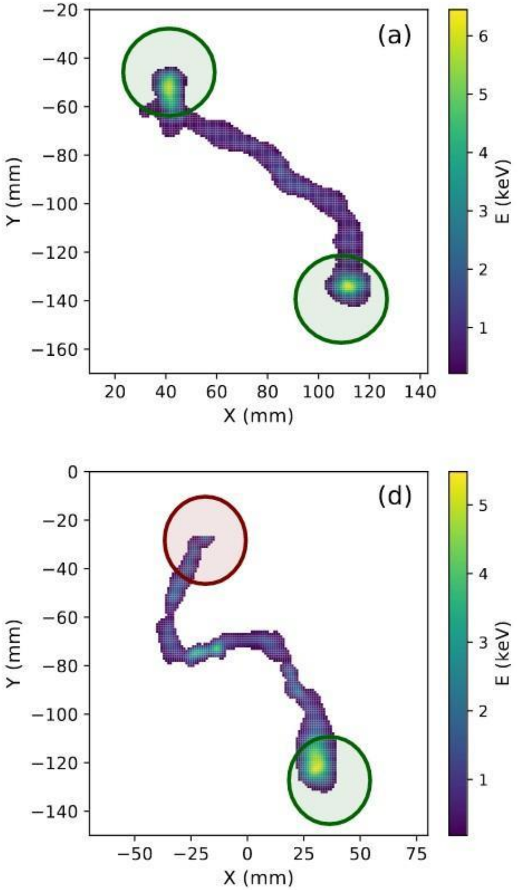
If normal hierarchy: $m_1 << m_2 << m_3$

0νββ detection signature

- Summed energy of the two electrons at $Q_{\beta\beta}$ eg, in calorimeters, CUPID, LEGEND



- and topology reconstruction of the two e- eg, NEXT, nEXO, SuperNEMO



Background index

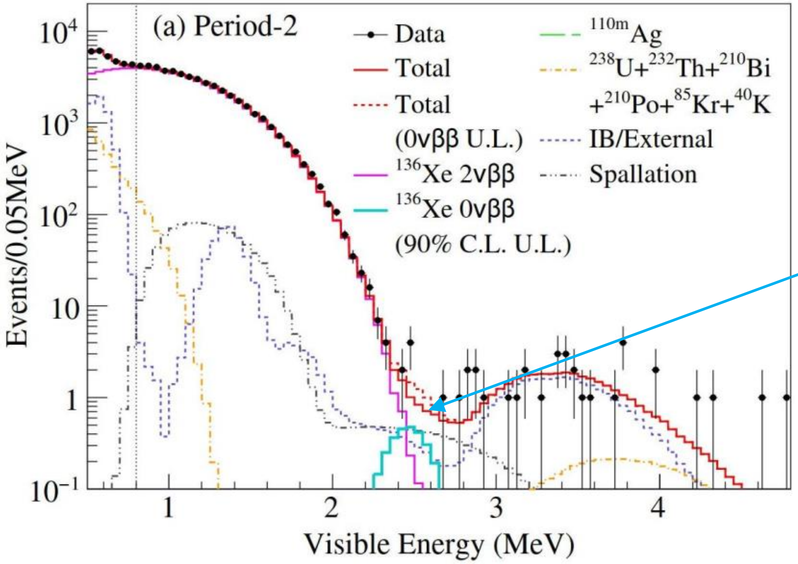
0νββ people define a background index:

- $$BI = \frac{background\ counts\ at\ Q_{\beta\beta}}{\Delta E\ x\ mass\ x\ time} \quad \frac{counts}{keV\ x\ kg\ x\ year}$$

- ΔE according to resolution

KamLAND-Zen-400: $Q_{\beta\beta}$ = 2457.83 keV, ROI: 160 keV

BI=5 x 10^{-4} counts/keV kg y

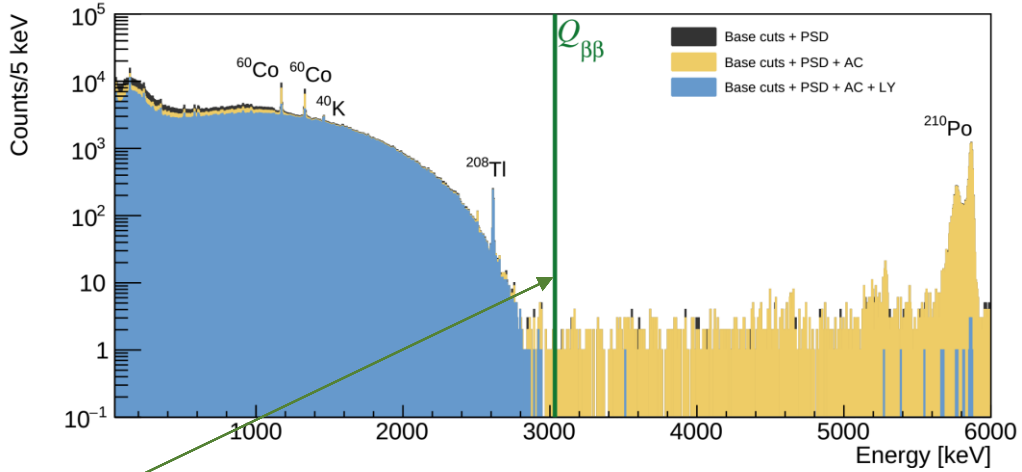


PRL117,082503 (2016)

The signal should be here

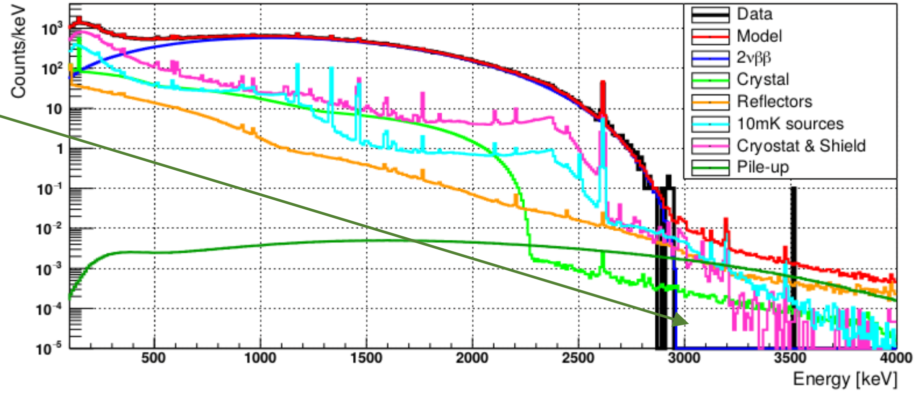
CUPID-Mo: $Q_{\beta\beta}$ = 3034.40 keV

Zero events in ROI, exposure = 2.71 kg y

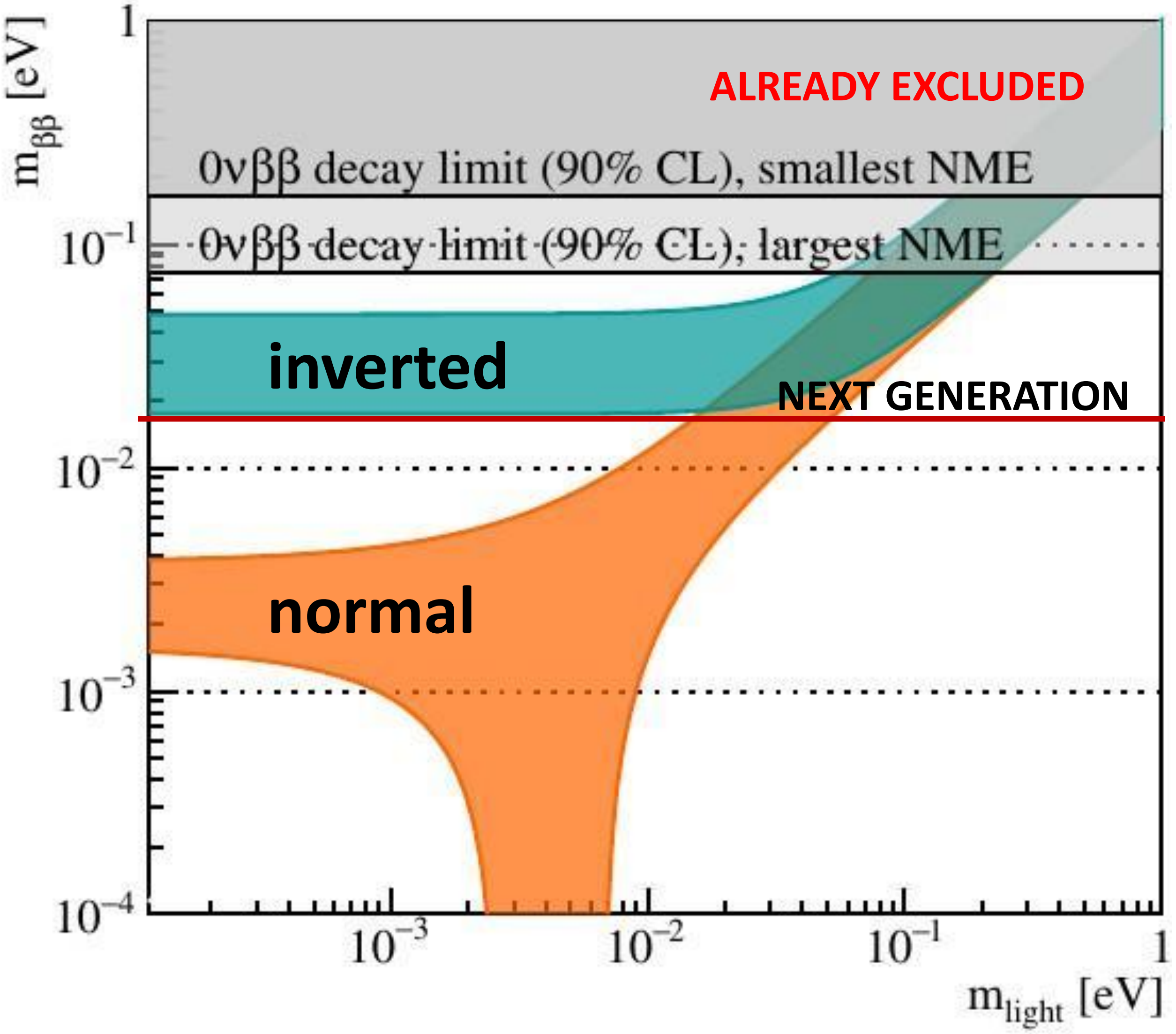


ROI: 30 keV BI=3 x 10^{-3} counts/keV kg y

(from background model)



Next generation $0\nu\beta\beta$ searches



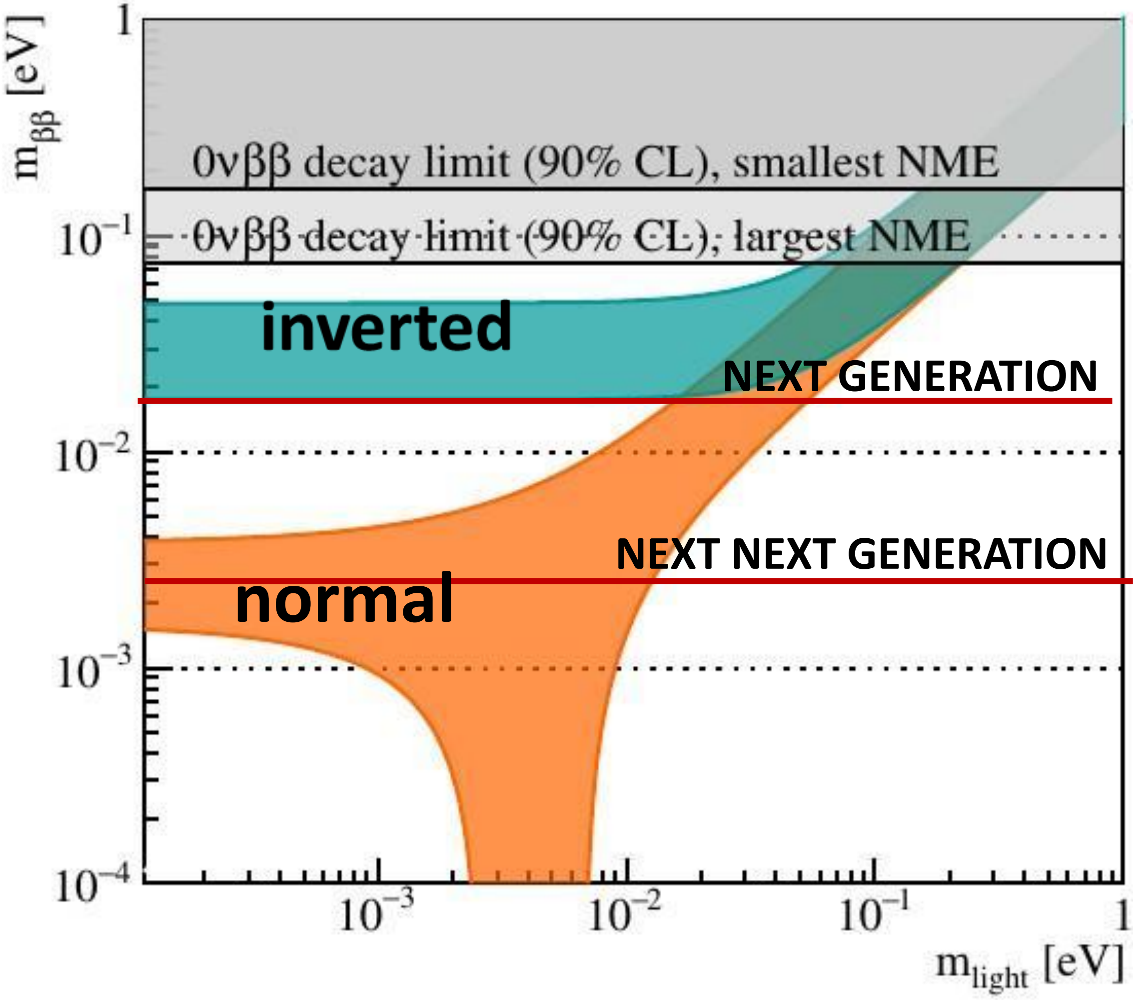
5-10 years from now

Bottom of the inverted hierarchy region 18.4 meV

- $T_{1/2}$ ~ 10^{27} y
- Background index ~ 10^{-4} - 10^{-5} counts/keV kg y

Next to next generation $0\nu\beta\beta$ searches

10 - 15 years from now



- Next to next generation experiments aim for a discovery
- $T_{1/2} \sim 10^{29}$ y
- $m_{\beta\beta} \sim 2.5$ meV

$m_{\beta\beta} \sim 8 - 10$ meV scale has some 'theoretical' args

- Some theoretical models focussing on the coarse structure of the mass matrix predict that :

$m_{\beta\beta} = \mathcal{O}(1) + \sqrt{\Delta m^2_{atm}} \times \theta_c^n$ n=1 or 2 →$m_{\beta\beta} \sim 10$ meV for n = 1

- Mass scale of solar neutrino mass squared difference:

$m_{\beta\beta} \sim \sqrt{\Delta m^2_{12}} = 8.6 \pm 0.1$ meV

- We'll need extremely low backgrounds

Background index $\sim 10^{-5} - 10^{-6}$ cts/keV kg y

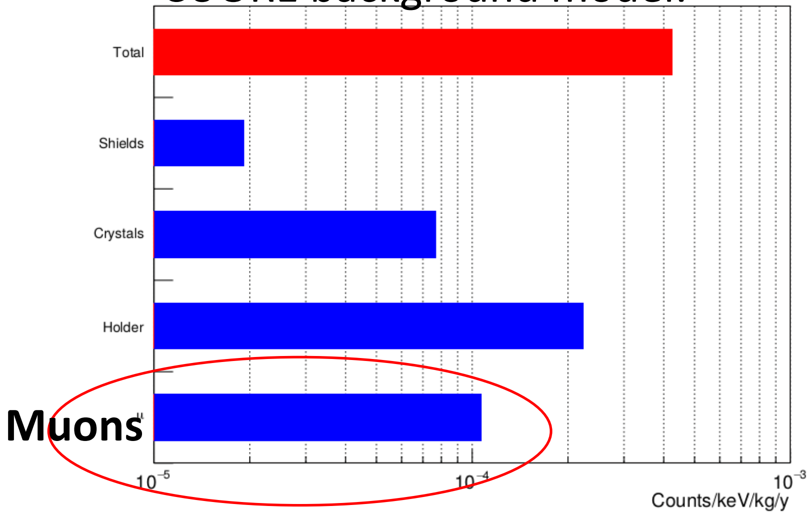
Cosmic rays background

- Once the experiments are placed in underground sites, high energy muons, E > 100 GeV, can produce background in $0\nu\beta\beta$ searches due to ionization in materials
- Muons can be tagged by:

  - reconstruction of the muon tracks in liquid Xe experiments

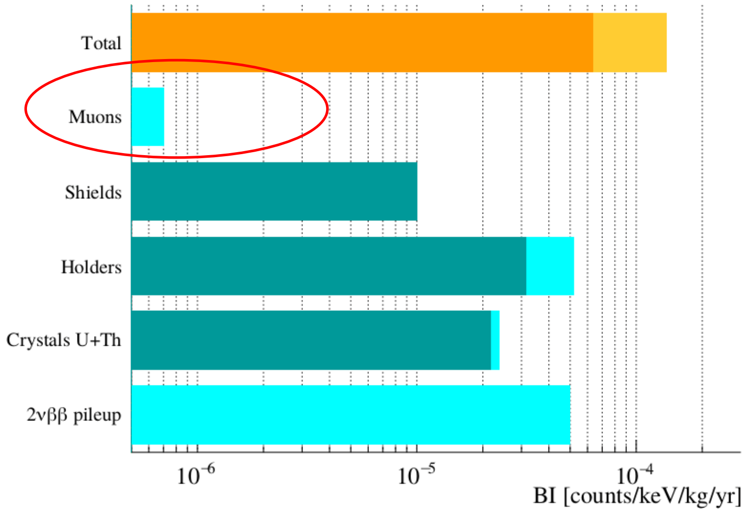
  - high multiplicity events in granular detectors
- Eg : CUPID, LNGS with only anticoincidence cut, muons contribute 1.4 x 10^{-4} cts/keV kg y

CUORE background model:



- Add plastic scintillators
- Tag and remove muons
- Simulation indicate > 99% geometric efficiency

CUPID background model:



Cosmic rays background : muon induced neutrons

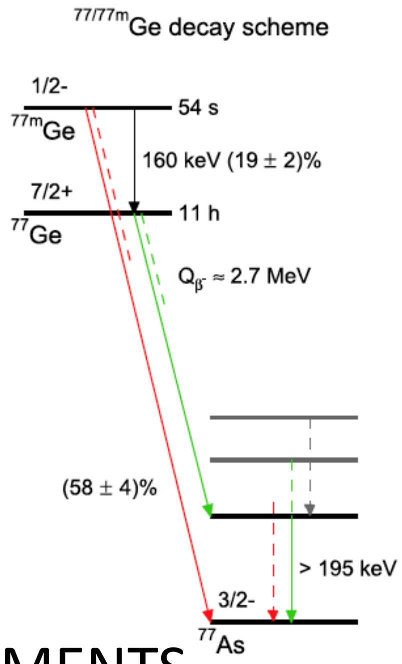
- Muons interact in materials and produce neutrons via spallation or hadronic showers. These neutrons are highly energetic, E up to 10 GeV
- Neutrons can then be captured, give unstable isotopes, which may decay with the emission of prompt gammas or e^- with energies in the $0\nu\beta\beta$ ROI, 2.5 – 3 MeV region . (*Activation in-situ)*
- Example: LEGEND-1000 is looking for $0\nu\beta\beta$ decay in ^{76}Ge.

  - ^{77m}Ge is formed by neutron capture on ^{76}Ge, its decay is expected to be the dominant in-situ cosmogenic contribution

  - At Gran Sasso depth , the background expected is $(1.1 \pm 0.2)\ 10^{-4}\ \frac{\mathrm{cts}}{\mathrm{keV\ kg\ y}}$ before active background rejection cuts

  - Reduced to 8.6 x 10^{-7} cts/keV kg y thanks to passive neutron moderators combined with delayed coincidences

  - The collaboration is considering as an option to place the detector in SNOLAB



GOING TO LSM IS DEFINITELY AN ADVANTAGE FOR FUTURE $0\nu\beta\beta$ EXPERIMENTS

Natural radioactivity

- ^{238}U, ^{232}Th, ^{40}K present in the rock and in the materials used to build the experiment
- γ's up to 2.6 MeV but can be summed, β's up to 3.2 MeV,

α's from 3 to 10 MeV

- We need to carefully select the materials
- Surface cleaning
- Reduce exposure to air

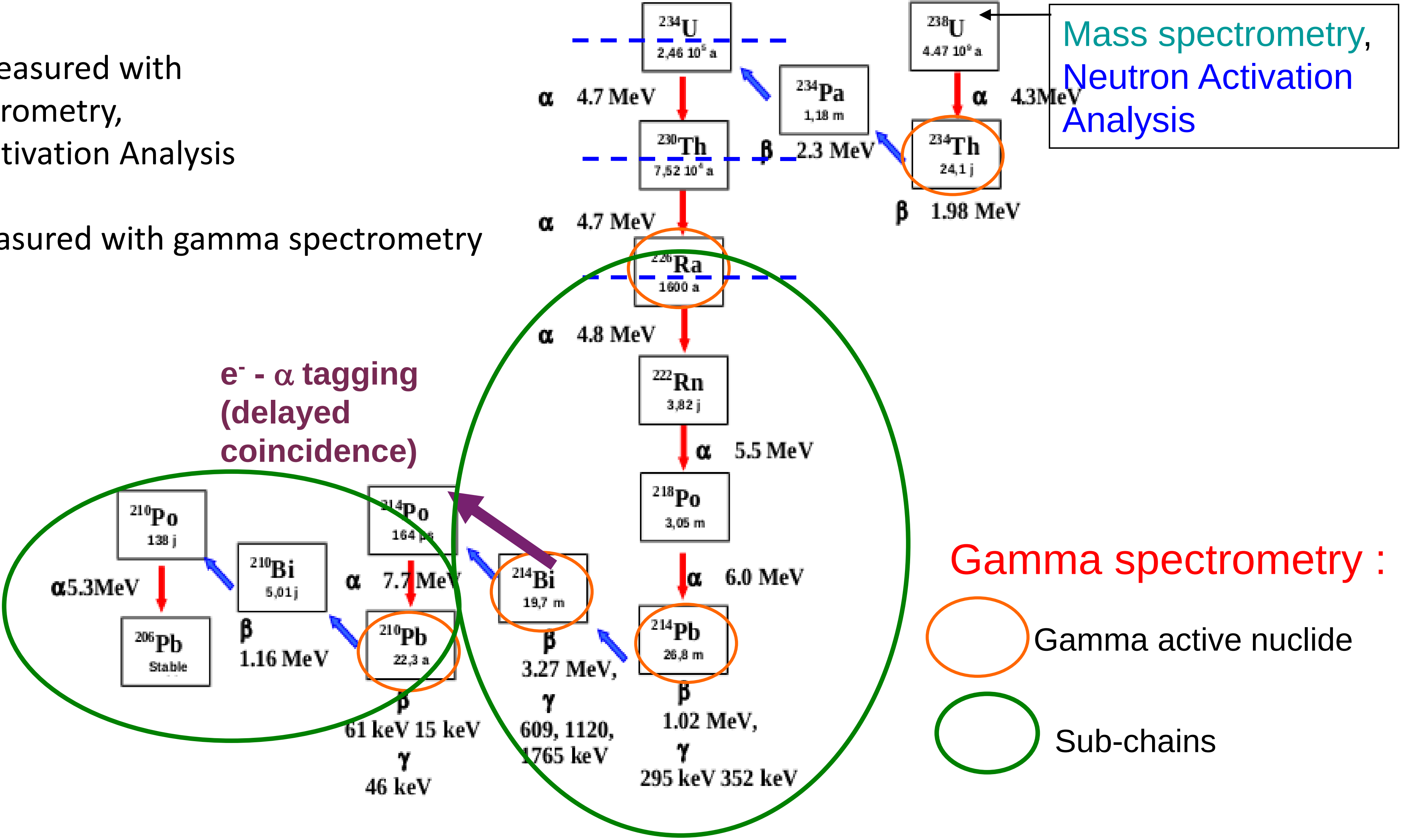
- Can be discriminated :
- Active discrimination (eg scintillating bolometers)
- Delayed coincidences

Natural radioactivity ^{238}U decay chain

Decay chain usually not in equilibrium

Progenitors measured with
- Mass Spectrometry,
- Neutron Activation Analysis

Daughters measured with gamma spectrometry



Mass spectrometry, Neutron Activation Analysis

e$^-$ - α tagging (delayed coincidence)

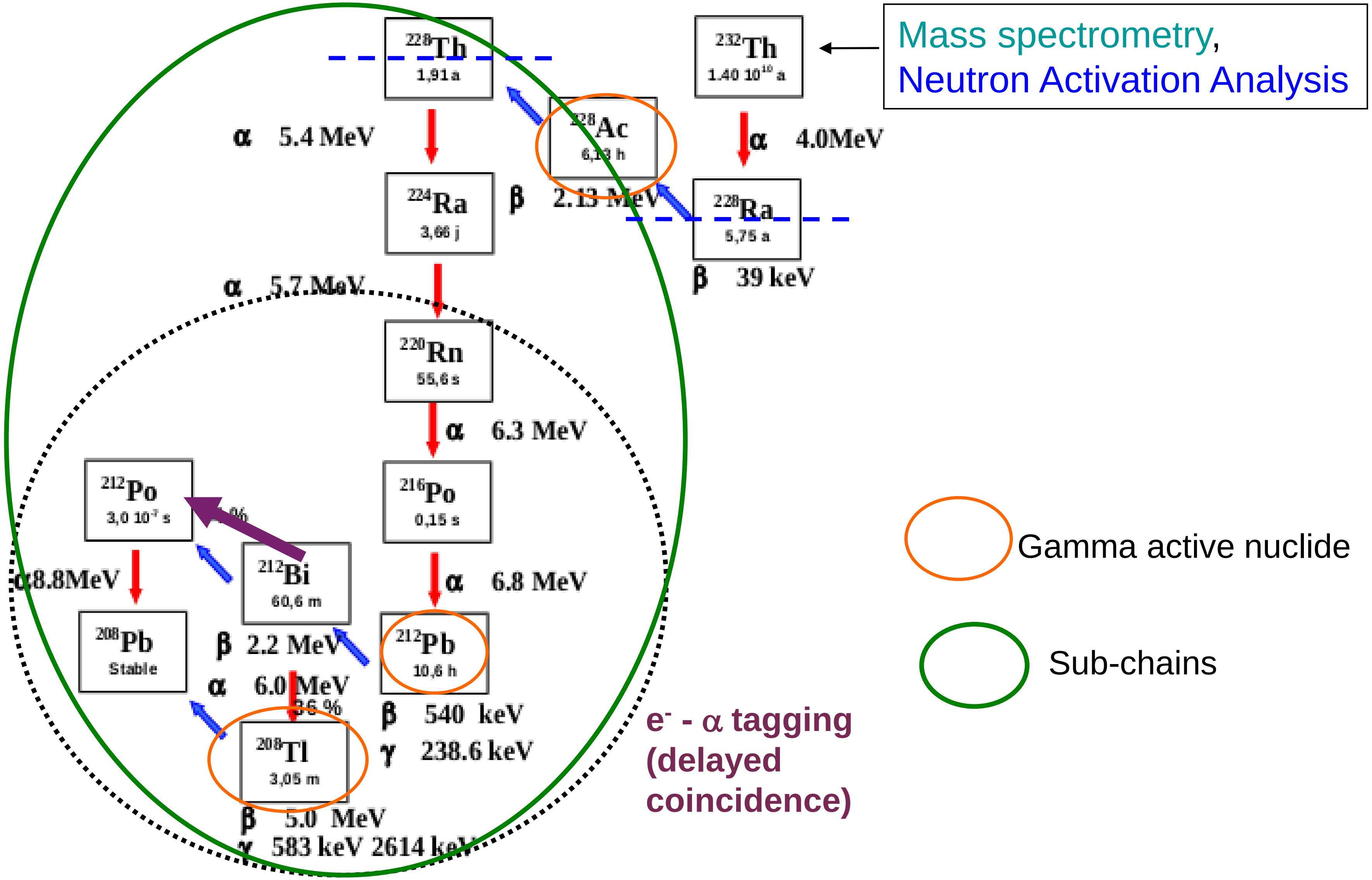
Gamma spectrometry :

Gamma active nuclide

Sub-chains

Natural radioactivity

^{232}Th decay chain



Mass spectrometry,
Neutron Activation Analysis

Gamma active nuclide

Sub-chains

e^- - α tagging (delayed coincidence)

Screening techniques

	Measure	**Sensitivities**
Mass Spectrometry, ICPMS, GDMS	Parent of chain	~ 10 µBq/kg
Neutron Activation Analysis	Parent of chain	~ 10 µBq/kg
Gamma-ray spectrometry, HPGe	Daughters	~ 100 µBq/kg - 1 mBq/kg

To get to the background levels required today we need sensitivities $\approx$ 10 µBq/kg

ICPMS, NAA ok, but can give information only on ^{238}U and ^{232}Th

HPGe can assay the dangerous radiocontaminants, but sensitivity is not enough

FOR NEXT NEXT GENERATION EXPERIMENTS WE SHOULD COME UP WITH INNOVATIVE SCREENING TECHNIQUES

— Je fais là un métier terrible.

Neutrons from environment and materials

Produced by :

- Fission
- (α, n)

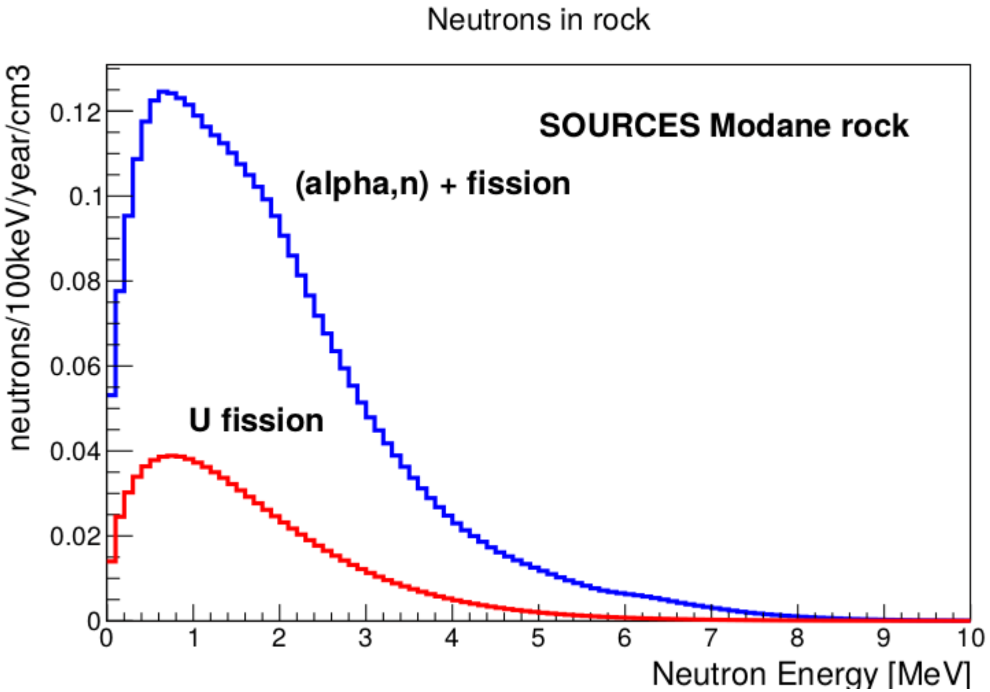
E < 10 MeV

Example in the rock :

$^{18}O + \alpha \rightarrow {}^{21}Ne + n$

Example in materials: PTFE

$^{19}F + \alpha \rightarrow {}^{22}Na + n$

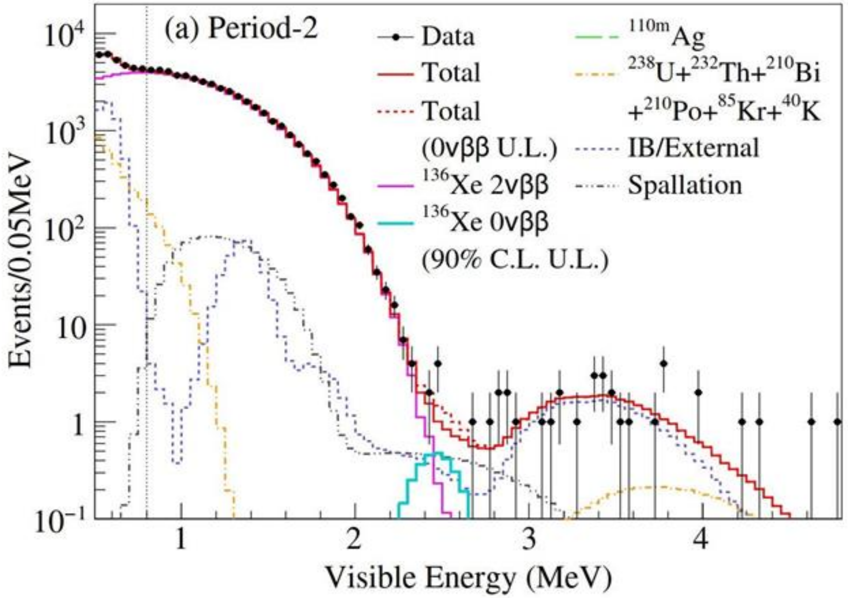


- The neutrons can then produce :
  - In-situ activation -> prompt gammas, e-
  - Gammas by inelastic scattering

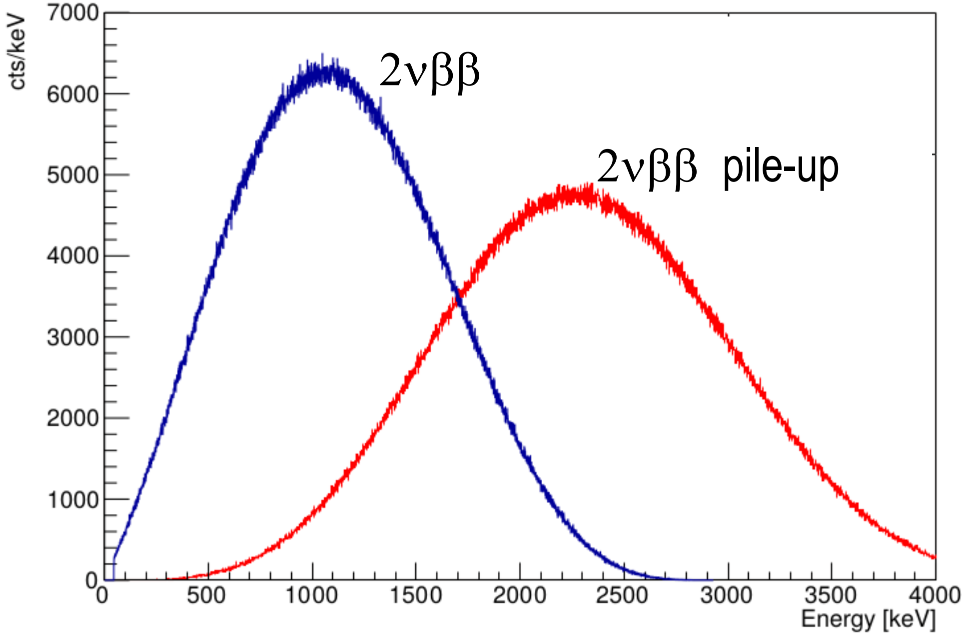
- Neutrons from the cavern can be efficiently suppressed by passive shielding, for example, polyethylene , water
  48 cm PE reduce neutron flux by a factor ~ 2 x 10^6 (depending on E_n)

Background from 2νββ

- 2νββ–decay tail can get into ROI due to limted energy resolution

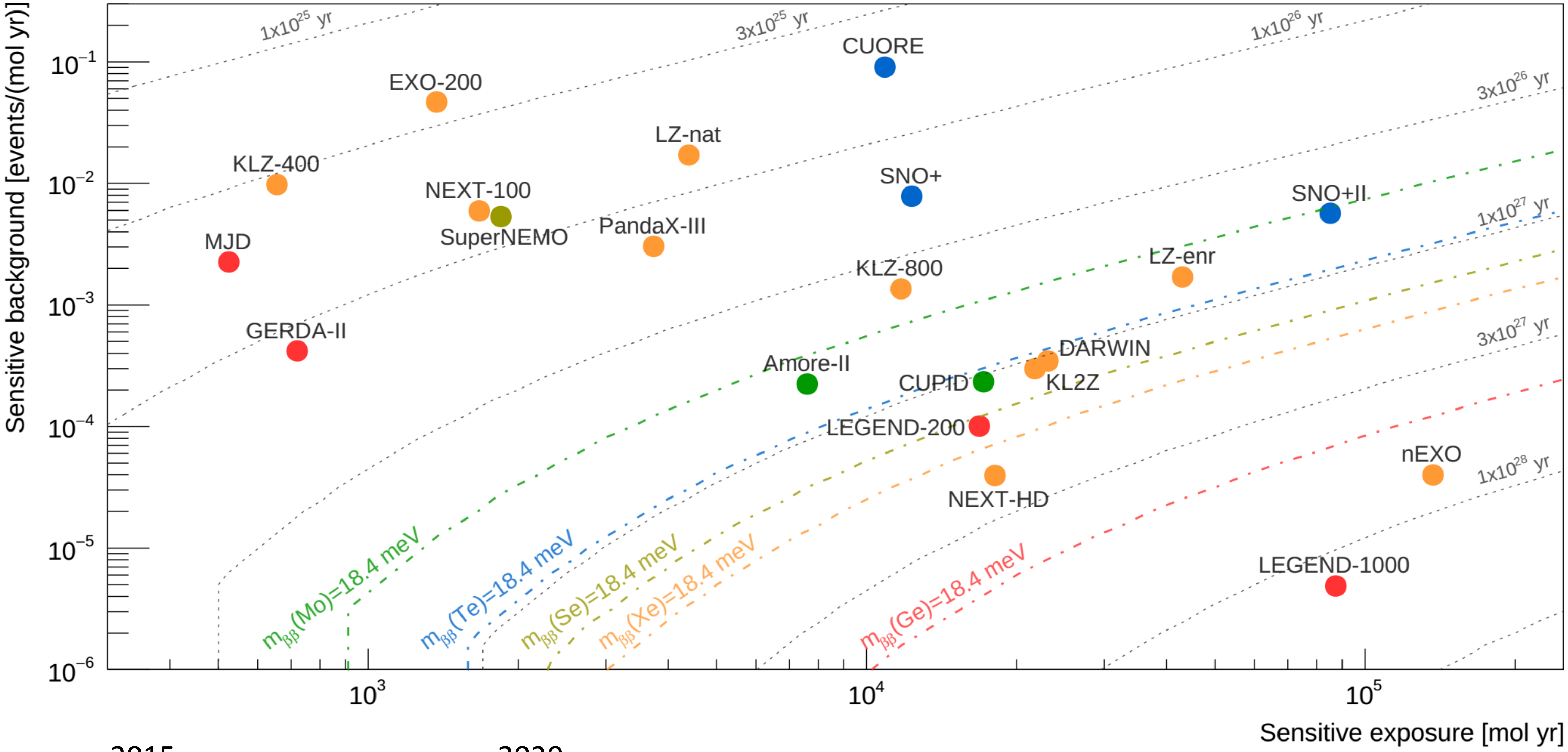


- Random coincidence of 2νββ events



Sensitive background and exposure for present and future experiments

Agostini, Benato, Detwiler, Vissani , arXiv: 2202.01787



2015

2020

2025

2030 →

From CUPID to CUPID-1T

Scintillating bolometers with dual read out capable to discriminate surface α background

Increase the mass and reduce the backgrounds

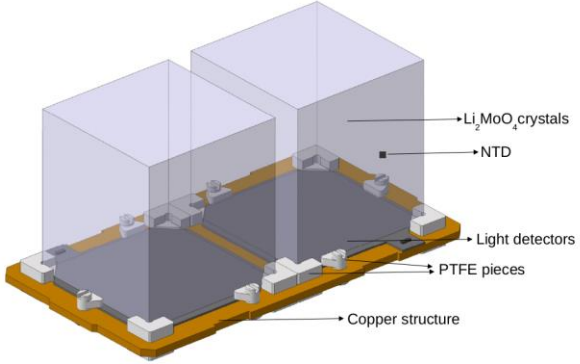
CUPID, LNGS

See Antoine Armatol talk

- $Li_2{}^{100}MoO_4$ crystals ~ 280 g
- ~ 240 kg of ^{100}Mo
- Ge light detectors

- Projected BI ~1 x 10^{-4} cts/keV kg y
- Discovery sensitivity in 10 y:

  - $\tau^{0\nu}_{1/2}$: 1.1 x 10^{27} y
  - $m_{\beta\beta}$ < 12 -20 meV

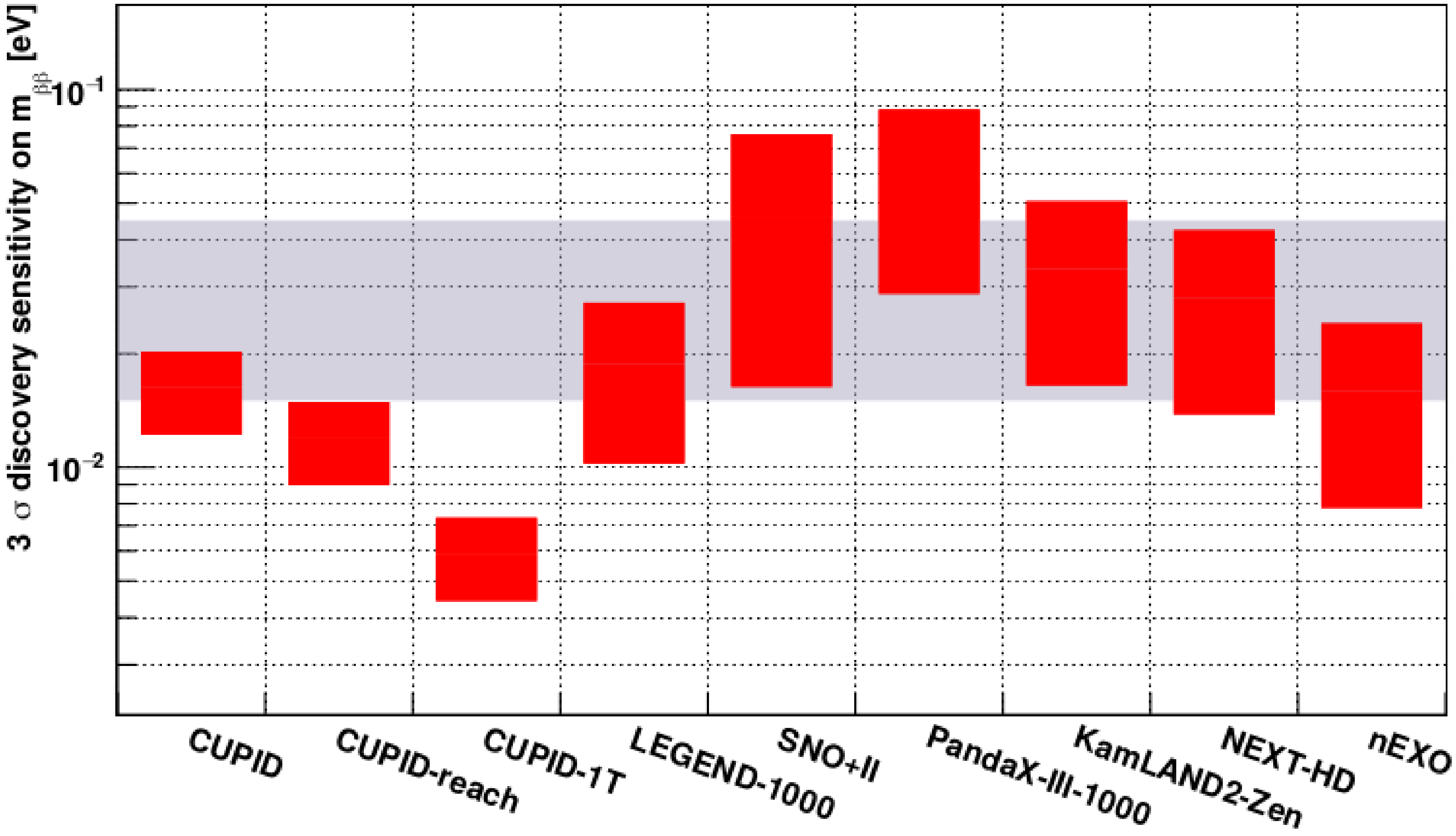


CUPID-1T

- 1000 kg of 100Mo → Need money and a new larger cryostat (or several cryostats)

- Background improvement by a factor 20 ~ 5 x 10^{-6} cts/keV kg y
- Discovery sensitivity in 10 y :
  - $\tau^{0\nu}_{1/2}$: 8 x 10^{27} y
  - $m_{\beta\beta}$ < 4 – 7 meV

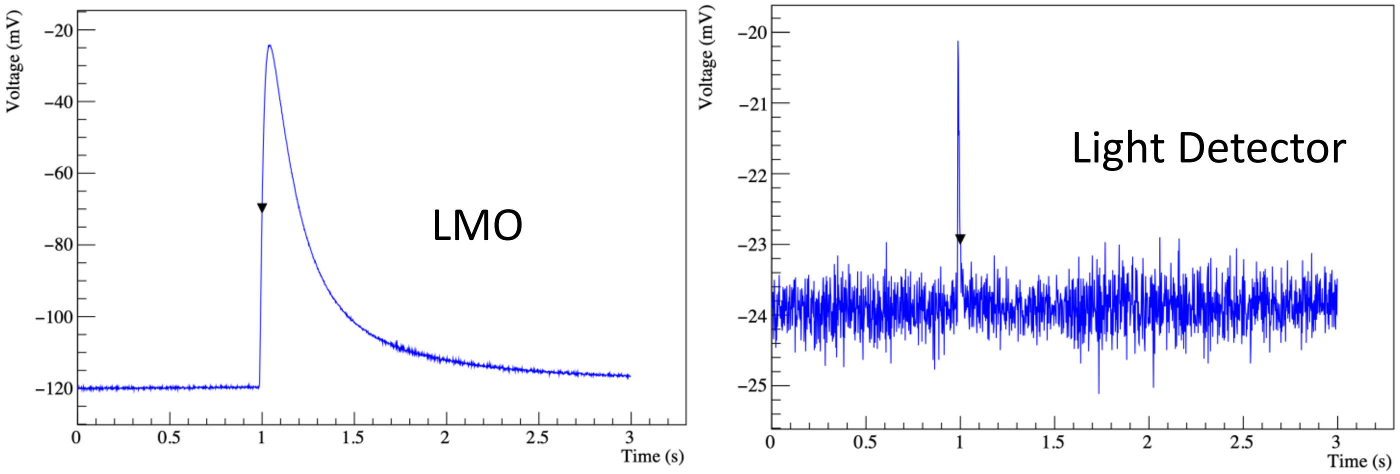
CUPID-1T expected sensitivity



How to reduce 2νββ pile-up ? Strategies for CUPID

Critical background component: random coincidence of 2νββ events. ^{100}Mo is the fastest 2νββ emitter with $\tau^{2v}_{1/2}$ = 7. 1 x 10^{18} y

To discriminate pile-up we need:
- fast sensor response
- signal/noise large enough



Today's performances: NTD thermal sensors

Heat	**S/N ~ 3000**	**Rise time ~ 10 - 15 ms**
Light	**S/N ~10**	**Rise time ~ 1 - 2 ms**

At present the use of only the light signal is not viable due to low signal/noise ratio

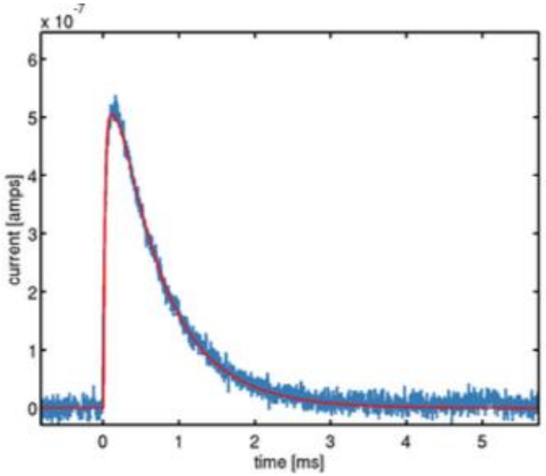
Work in progress to improve pile-up discrimination for CUPID: Neganov Luke assisted NTDs, algorithms

BI expected ~ 10^{-4} cts/keV kg y

How to reduce 2νββ pile-up ? : Strategies for CUPID-1T

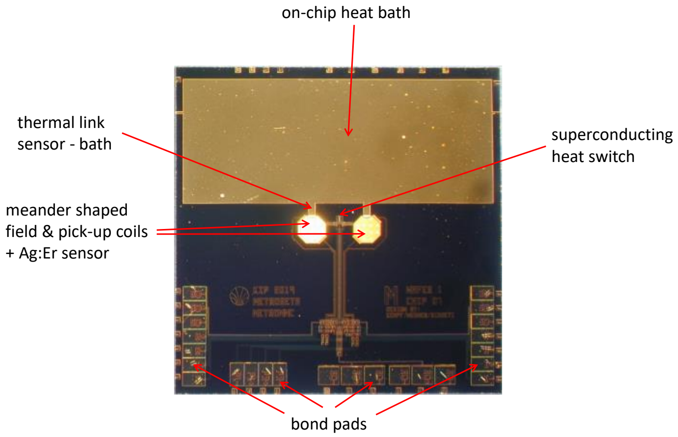
TES : Transition Edge Sensors

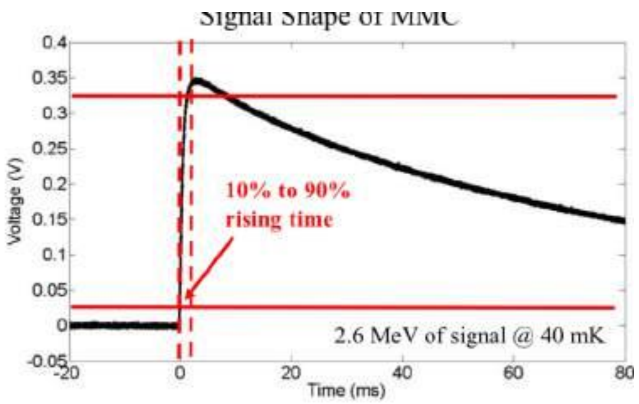
- Superconducting films
- SQUID readout
- Fast signal, rise time ~ 100 µs (depending on implementation)
- Multiplexing



MMC : Metallic Magnetic Calorimeters

- Au:Er/ Ag:Er paramagnetic sensor
- SQUID readout
- Fast signal, rise time:
  500 µs (crystal), 200 µs LD (AMORE) (depending on implementation)
- Multiplexing





Other options

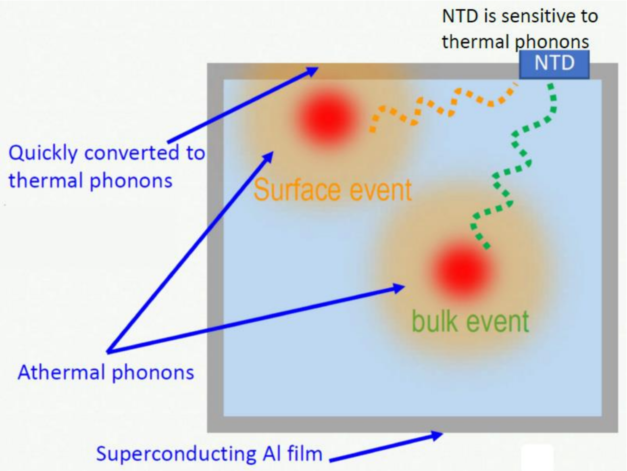
MKIDS

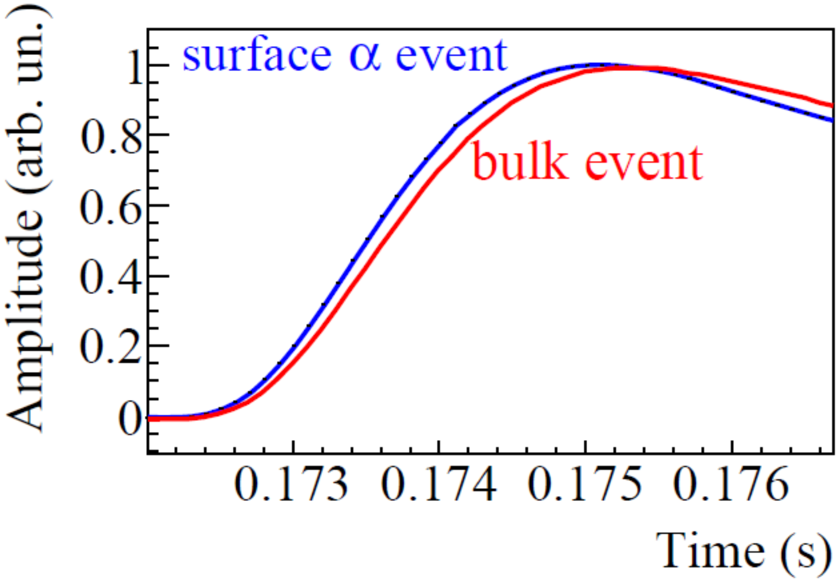
Neganov Luke assisted LD

- Need to go to a thin film
- JFET readout (as in CUPID)
- R&D needed

R & D to improve background

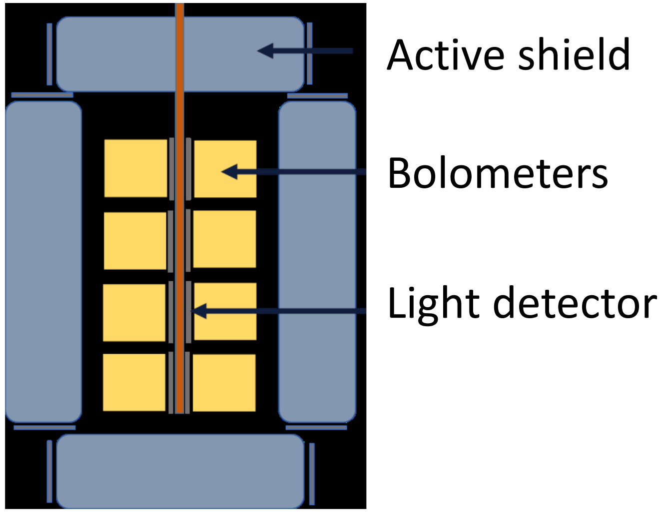
CROSS: rejection of surface events by pulse shape discrimination assisted by metal film coating





BINGO: See Hawraa's talk

- Internal active veto, $ZnWO_4$ or BGO scintillators
- Reduction of passive materials
- Neganov-Luke Light Detectors



Summary

- Next to next generation $0\nu\beta\beta$ experiments will be designed for discovery, and not limit setting
- Will fully explore inverted hierarchy and part of normal hierarchy
- Formidable experimental challenges for ton-year exposures
- Will need extremely low backgrounds

→ Increase exposure and reduce backgrounds !

In this framework, going to a deep site like LSM is definitely an advantage

- CUPID-1T, the next to next generation bolometric $0\nu\beta\beta$ search:
- Increase mass to 1 ton of $0\nu\beta\beta$ isotope
- Reduce backgrounds to 5×10^{-6} cts/keV kg y

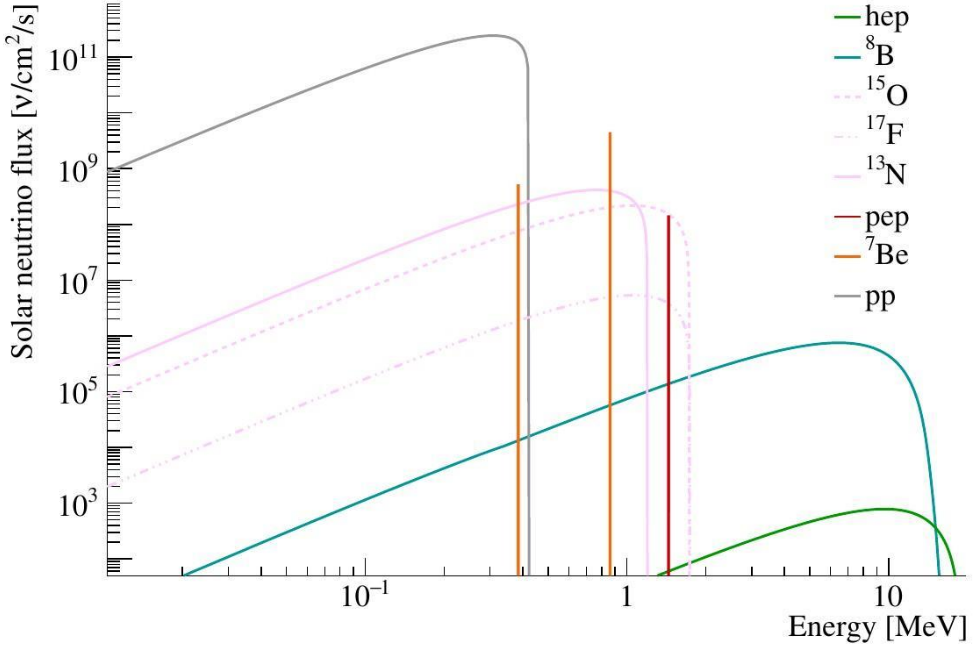
- Discovery sensitivity in 10 y :
- 8×10^{27} y
- $m_{\beta\beta} < 4 - 7$ meV

Solar Neutrinos

Elastic scattering

ES   ν + e- -> ν + e-

- e- non-isotropic, continuous spectrum
- Only ^{8}B relevant background for $0\nu\beta\beta$
- Significant only for liquid scintillators with dissolved sources
- Partially suppressed exploiting signal directionality

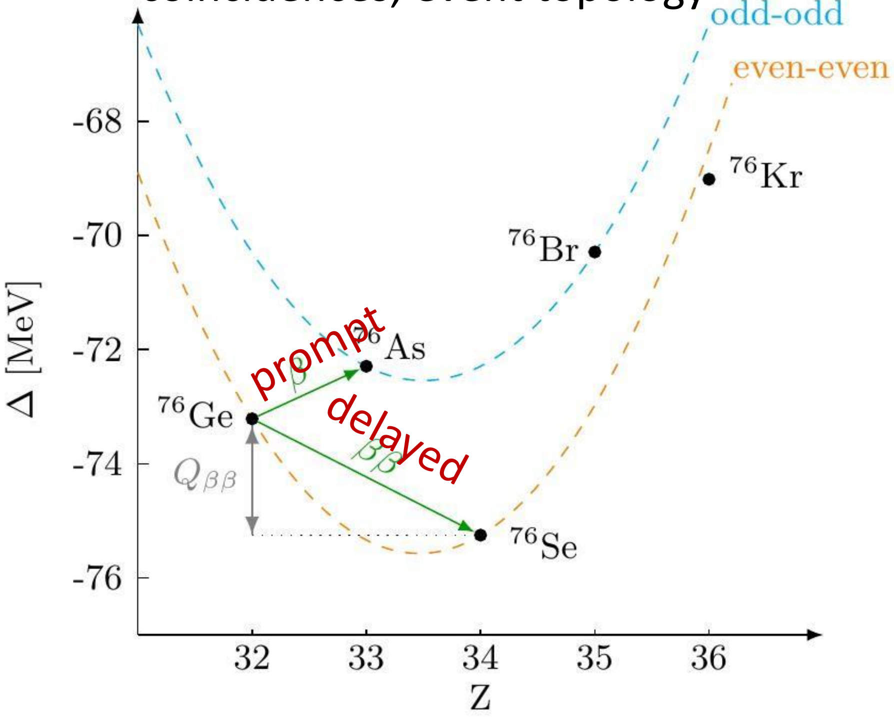


Charge Current

CC A^Z + ν -> A^{Z+1} + e$^-$ [+ γ's] + Q_ν (prompt)

A^Z + ν -> A^{Z+2} + β$^-$ + ν [+ γ's] + Q_β (delayed)

- 10^{-3} - 10^{-1} evts/keV ton y
- Depends on isotope, could be suppressed via delayed coincidences, event topology



More radionucleids

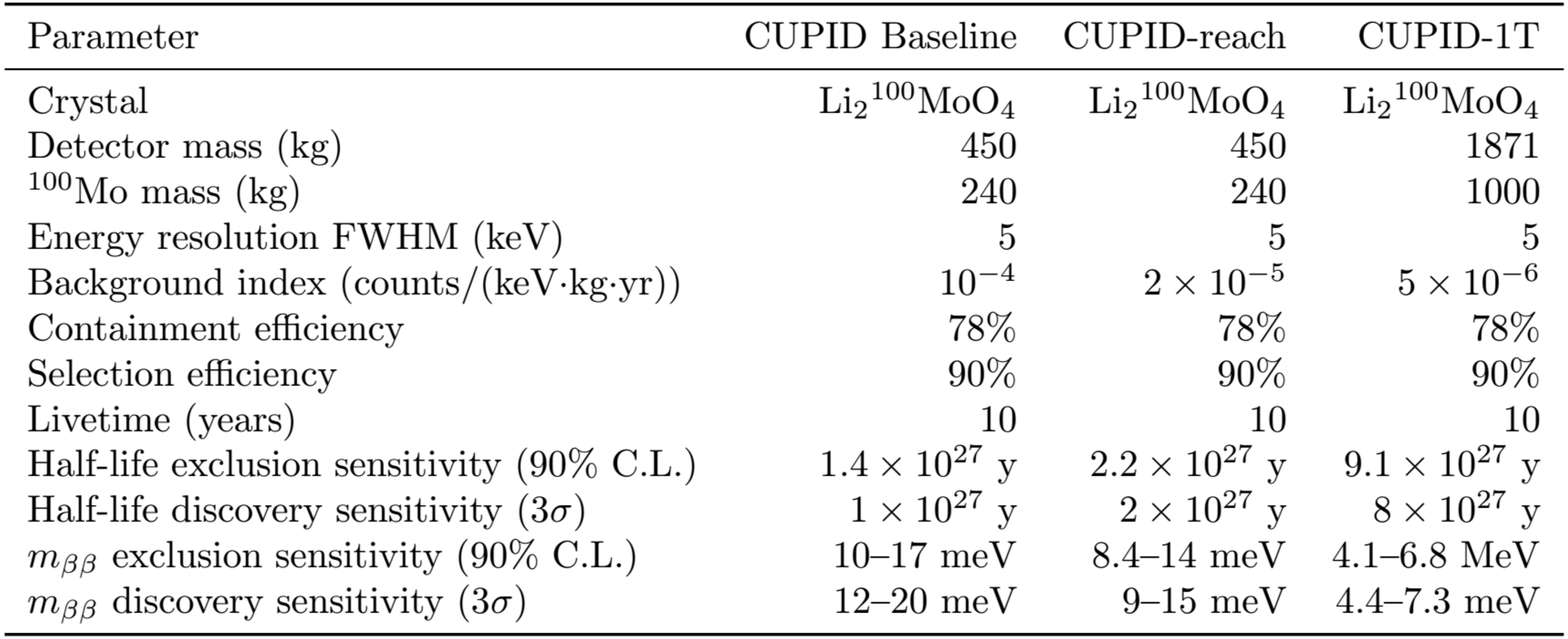
Antropogenic

- Ag in Kamland
- Sr/Y, Rb in our bolometers

Cosmogenics on surface

- in Copper
- in Ge, LMO’s,
- In Ar

From CUPID to CUPID-1T



Parameter	CUPID Baseline	CUPID-reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	450	450	1871
^{100}Mo mass (kg)	240	240	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2×10^{-5}	5×10^{-6}
Containment efficiency	78%	78%	78%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.4×10^{27} y	2.2×10^{27} y	9.1×10^{27} y
Half-life discovery sensitivity (3σ)	1×10^{27} y	2×10^{27} y	8×10^{27} y
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.4–14 meV	4.1–6.8 MeV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	9–15 meV	4.4–7.3 meV