Developing the SuperNEMO ββ source

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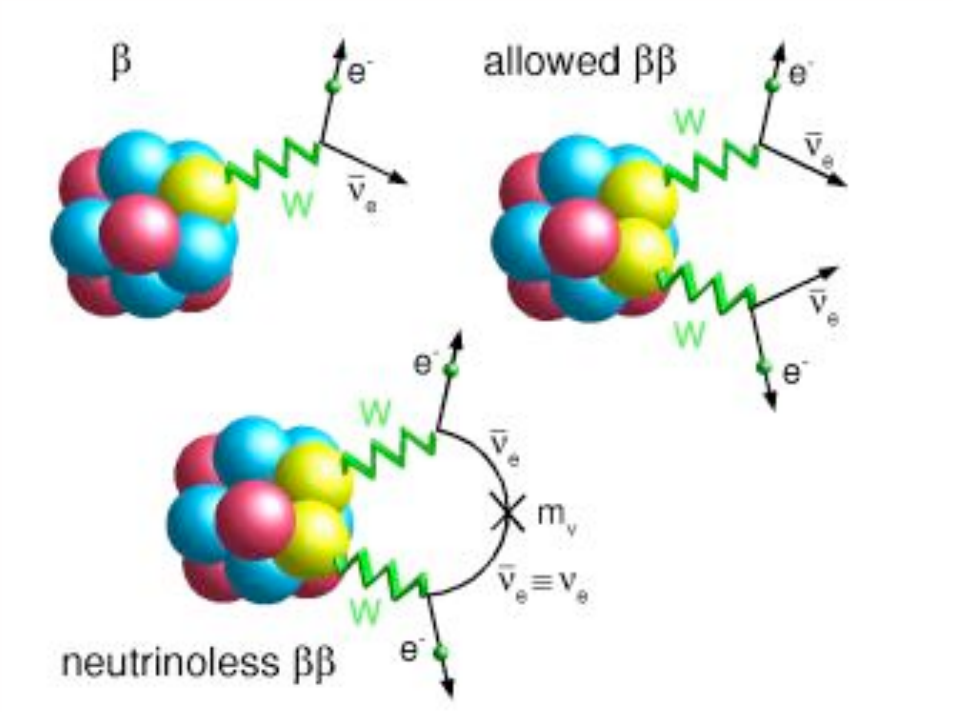
The neutrino-less double beta decay

2νββ decay: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

- 2nd order process **allowed** in the SM

0νββ decay: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- process **forbidden** in the SM



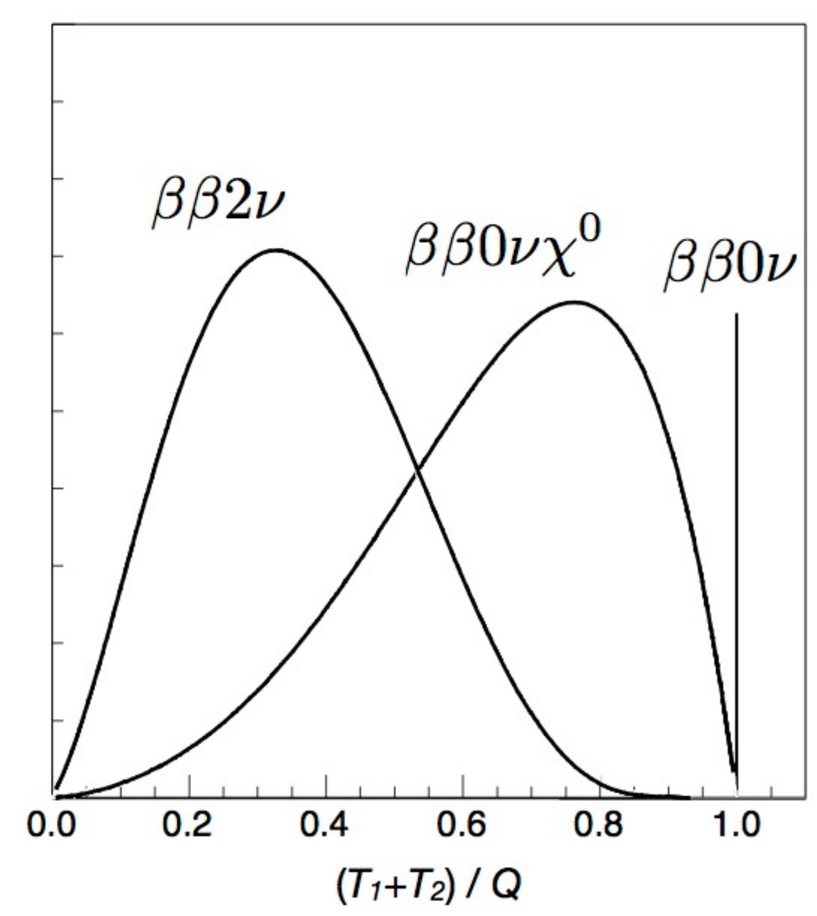
Interesting implication for particle physics:

- Lepton number violation must occur
- GUT, Leptogenesis model, See-Saw mechanism

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\eta^2$$

- **Light Majorana neutrino exchange**
- Right-handed current (V+A), SUSY, 1 Majoron, etc.

Different event topology in the final state



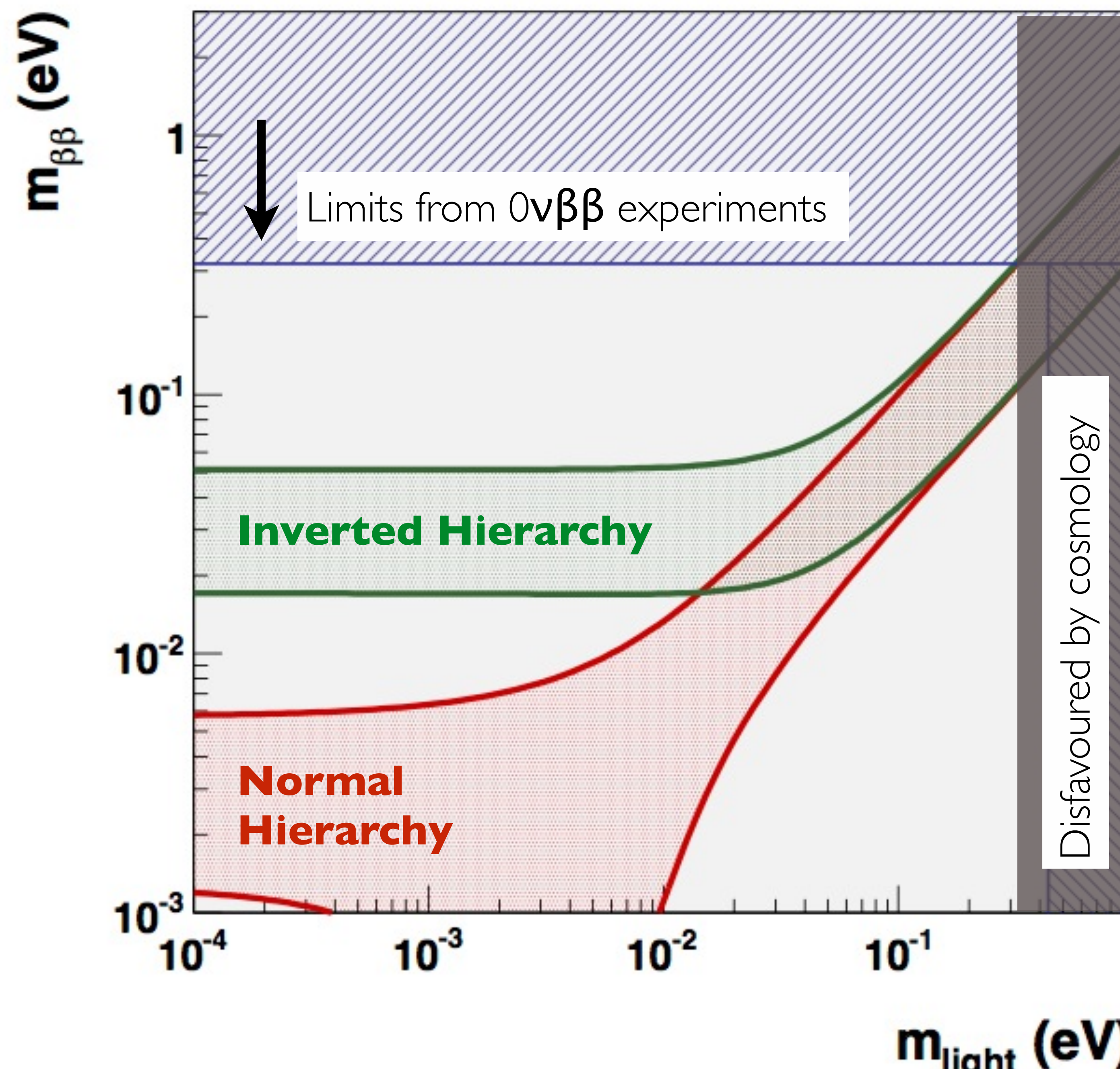
Sensitivity on neutrino mass scale

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M_{0\nu}|^2 \frac{\langle m_{ee}\rangle^2}{m_e^2}$$

Effective mass term: $\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2 m_i\right|$

Related to neutrino mixing matrix

Sensitive to the neutrino mass scale (m_{light})



ArXiv:1109.5515

What's the status?

1993 - 2000:

- **HdM** (~11 kg) & **IGEX** (~2 kg), ^{76}Ge
  - $T^{0\nu}_{1/2}$ > 1.9 10^{25} y @ 90% C.L.
- **HdM claim**: ⟨m_{ee}⟩ = 0.32 +/- 0.03 eV

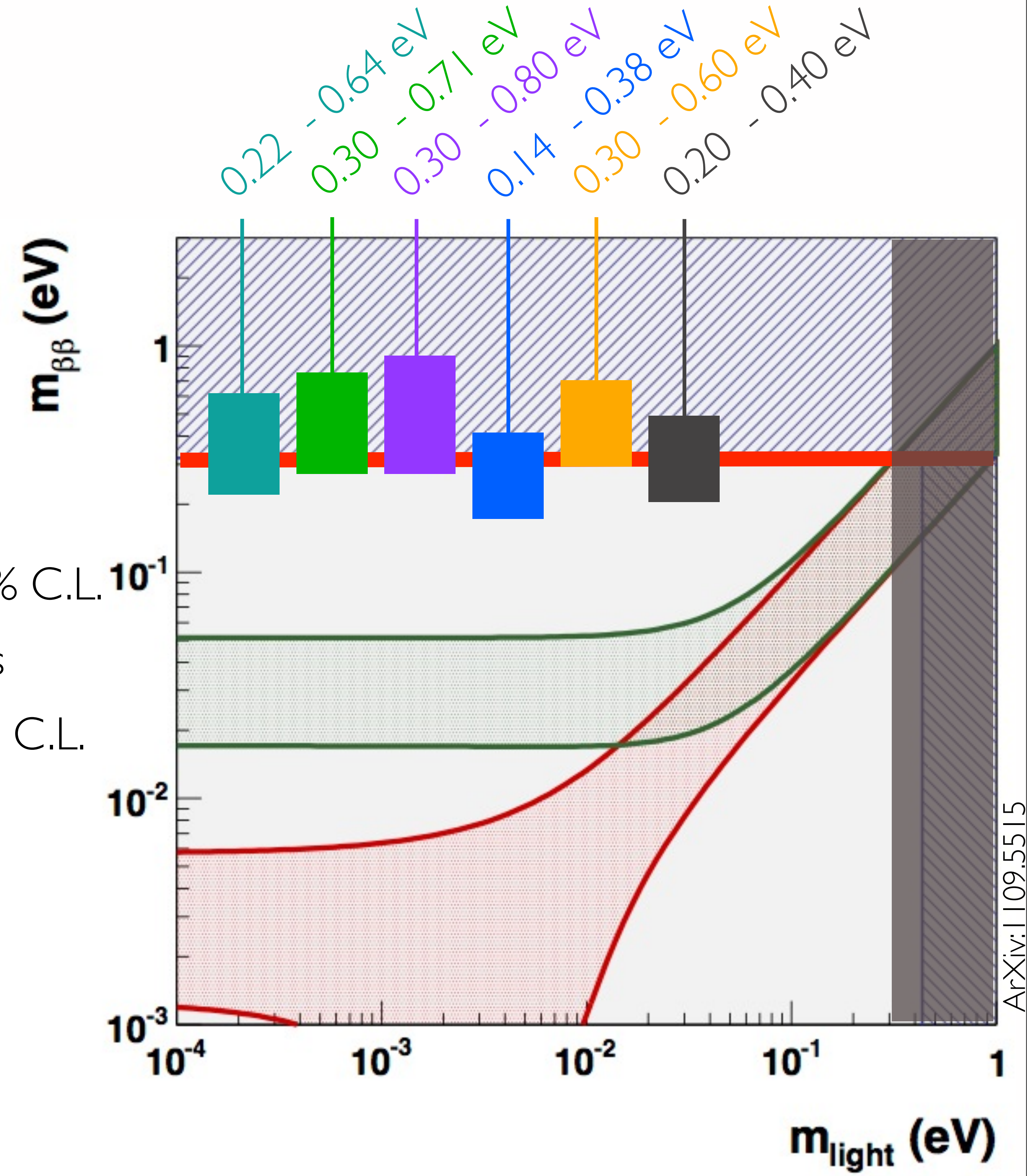
2000 - 2010:

- **Cuoricino**: TeO_2 bolometric detector
  - ~11 kg ^{130}Te: $T^{0\nu}_{1/2}$ > 2.8 10^{24} y @ 90% C.L.
- **NEMO3**: Tracko-Calo, 7 different isotopes
  - ~7 kg ^{100}Mo: $T^{0\nu}_{1/2}$ > 1.1 10^{24} y @ 90% C.L.

Since 2011: new generation

10 - 100 kg, R&D for future scaling

- **EXO200** (^{136}Xe): Liquid TPC
- **Kamland-ZEN** (^{136}Xe): Liquid Scintillator
- **GERDA** Phase I (^{76}Ge): Ge diodes



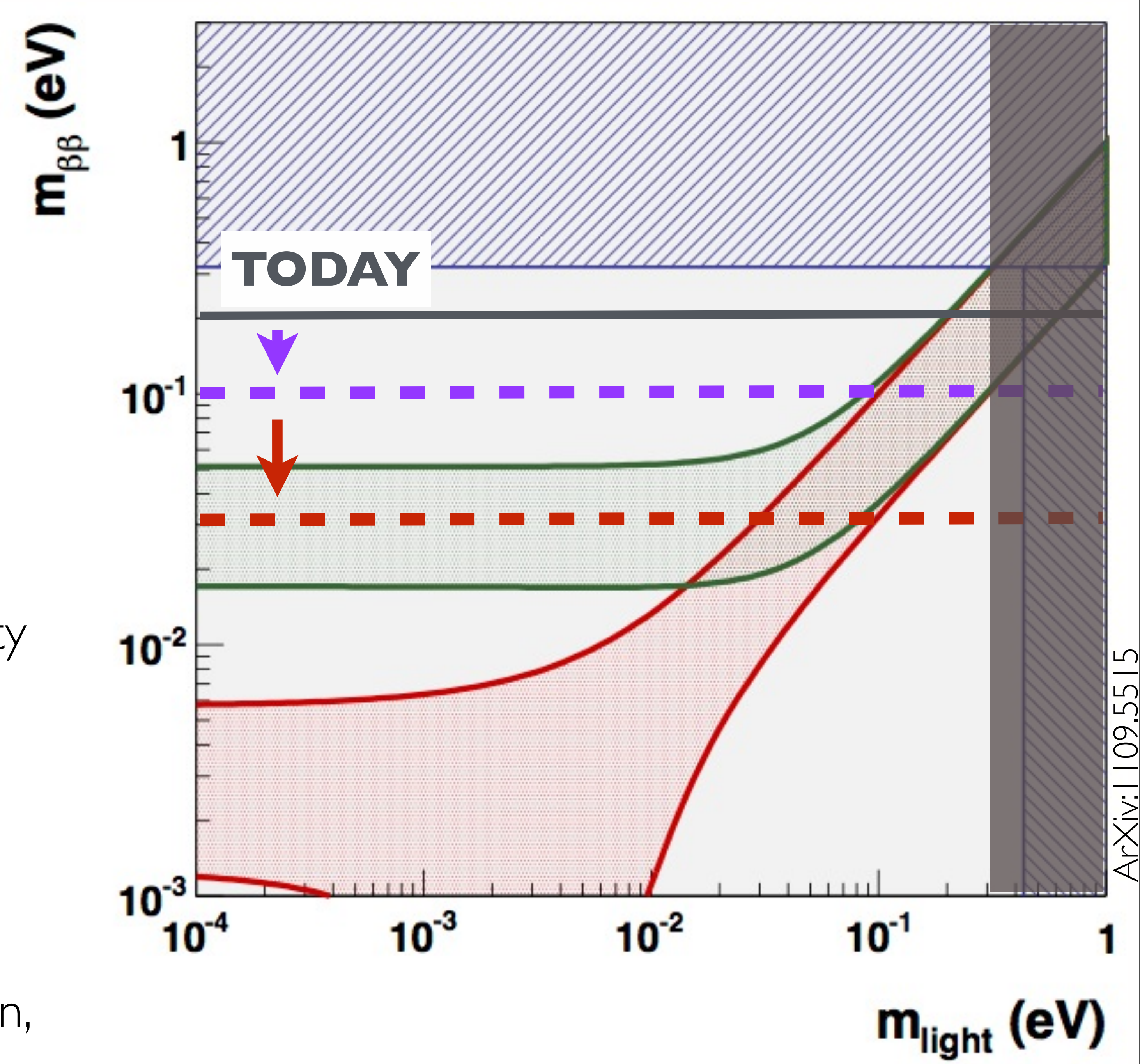
Future projects

5 years time scale:

- M ~ 10 - 50 kg of ββ isotope
- Background level 10^{-3} cts./(keV kg y)
- Explore quasi-degenerate region

10 years time scale:

- M ~ 100 kg - 1t of ββ isotope
- Background level 10^{-4} cts./(keV kg y)
- Approach Inverse Hierarchy region



- Multi-phase approach: demonstrate scalability to higher mass and background reduction

CUORE, Gerda, Majorana, Lucifer, AMORE, NEXT, COBRA, EXO, SNO+, KamLAND-Zen, Candels, **SuperNEMO**, MOON, DCBA, ...

NEMO3 and the tracko-calo technique

Running @ LSM 2003 - 2011

Detector ≠ ββ source

- **Multiple isotopes** at the same times
- 7 isotopes in NEMO-3

Full reconstruction of $2e^-$ kinematics → **unique!**

- Individual e- energy, arrival time, track curvature in magnetic field, emission vertex and tracks angle

Excellent background rejection

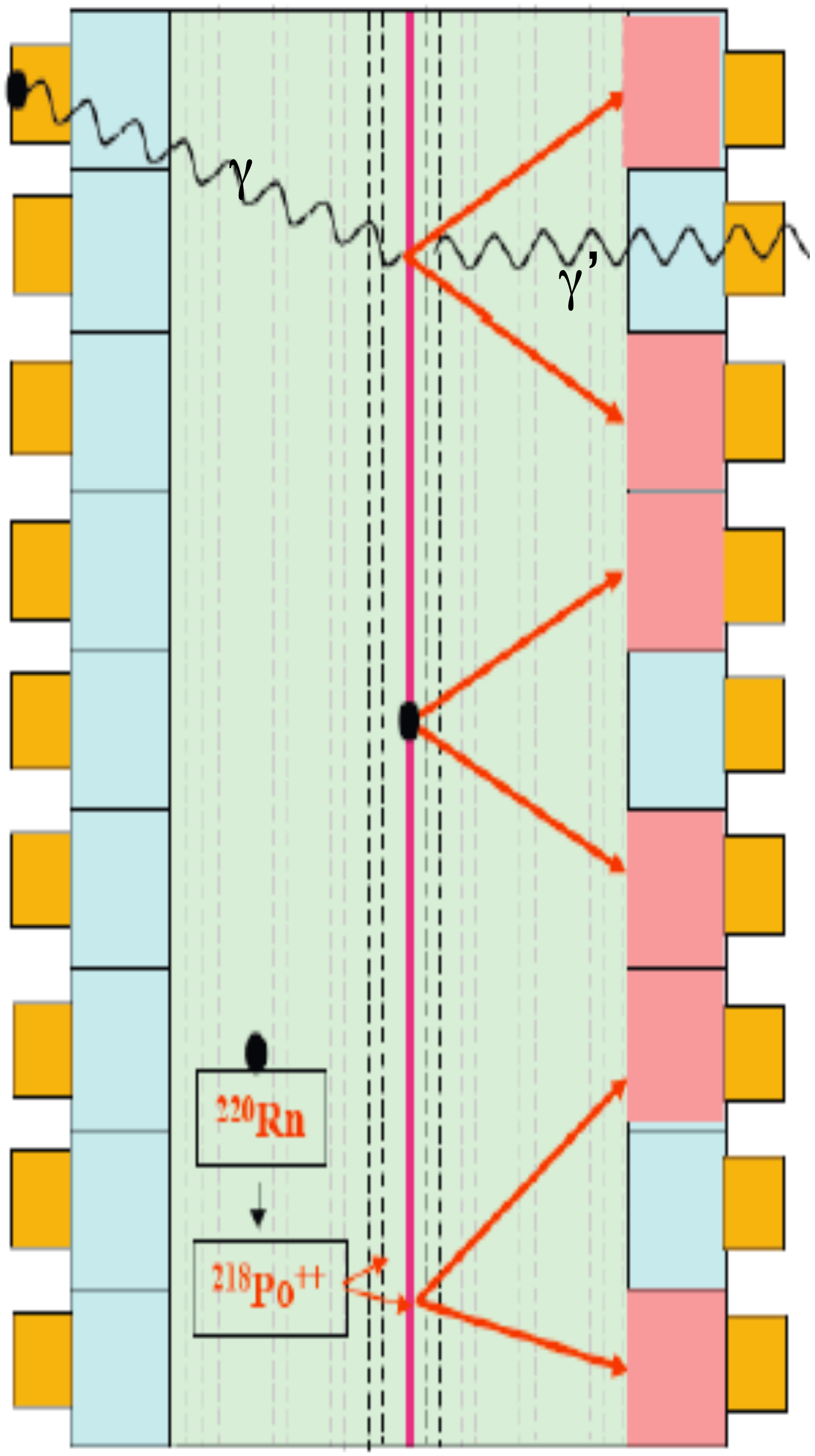
- Identification e^-, e^+, γ, α

Low energy resolution: [14 - 17] % / Sqrt(E)

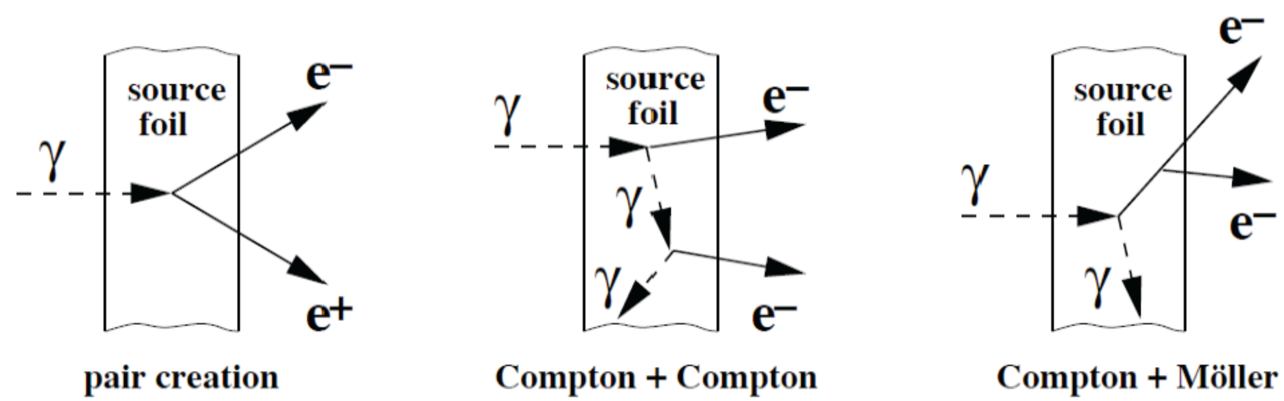
Equivalent to best calorimetric experiment

Discrimination of physics mechanism beyond ββ0ν!

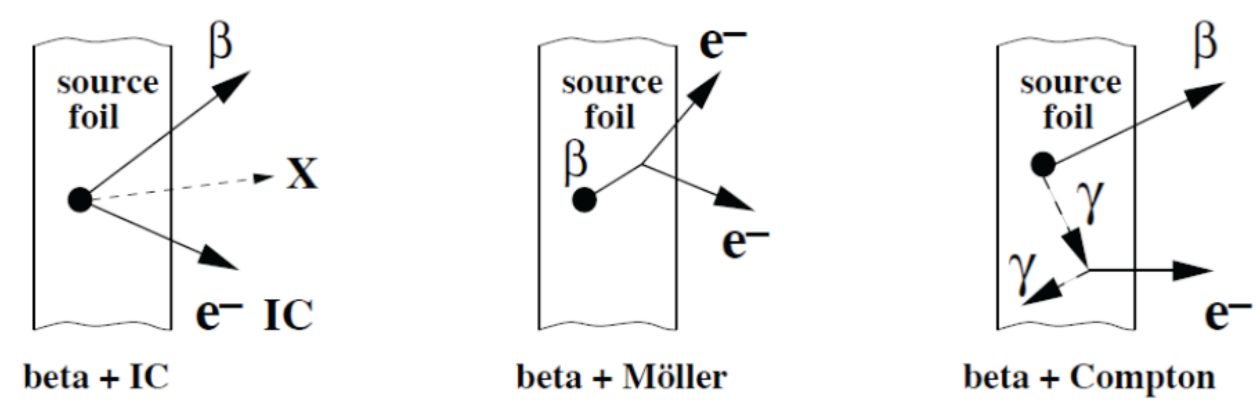
Backgrounds



External background: Radio-impurities in material, γ from (n,γ) and μ bremstrahlung



Internal background: ββ2ν tail, ^{214}Bi (from ^{238}U) and ^{208}Tl (from ^{232}Th) contamination in foil source



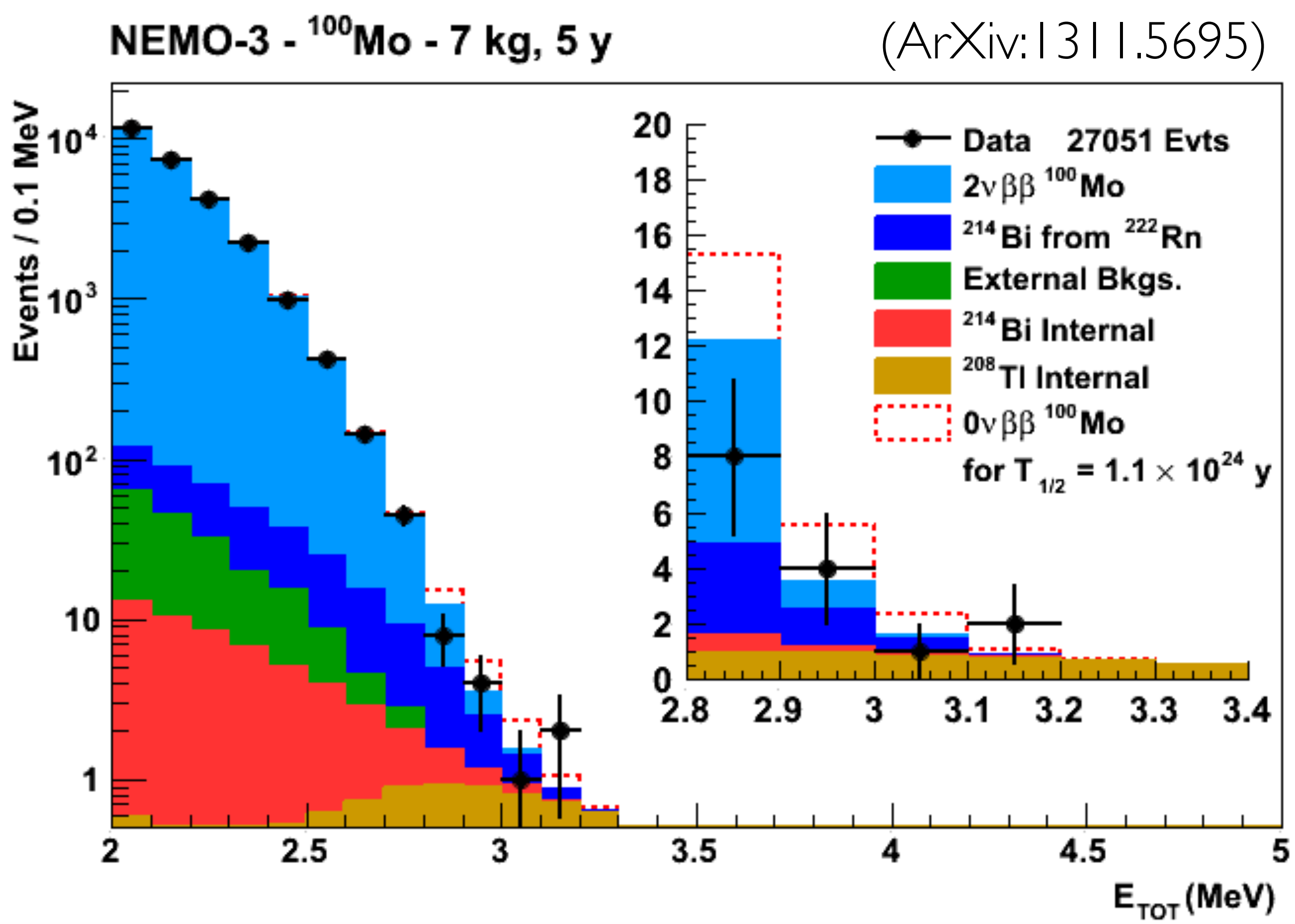
Radon background: ^{214}Bi from Rn decay in tracker volume

Direct measurement of background in different channel combining calo + tracker infos

Latest NEMO-3 results

- Full ^{100}Mo exposure 7 kg, 5 y
- $T^{0\nu}_{1/2} > 1.1\ 10^{24}$ y @ 90% C.L.
- Background level ~ 0.02 cts. / (keV kg y) @ $Q_{\beta\beta}$
- No background event > 3.2 MeV

(ArXiv:1311.5695)



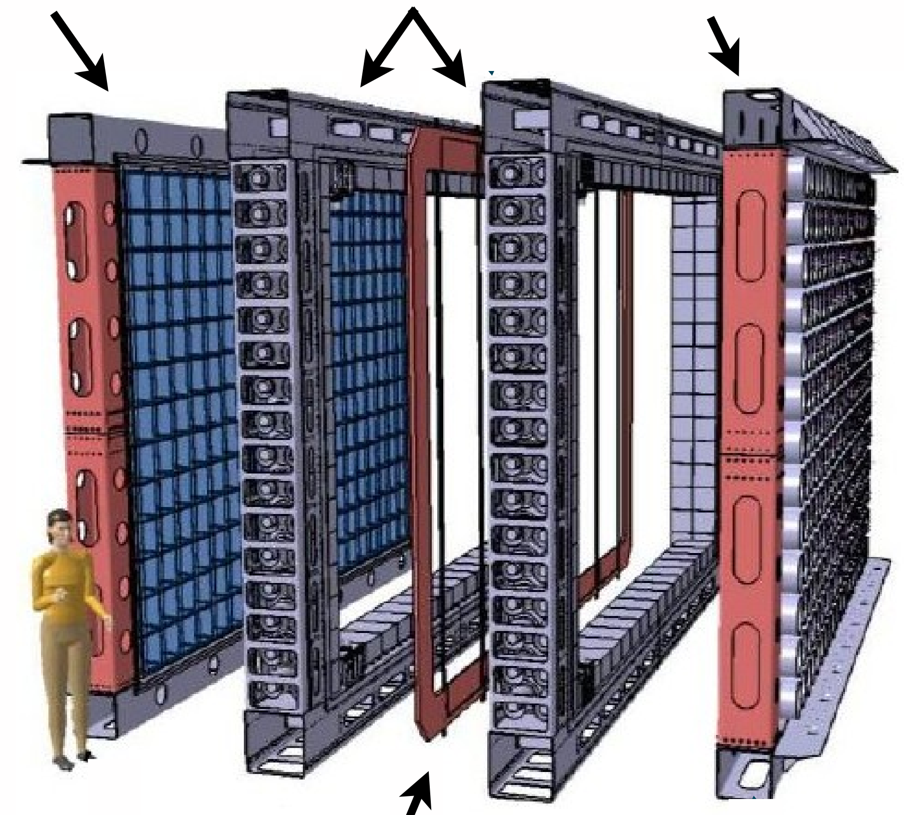
Potential background free technique for high energy $Q_{\beta\beta}$ isotopes (^{48}Ca, ^{150}Nd, ^{96}Zr)

The next step: SuperNEMO

Extrapolate a well known technique:

- 100 kg of **ββ** emitter in 20 detection module
- Approach IH region

	NEMO-3	SuperNEMO
Efficiency	18%	~30%
Isotope	7 kg ^{100}Mo	~100 kg ^{82}Se (^{150}Nd, ^{48}Ca)
Exposure	35 kg y	~500 kg y
Energy res.	8% @ 3 MeV	4% @ 3 MeV
^{208}Tl (source)	~100 μBq/kg	< 2 μBq/kg
^{214}Bi (source)	~ 300 μBq/kg	< 10 μBq/kg
Rn (in tracker)	5 mBq/m^3	0.15 mBq/m^3
$T_{1/2}$	10^{24} y	10^{26} y
$\langle m_{ee} \rangle$	0.31 - 0.79 eV	0.04 - 0.1 eV



- A **challenge** under **many** aspects
- Extended R&D program in the past years
  - Almost completed!
- Next step → **Demonstrator module**

The demonstrator module

One SuperNEMO module → **7 kg ^{82}Se running ~2.5 y**

- To be installed @ LSM (replacing NEMO-3)

Match SuperNEMO requirements

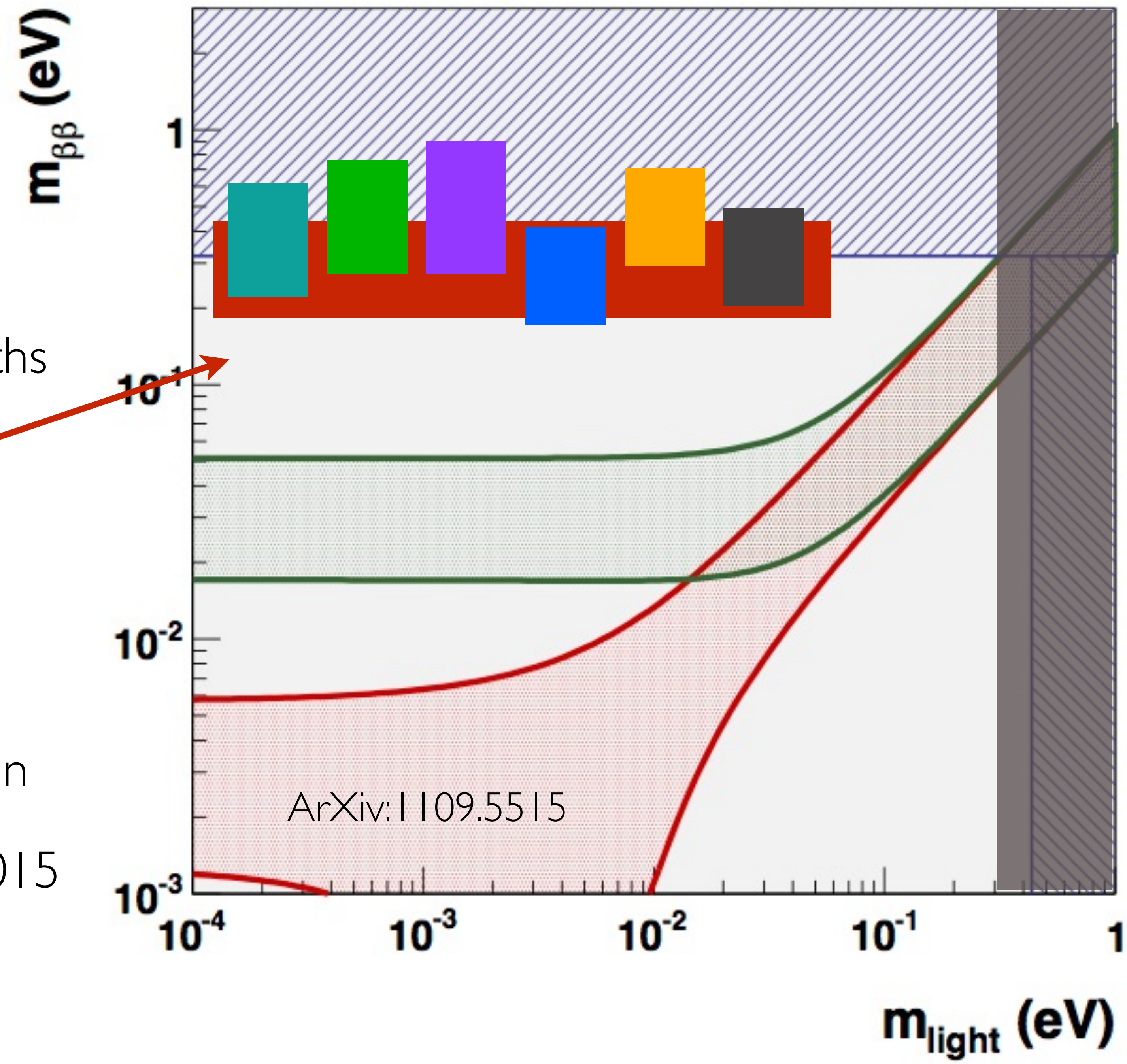
- Background level ~ 10^{-4} cts./(keV kg y)
- Background free at high energy (^{150}Nd)

Reach NEMO-3 (^{100}Mo) sensitivity in 4.5 months

- Sensitivity: $\langle m_{ee} \rangle$ ~ **0.20 - 0.40 eV**
- Test HdM claim with ^{82}Se

Schedule:

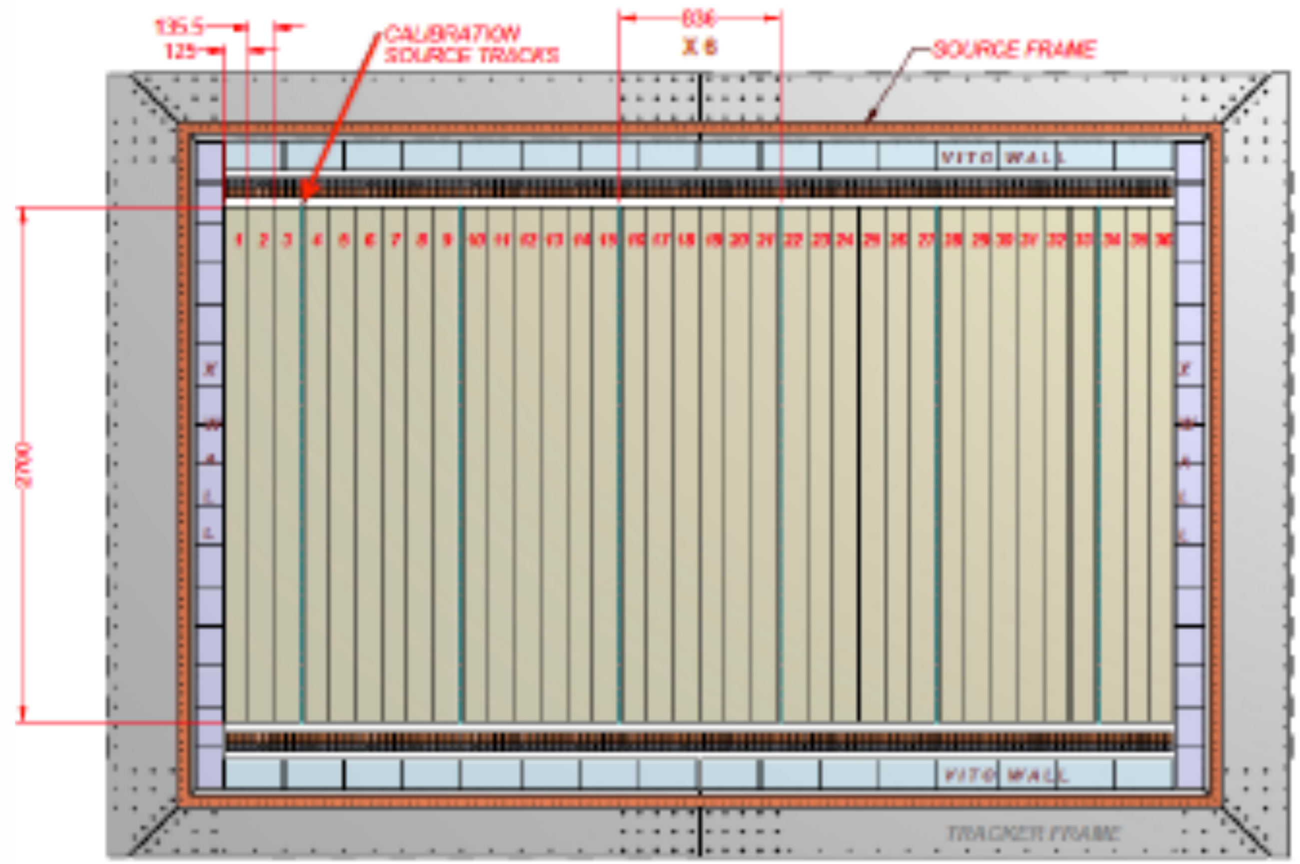
- Calorimeter and tracker under production
- Installation & commissioning beginning 2015
- First **physics data in 2015!**

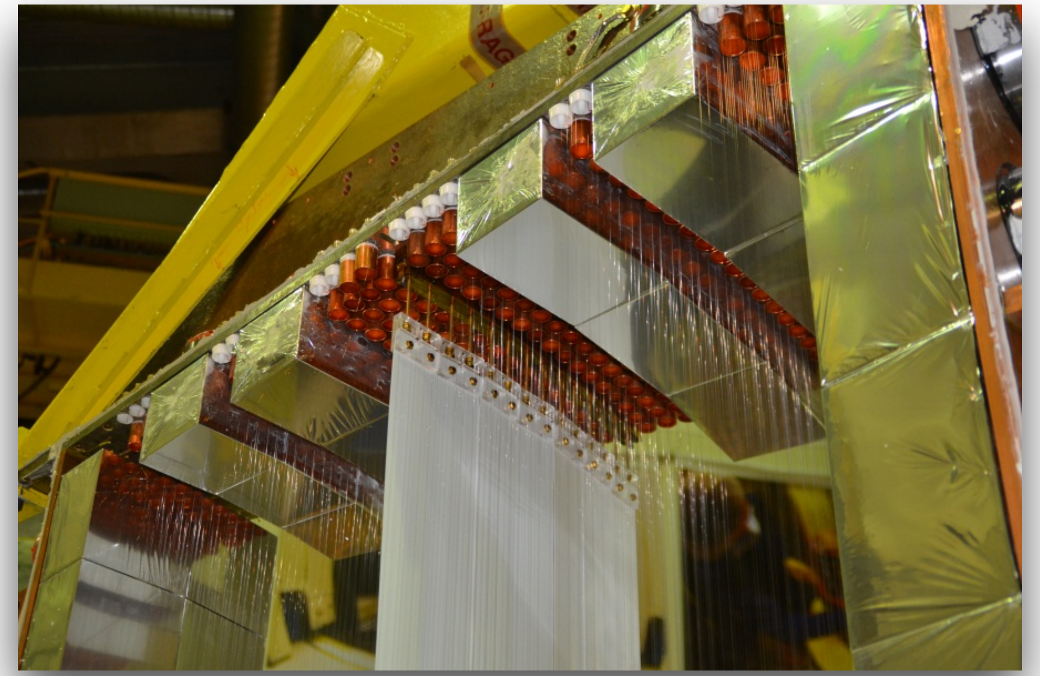


Developing the foil source @ LAPP

- 36 strips 3 m long, ~200 um thick (50 mg/cm^2)
- Strong material radio-purity constrain:

^{208}Tl	< 2 μBq/kg
^{214}Bi	< 10 μBq/kg



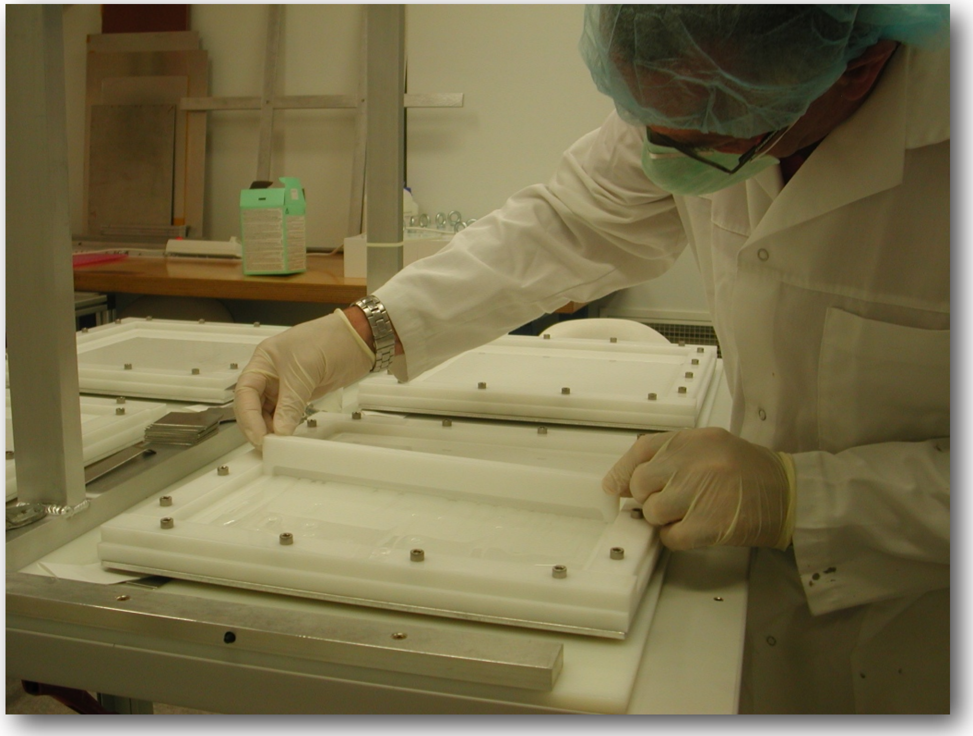


Similar to NEMO-3:

- Enriched Se powder: > 99 % ^{82}Se
- PVA glue: 5 % - 10 % of Se mass
- **Mechanical support…**
  - Three solutions under consideration

LAPP recently join the collaboration and start R&D activity on the foil source (March 2013)

Developing the foil source @ LAPP



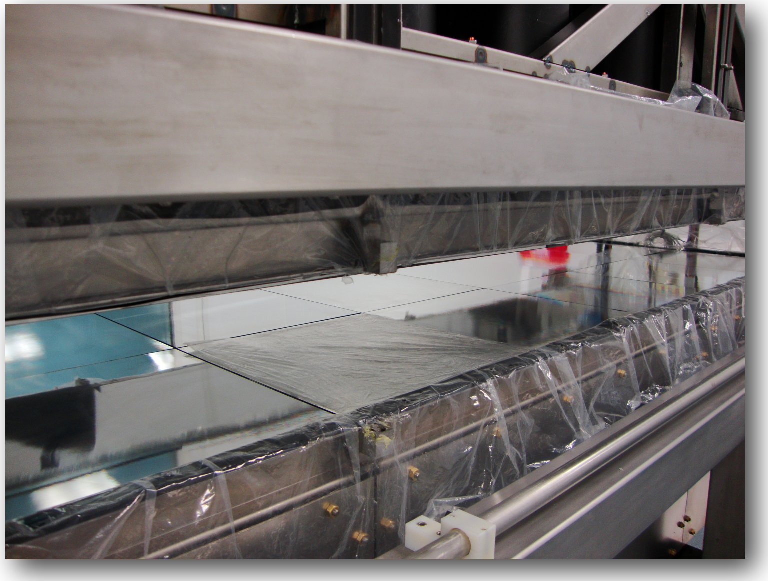
R&D with PVA glue (July - September 2013)

- Defining and training thin foil production technique

Radio-purity measurement

- HGe (LSM): ~1.5 kg PVA powder
- BiPo (LSC): 20 thin foil → 30x30 cm 200 μm thick

	M [g]	T [d]	A(^{208}Tl) [μBq/kg]	A(^{214}Bi) [μBq/kg]
Ge	1485	26	< 120	<350
BiPo	210	71	< 32	no yet
Limit	5 (10) % M_{Se}	—	40 (20)	200 (100)

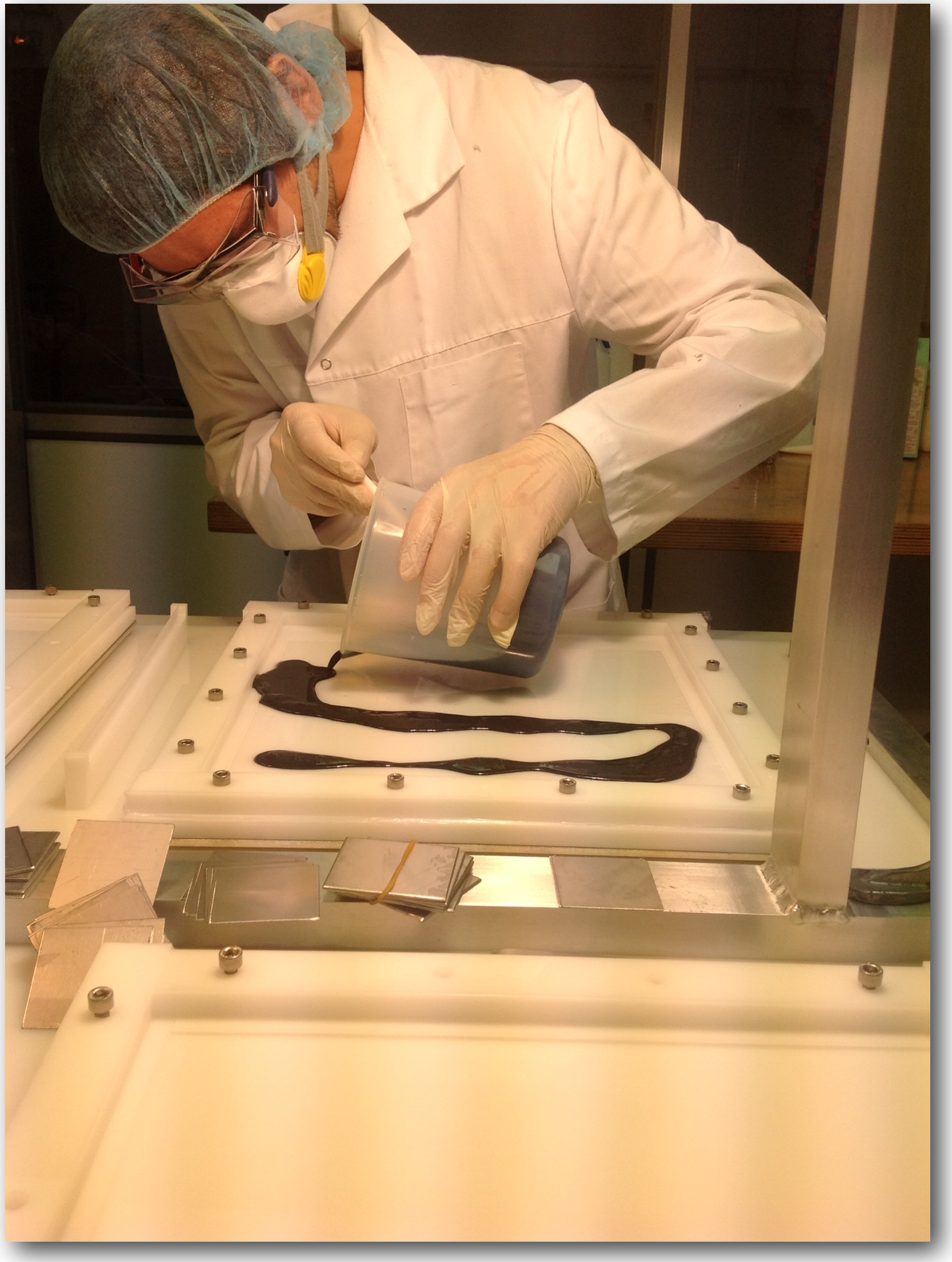


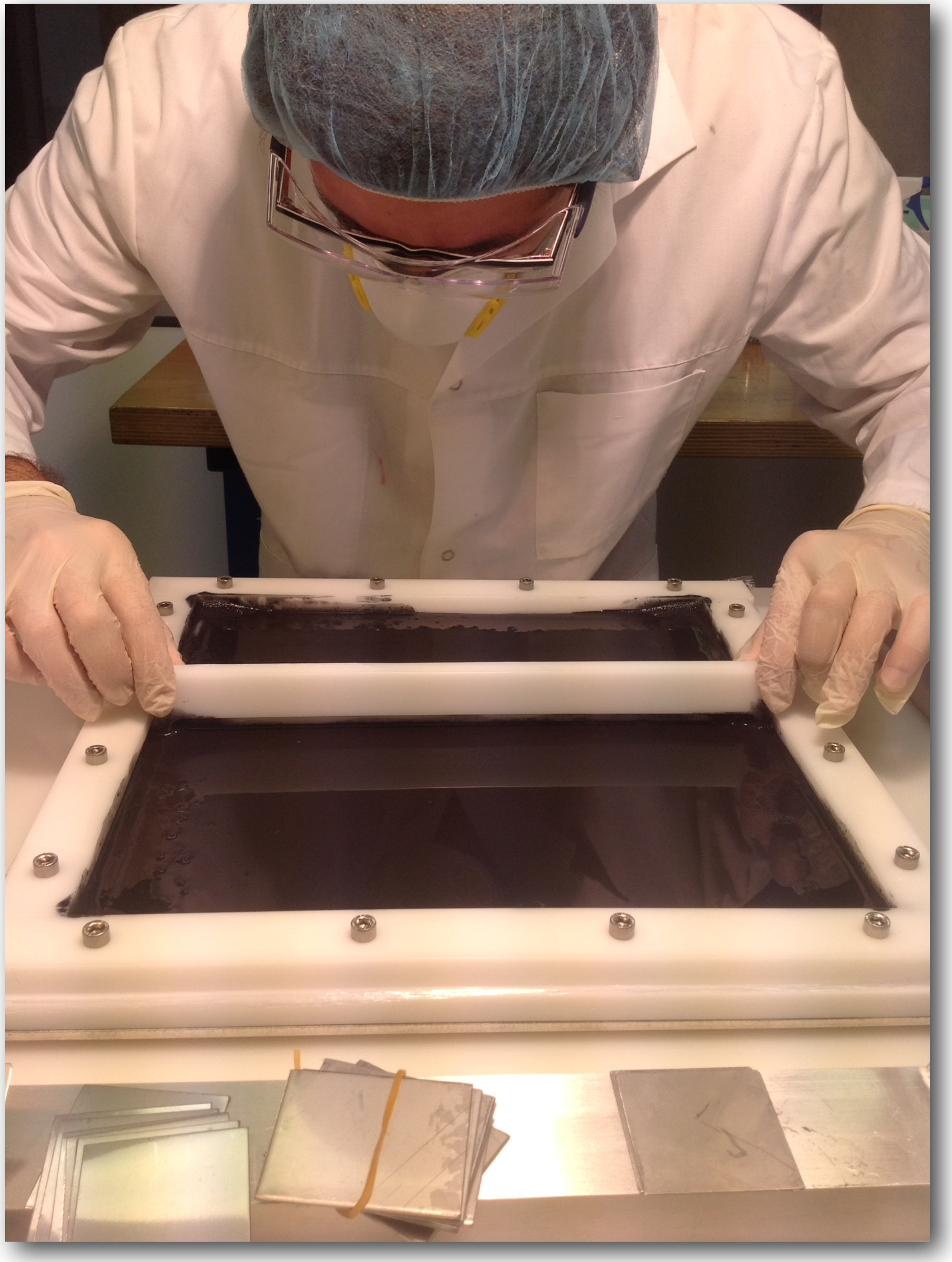
PVA radio-purity is good enough!

Developing the foil source @ LAPP

R&D with Se powder (October 2013)

Defining working procedure with Se, approach main problematics

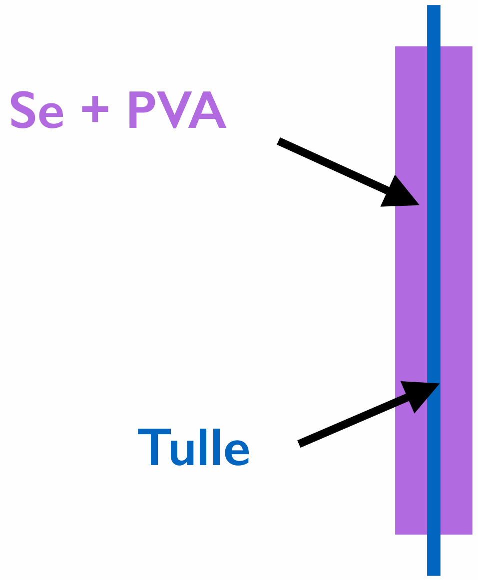


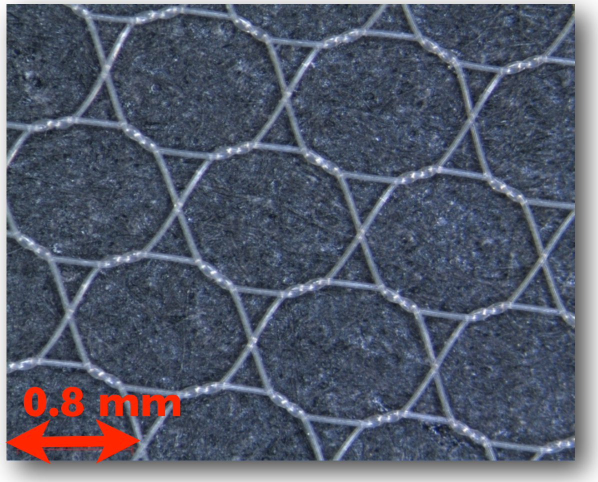


Developing the foil source @ LAPP

R&D for mechanical support (November 2013 - January 2014)

- Fine mesh fabric (Tulle) as central backbone
- New idea proposed by LAPP:
  - Flexible and resistant foil
  - Small support mass ~ 1 % of Se mass
  - High level of radio-purity is expected
- Preparing samples for radio-purity measurement

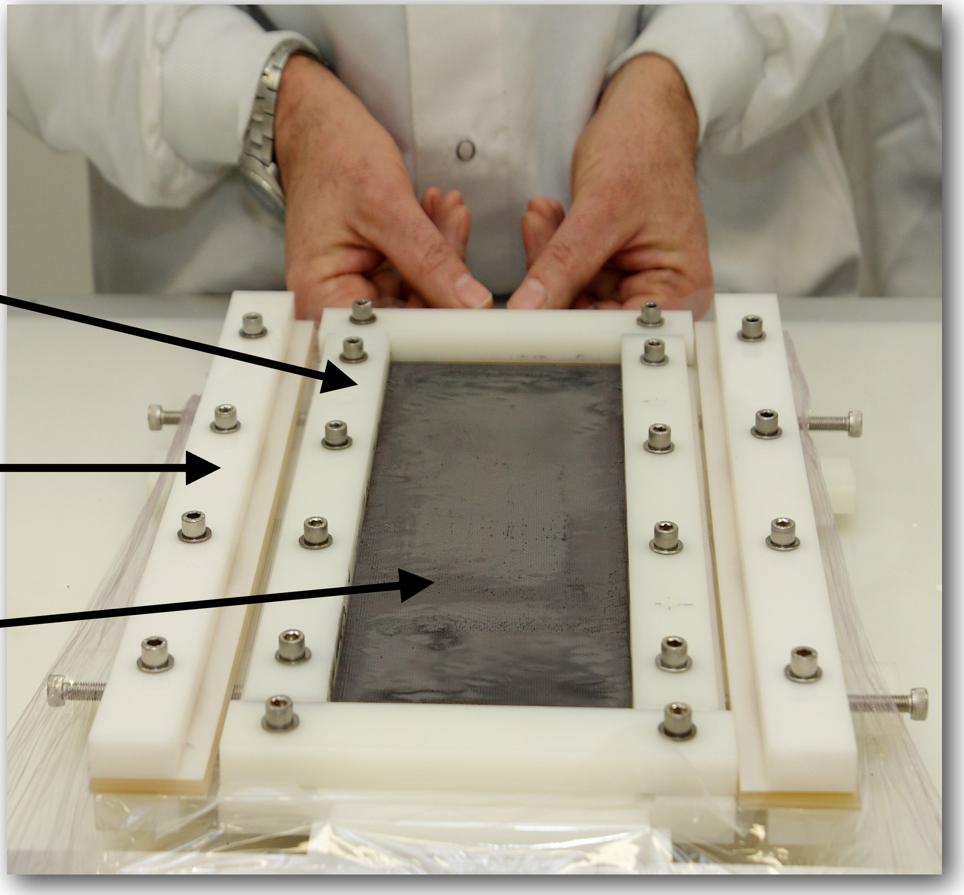




Derlin support

Tulle tensioning bars

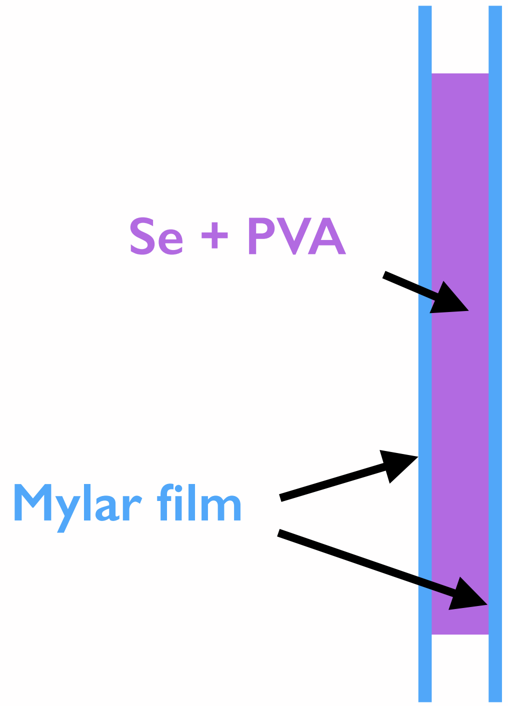
Se + Tulle foil
(30 cm x 12 cm)

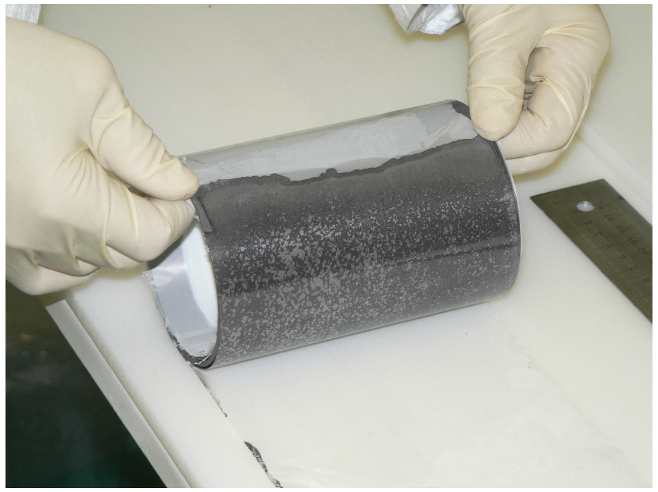


Alternative solution under consideration

Mylar backing film

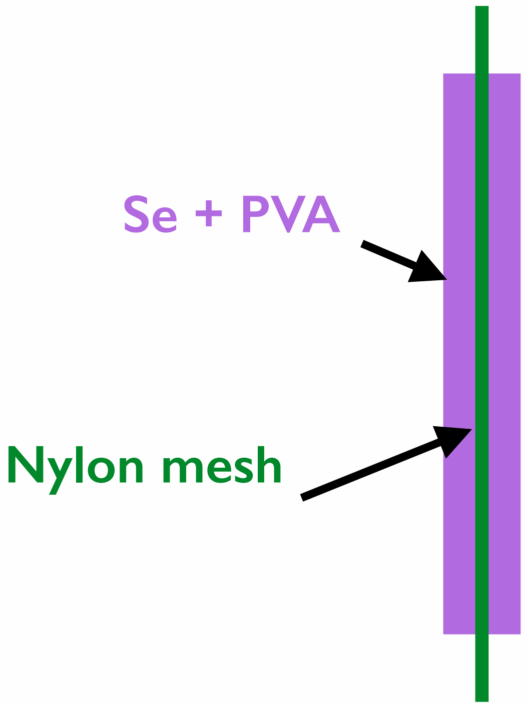
- Solution adopted in NEMO-3
- Resistant and flexible foil
- Higher support mass ~ 10 % of Se mass
- Issue with radio-purity [A(^{208}Tl) ~7 µBq/kg]

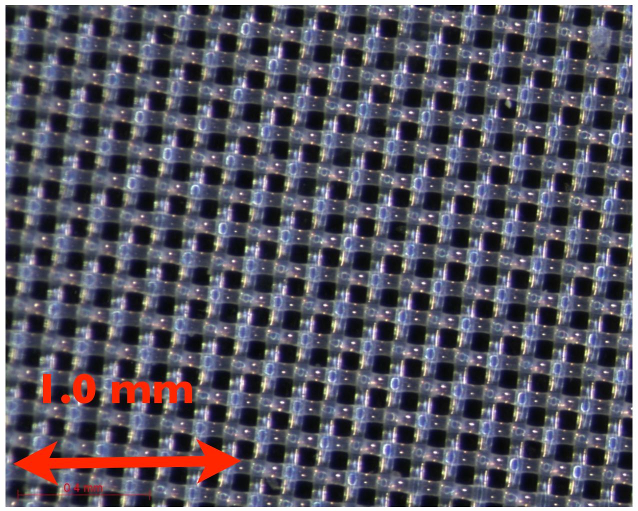




Nylon mesh

- Used for screen printing and liquid filtering
- Similar to Tulle but more dense
- Higher support mass ~ 50 % of Se mass
- Preparing for radio-purity measurement

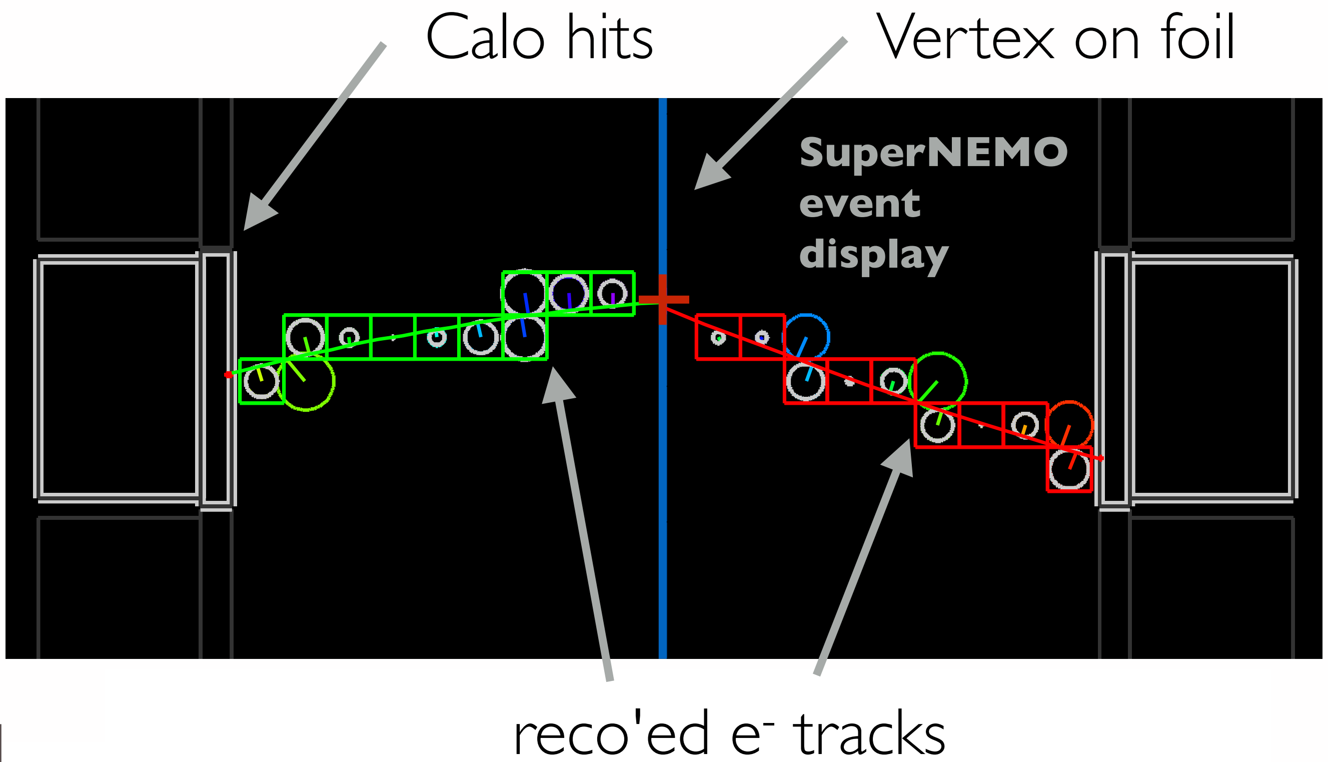


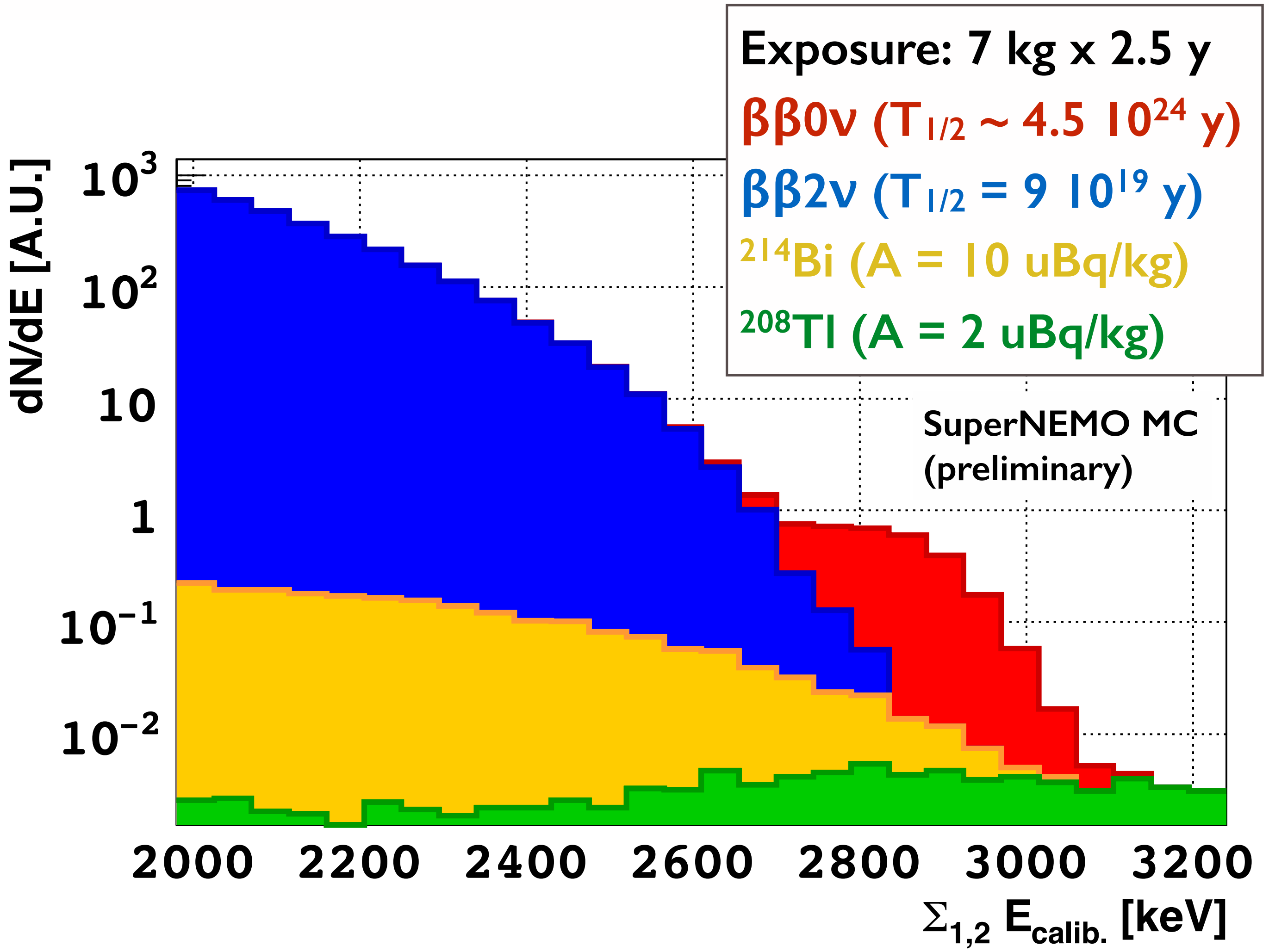


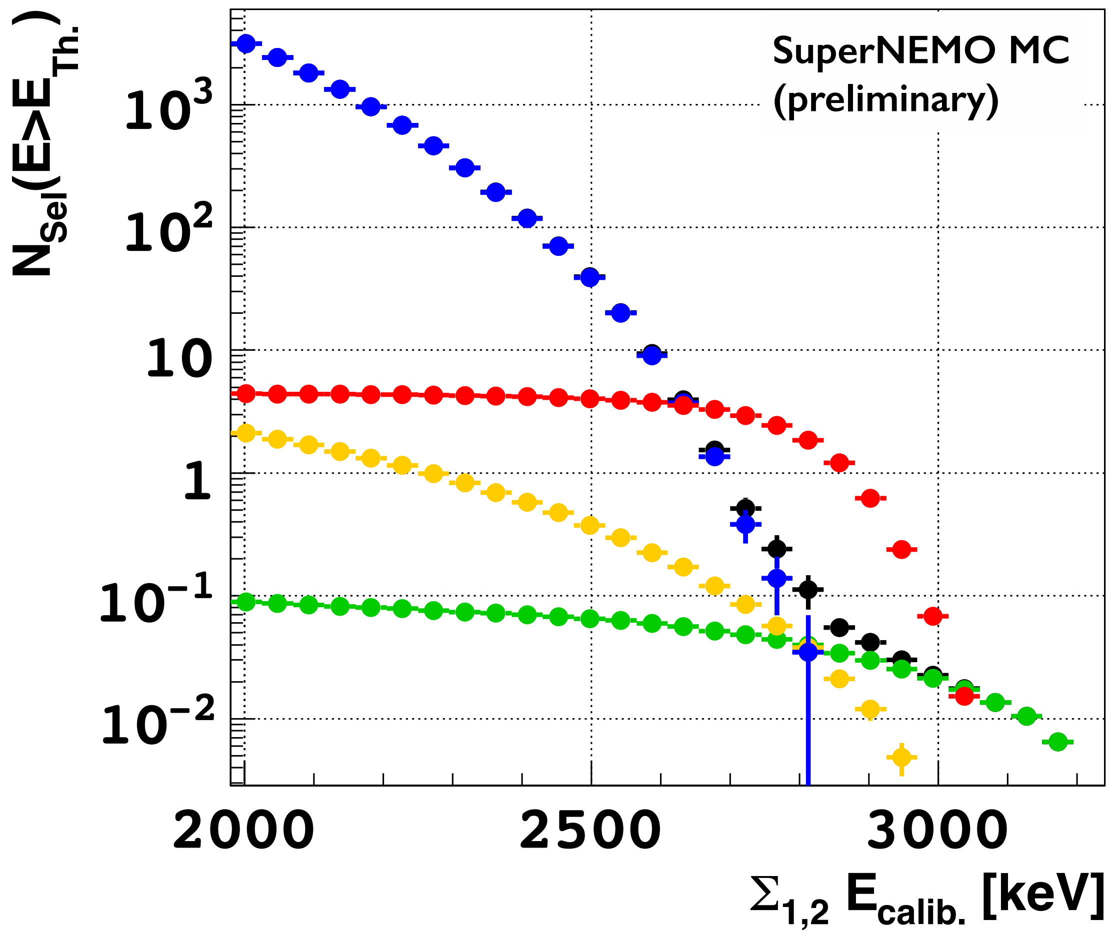
Final decision will depend from radio-purity, feasibility and performances

ββ0ν Sensitivity study

- Study **ββ0ν** sensitivity w.r.t. foil design
- Check the foil design doesn't alter physics performance and results
- Generating signal and background
- Simple event selection: 2 calo hit associated to 2 negative tracks + Vertex on foil



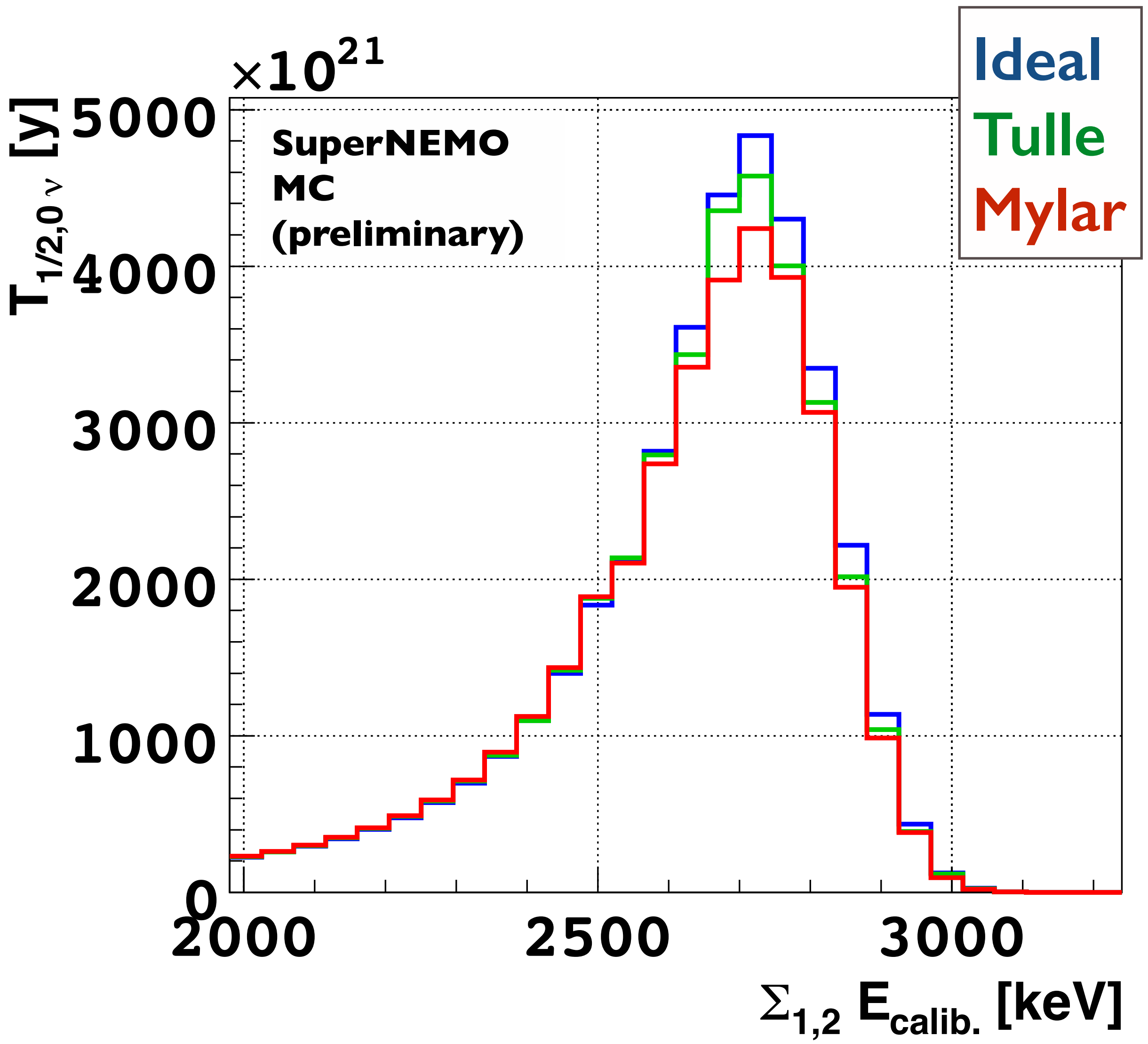




ββ0ν Sensitivity study

In hypothesis there is no signal, which the best limit on **ββ0ν** half-life?

$$T_{1/2}^{0\nu} > \frac{\log 2 N_A}{W} \times \epsilon^{0\nu} \frac{M \times T}{N_{\mathrm{EXC.}}}$$



- Consider 0**ν** and 2**ν** only for the moment
- Study performed as function of E_{cut}

	$T_{1/2}$ [10^{24} y]
Ideal	4.83 (1)
Tulle	4.68 (0.969)
Mylar	4.57 (0.946)

There is a slight preference for the **"tulle"** design…

What next?

Foil R&D @ LAPP:

- Measure radio-purity of tulle → Is it good enough?
- Finalise production protocols → start testing on final dimensions (3 m)
- Test radio-purity on final foil design in BiPo (natural & enriched Se)

Foil design optimisation studies:

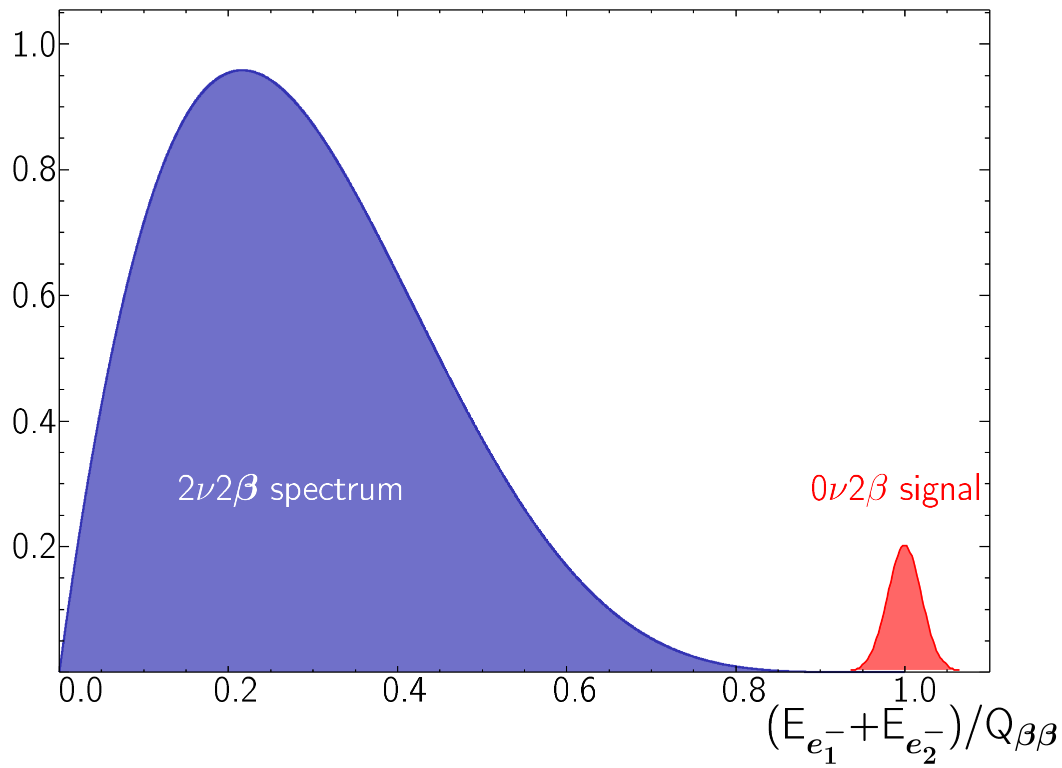
- Account for internal backgrounds and material radio-purity level
- Setup a complete sensitivity study → Master 2 project from March
- Provide the best foil design choice w.r.t. detector performance

Prospectives

- Wide interest on $0\nu\beta\beta$ searches → answer a fundamental question
- SuperNEMO aims to IH region with a Tracko-Calo detector → Unique!
- The Demonstrator module is the first step → Match SuperNEMO requirements
- Sensitivity of ~ 0.20 - 0.40 eV in 2 years
- Tracker & Calorimeter under production
- **Installation & commissioning in early 2015**
- **Data analysis shortly after → Results in 2017**

Backup slides

Searching for 0νββ process



Measure the 2 e⁻ energy spectrum

- 2νββ signature → Broad spectrum
- 0νββ signal signature → **Peak** @ $Q_{\beta\beta}$

If no signal → set a **limit** on half life

$$T_{1/2}^{0\nu} > \frac{N_A \ln 2}{n_\sigma} \times \frac{\epsilon}{A} \times \sqrt{\frac{M \times t}{B \times \Delta E}}$$

Detection efficiency

ββ emitter mass

Exposure time

Excluded events at a given C.L.

Atomic mass

Bkg. index

E res. @ $Q_{\beta\beta}$

Choosing the ββ isotopes

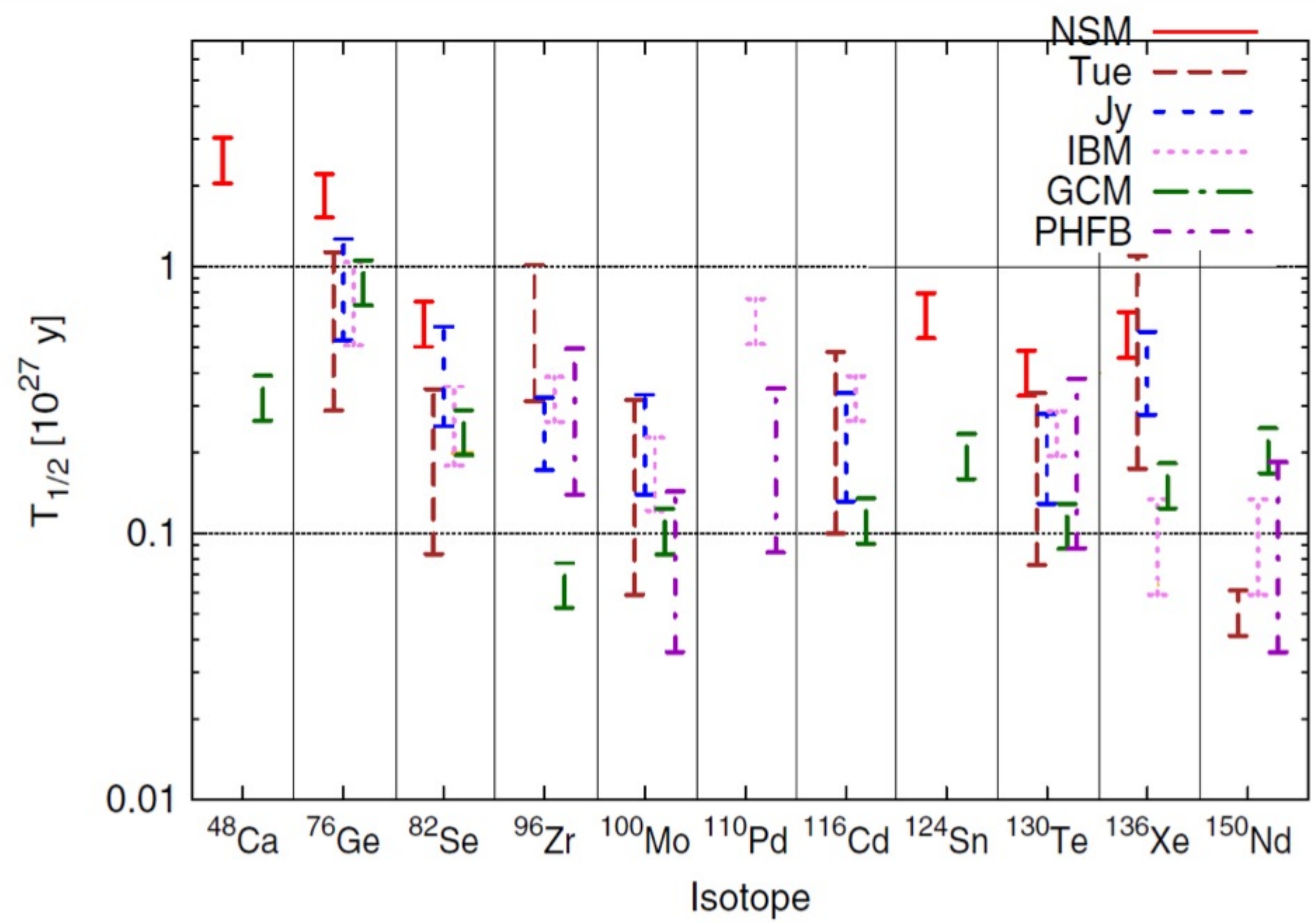
Isotopes enrichment and $T^{2\nu}_{1/2}$ from respective experiment

Isotope	**$Q_{\beta\beta}$ [keV]**	**Nat. abund. (enrich.) [%]**	**$G_{0\nu}$ [10^{-14} y^{-1}]$^{(*)}$**	**$T^{2\nu}_{1/2}$ [10^{19} y]**	**Experiment**
^{48}Ca	4270	0.187 (73)	6	$4.2^{+2.1}_{-1.0}$	NEMO3
^{76}Ge	2039	7.8 (86)	1	150±10	HM
^{82}Se	2995	8.7 (97)	3	9.0±0.7	NEMO3
^{96}Zr	3350	2.8 (57)	6	2.0±0.3	NEMO3
^{100}Mo	3034	9.6 (99)	4	0.71±0.04	NEMO3
^{116}Cd	2802	7.5 (93)	5	3.0±0.2	NEMO3
^{130}Te	2527	34.5 (90)	4	70±10	NEMO3
^{136}Xe	2480	8.9 (80)	4	238±14	KamlandZEN
^{150}Nd	3367	5.6 (91)	19	0.78±0.7	NEMO3

Nuclear Matrix Element

Contain nuclear structure effects → only **approximative** theoretical calculation

Required $T^{0\nu}_{1/2}$ sensibility for $\langle m_{ee} \rangle \sim 0.05$ eV (IH)

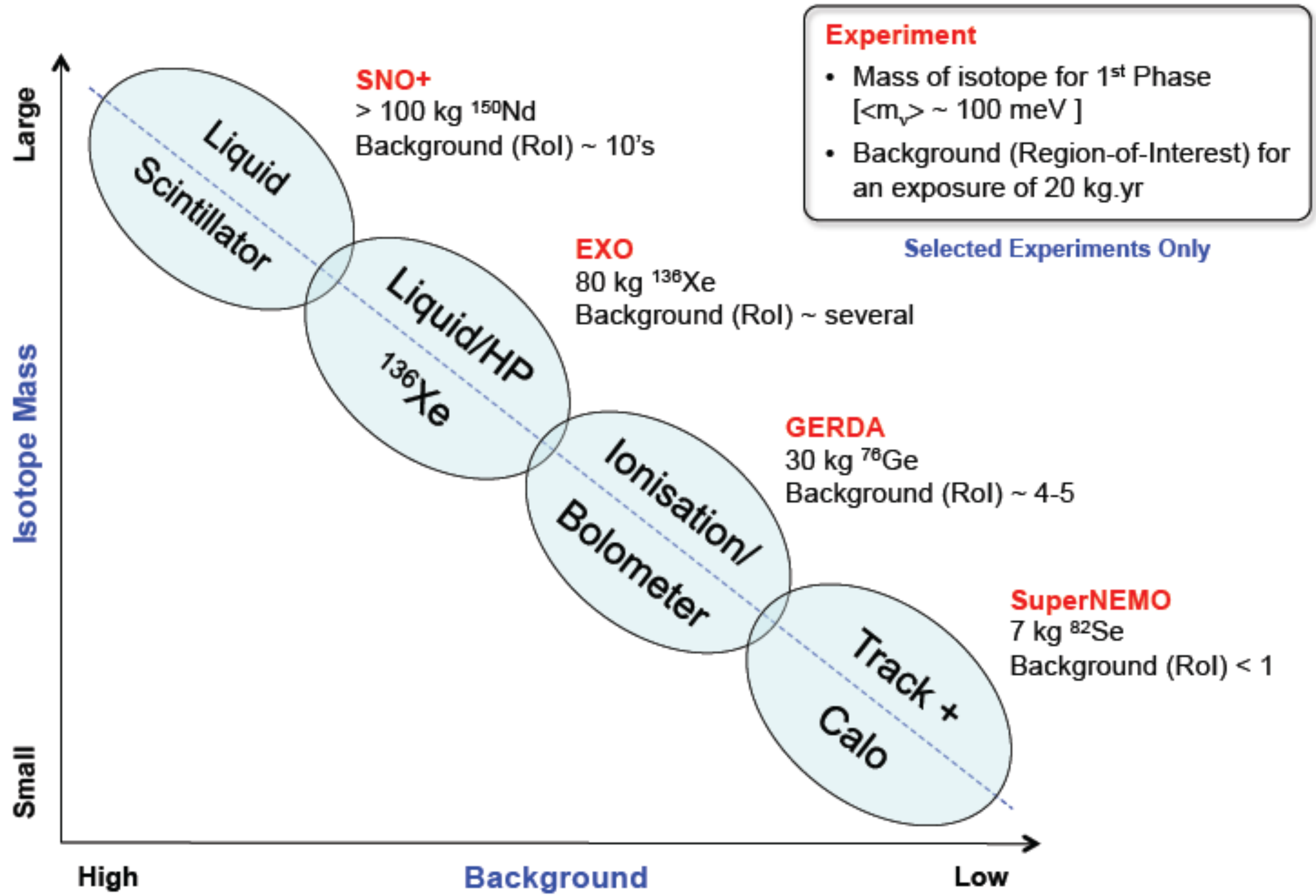


PRD 83, 113010 (2011)

- Many approximation methods
- Variation up to factor ~10
- Different among isotopes
- Up to factor 10 on required mass! (^{150}Nd, ^{100}Mo w.r.t. ^{76}Ge)

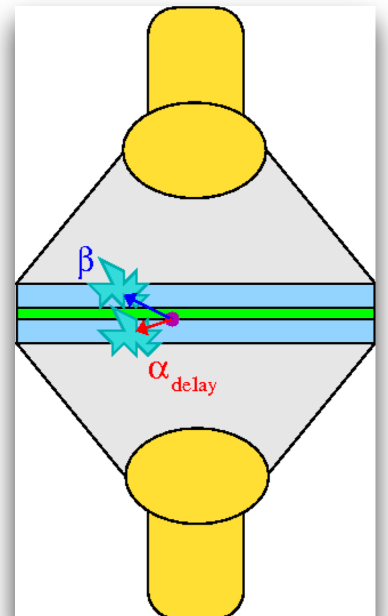
Main **limitation** in interpreting result & comparing among different isotopes

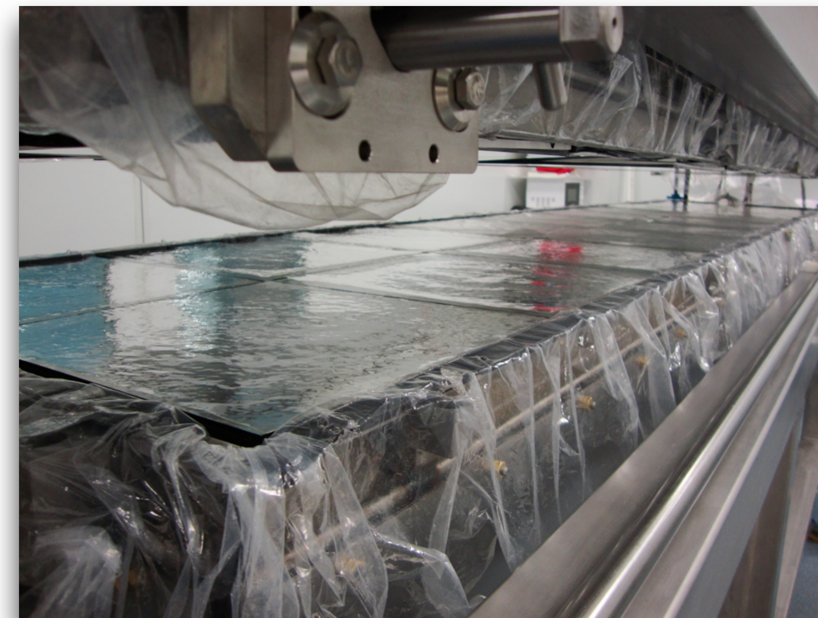
Comparison of Current Techniques



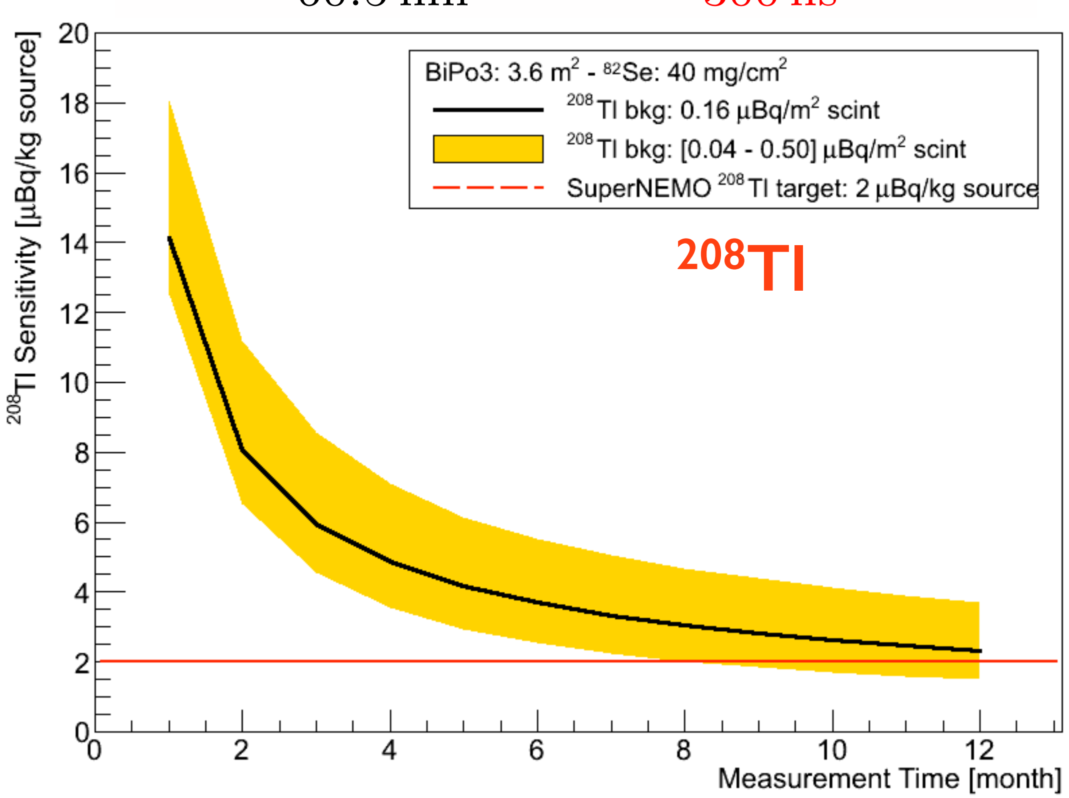
Radio-purity measurement with BiPo

- HGe sensitivity is not enough for SuperNEMO
  - ~ 1 mBq/kg in 1 month measurement
- Dedicated detector measuring the Bi-Po chain
  - Up and running since July 2012 in Canfranc
  - ~ 10 uBq/kg in 2 months measurement (^{208}Tl)

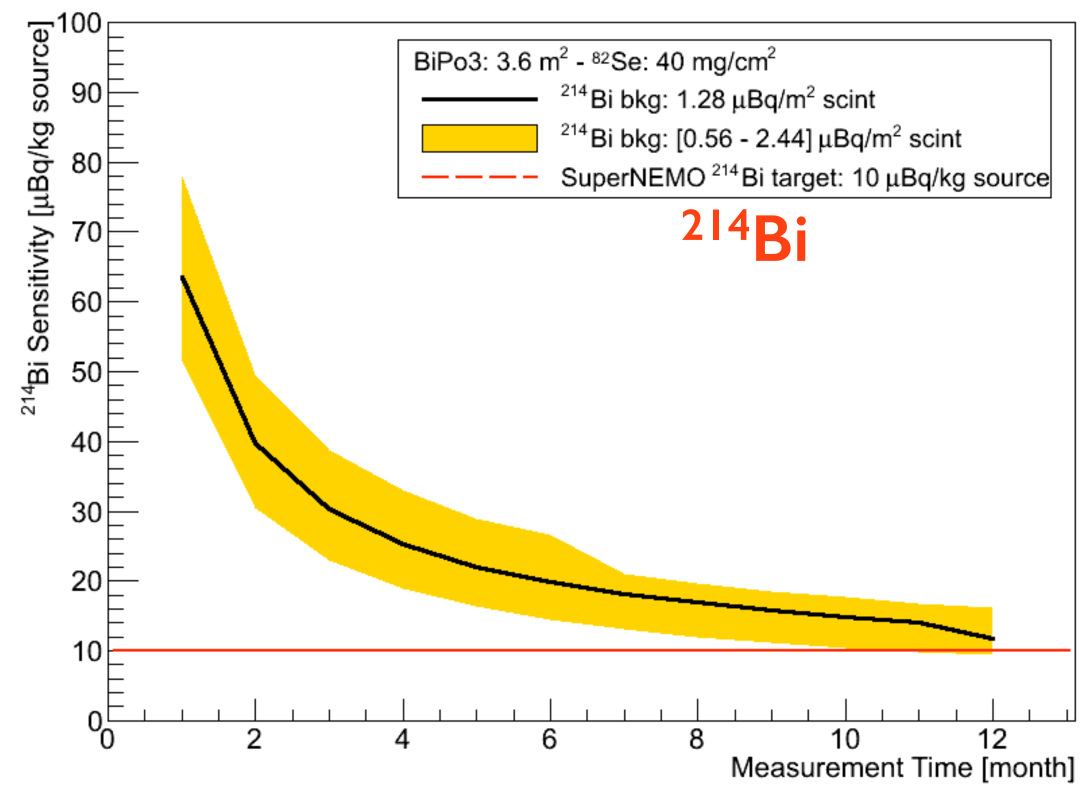




$$^{212}\mathrm{Bi} \xrightarrow[60.5\,\mathrm{mn}]{\beta} {}^{212}\mathrm{Po} \xrightarrow[300\,\mathrm{ns}]{\alpha} {}^{208}\mathrm{Pb}$$



$$^{214}\mathrm{Bi} \xrightarrow[19.9\,\mathrm{mn}]{\beta} {}^{214}\mathrm{Po} \xrightarrow[164\,\mu\mathrm{s}]{\alpha} {}^{210}\mathrm{Pb}$$



SuperNEMO demonstrator: status

Most R&D completed

Radio purity measurements of materials ongoing

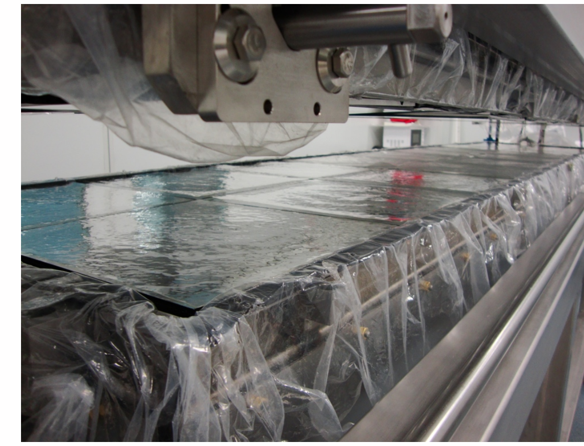
- HPGe, Radon emanation chamber, BiPo

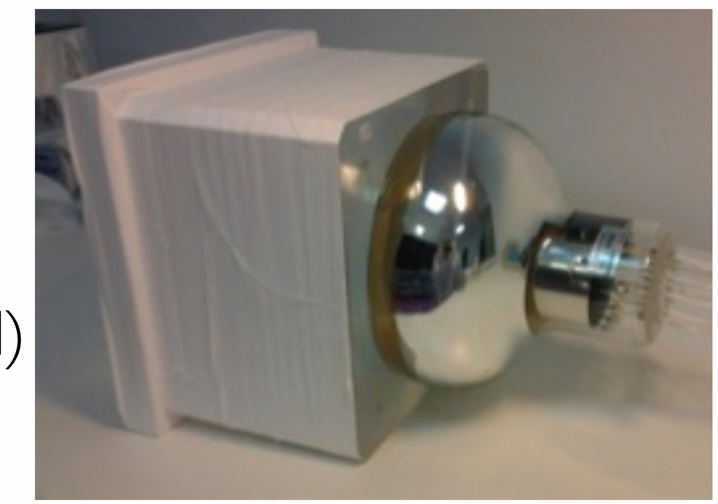
Calorimeter: main wall under construction

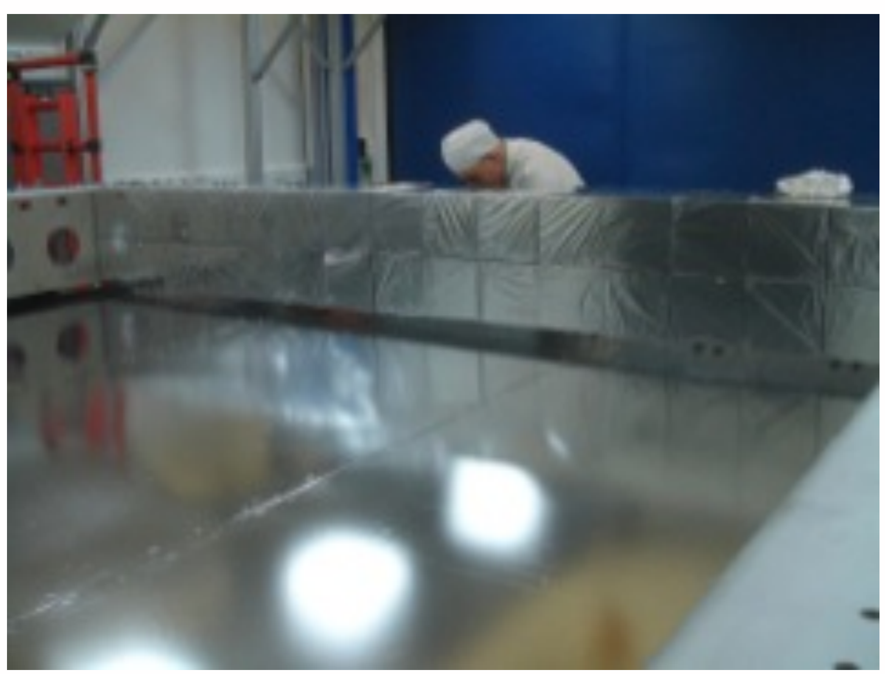
- Scintillator block under production
- 8'' Hamamatsu PMT by February 2014
- Electronic (FE digitiser & trigger board) under production

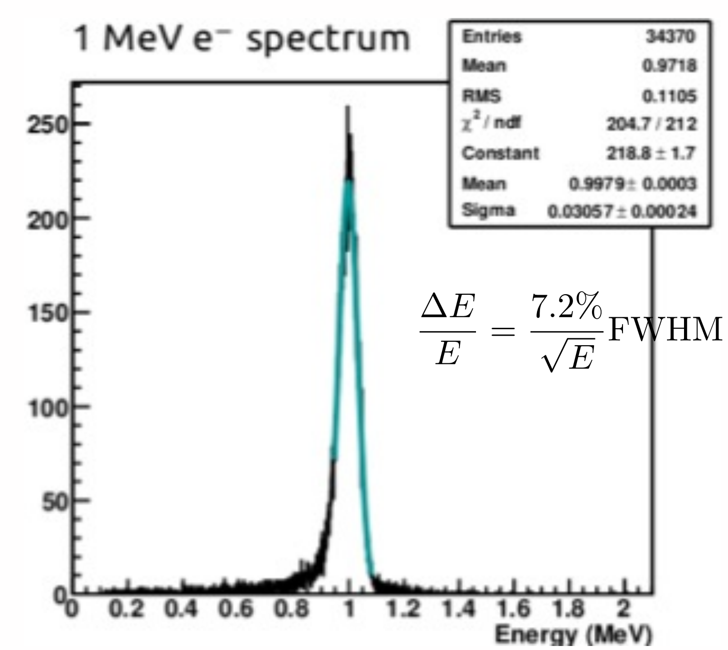
Tracker: Under construction.

- Commissioning begin 2014 (surface), end 2014 (underground)

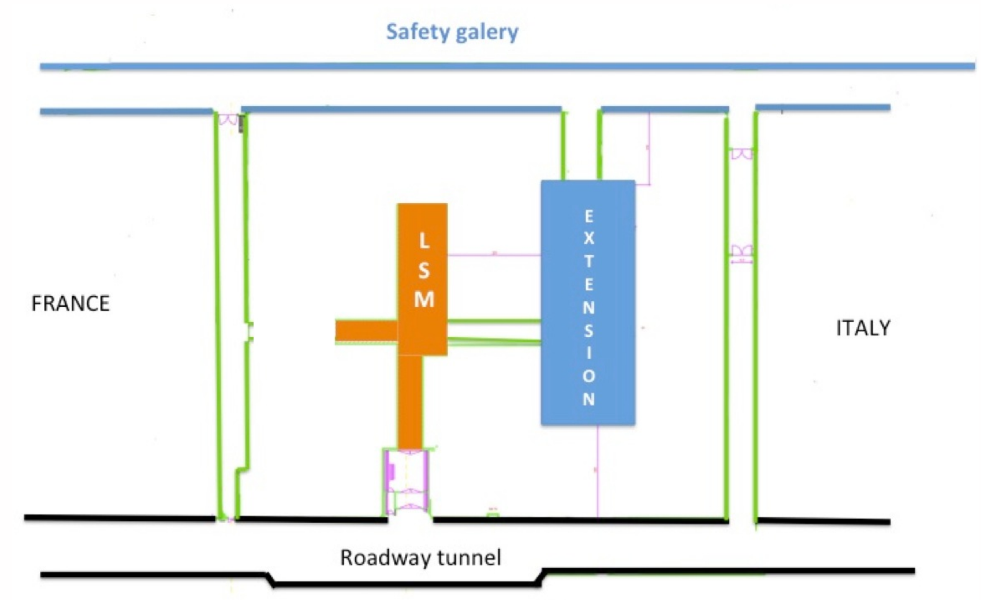






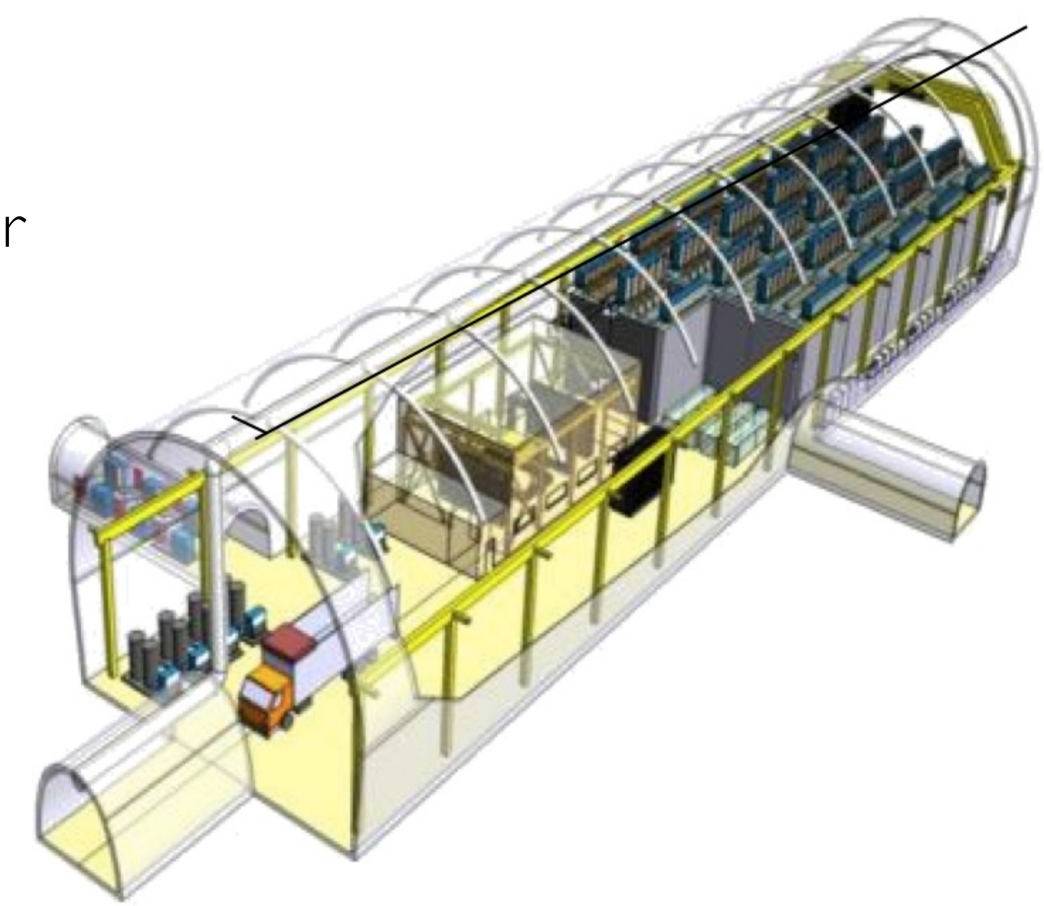


LSM Extension: DOMUS



From F. Piquemal (TAUP2013)

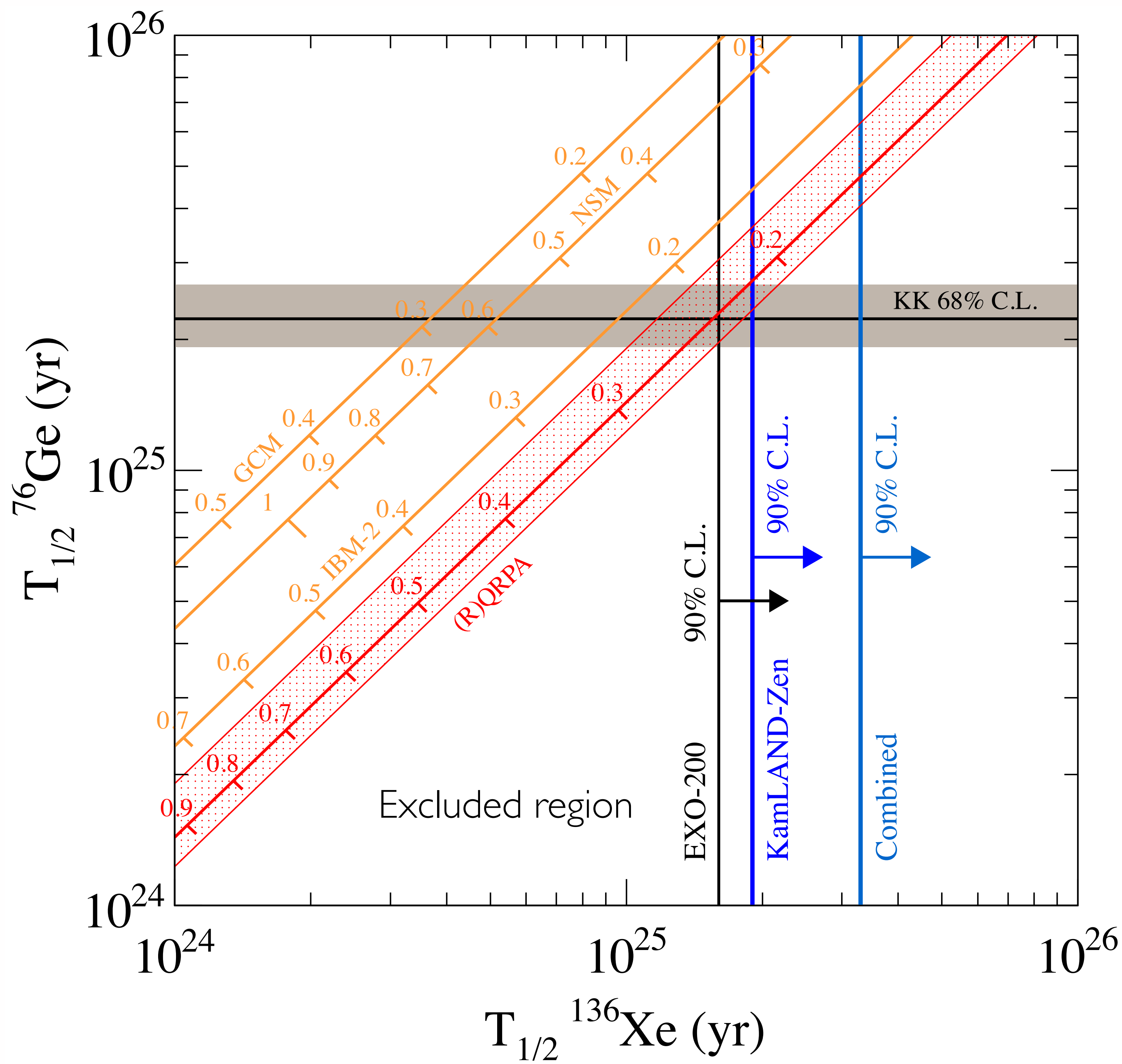
- Project accepted by Ministery of Research and programmed by CNRS
- Cost estimated by project supervisor of safety galery :
- 7 M€ including 20% hazards
- Funding secured from CNRS, Rhône-Alpes region, Savoie department, FEDER
- Technical studies completed
- Negociations with the civil work company in October
- Digging Spring 2014 or end 2015 depending of the company schedule
- 6 months for excavation, 10 months for outfittings
- Extension in operation 2016 -2017



Developing the foil source (2)

Setting up a test area in ISO 5-6 clean room (May - June 2013)

KamLAND-Zen & EXO results



EXO-200

$T_{1/2,0\nu} > 1.6\times10^{25}$ y

$\langle m_{\beta\beta}\rangle < 0.14 – 0.38$ eV (90% C.L.)

KamLAND-Zen

$T_{1/2,0\nu} > 1.9\times10^{25}$ y

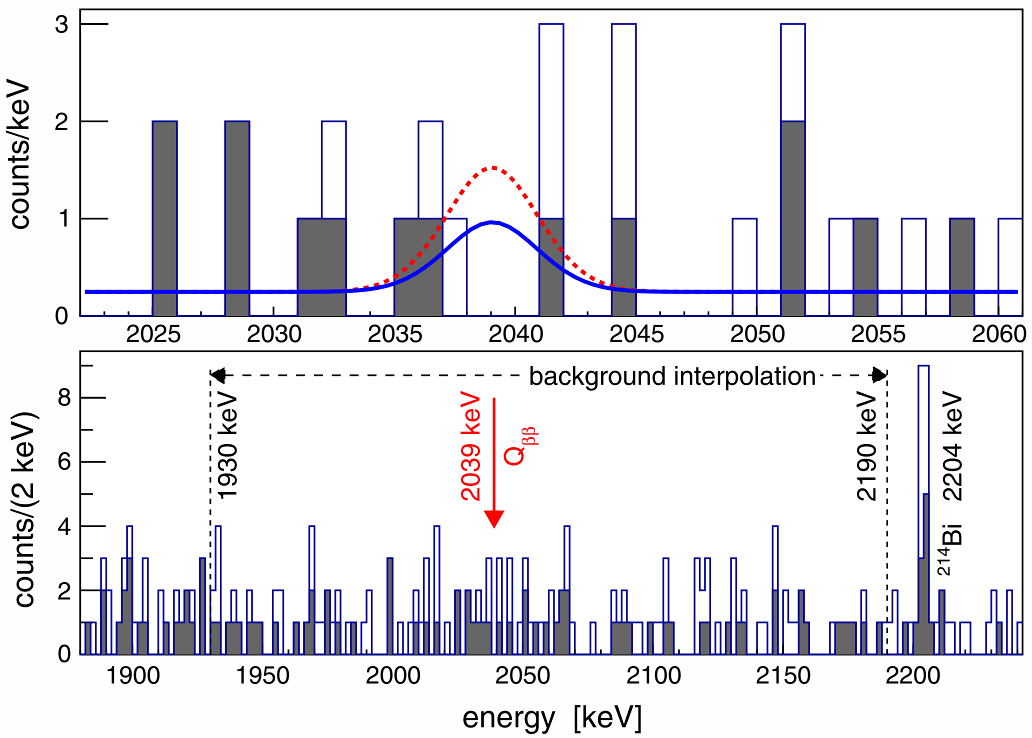
Combined

$T_{1/2,0\nu} > 3.4 \cdot 1025$ yr

$\langle m_{\beta\beta}\rangle < 0.12 – 0.25$ eV (90% C.L.)

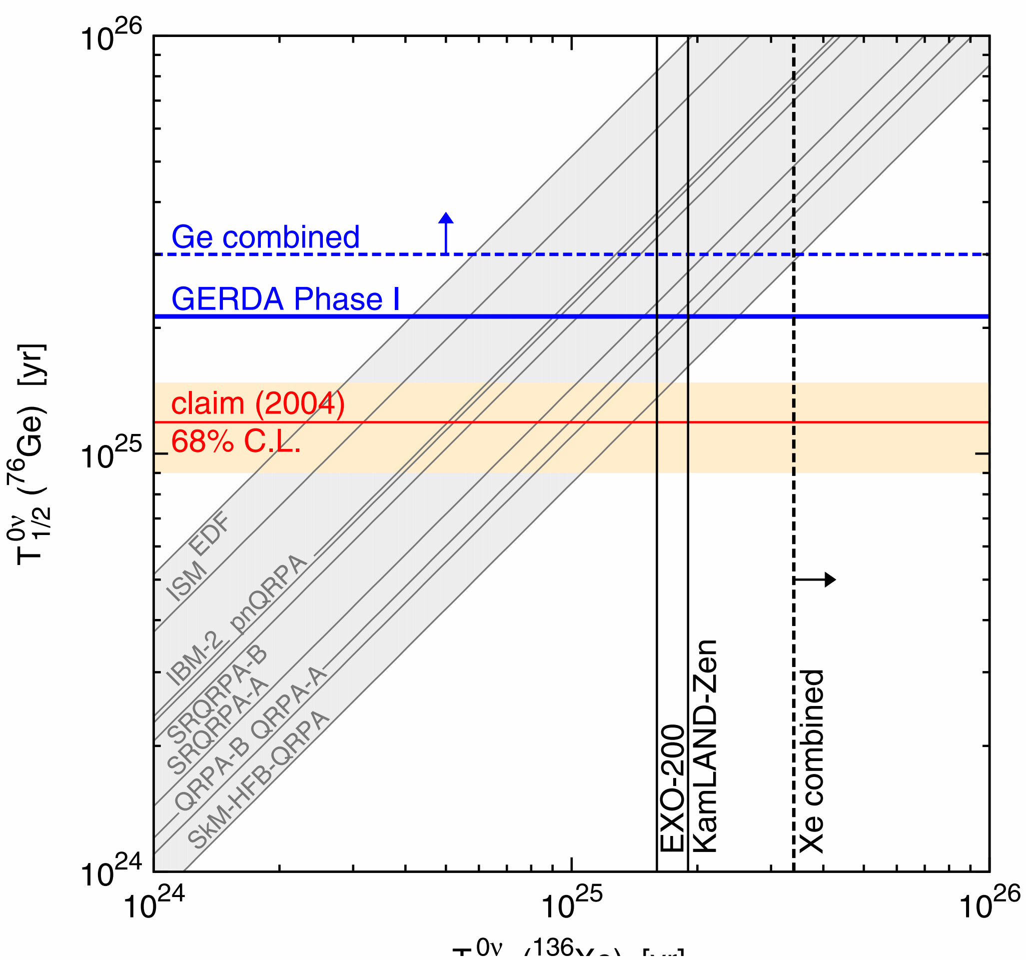
Phys.Rev.Lett.110:062502 (2013)

Gerda phase I results



- Backgroundindex: 0.01 cts/(keV kg yr)
- Exposure: 21.6 kg yr

- No$0\nu\beta\beta$-signalobserved at $Q_{\beta\beta}$=2039keV
- Background-only hypothesis H0 strongly favoured
- Claim strongly disfavoured



Limit on half-life:

- GERDA: $T_{1/2,0\nu} > 2.1\times10^{25}$yr (90%C.L.)
- GERDA+IGEX+HdM: $T_{1/2,0\nu} > 3.0\times10^{25}$yr (90%C.L.)

$\langle m_{\beta\beta}\rangle$ < 0.2-0.4eV

Phys.Rev.Lett. 111:122503 (2013)