Status of the SuperNEMO Experiment and physics objectives

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Comenius University
Bratislava

XXI Workshop on Neutrino Telescopes, Padova 29.9. – 3.10.2025









OUTLINE

BSM Double beta decays

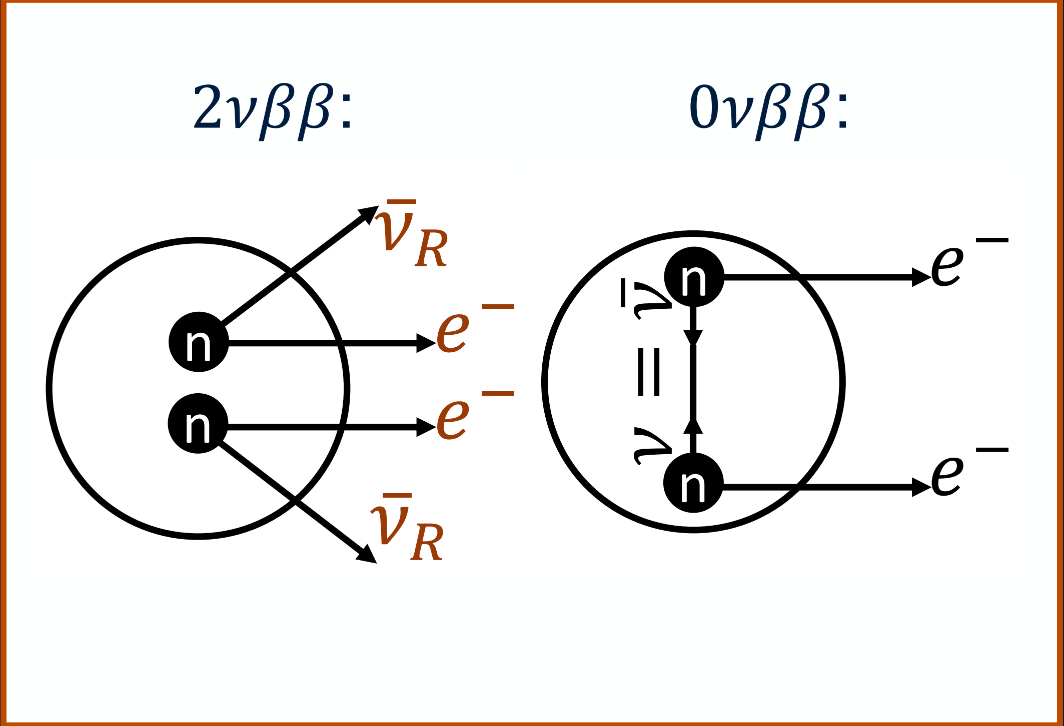
SuperNEMO Demonstrator

Background

Sensitivity to new physics

OUTLINE

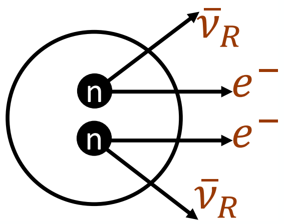
- **BSM Double beta decay**
- SuperNEMO Demonstrator
- Background
- Sensitivity to new physics



BSM Double beta decay

Two-neutrino double-beta decay

$2\nu\beta\beta$



- Allowed in SM
- Measured for 11 isotopes
- Goal now precision measurements
- Possible new physics

BSM Double beta decay

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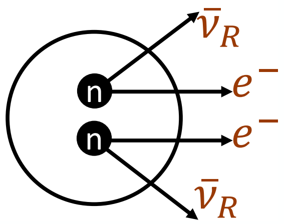

- Allowed in SM
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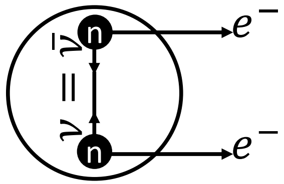
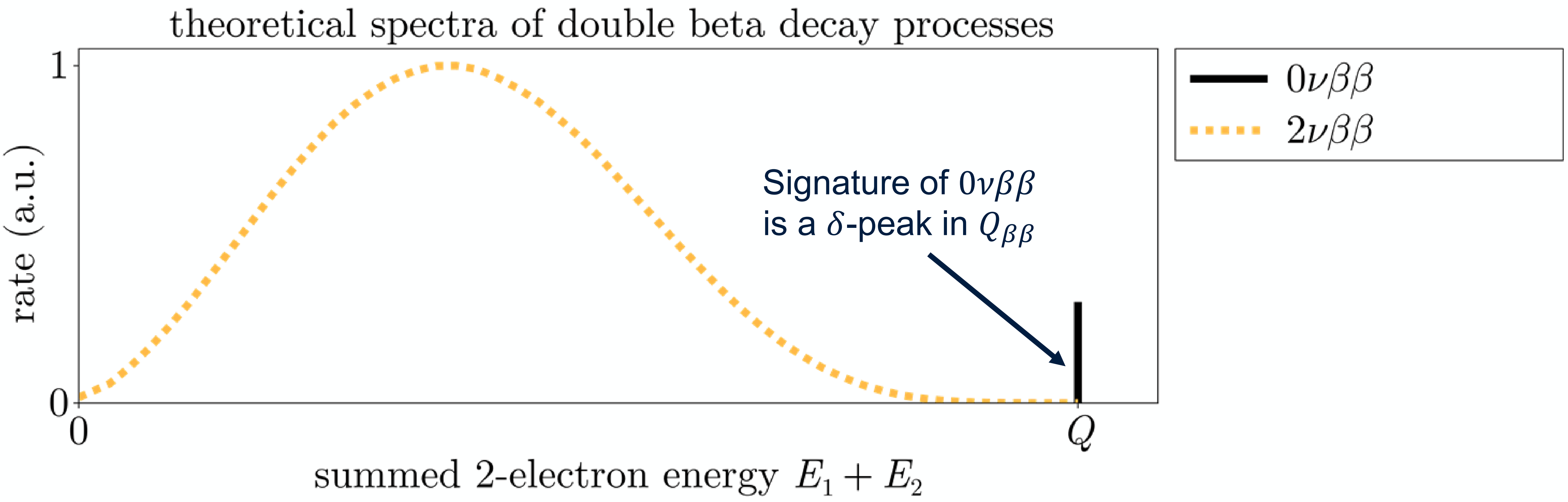
Neutrinoless double-beta decay

- Beyond SM physics
- Lepton Number violation
- Majorana vs Dirac
- Search ongoing

$0\nu\beta\beta$



BSM Double beta decay



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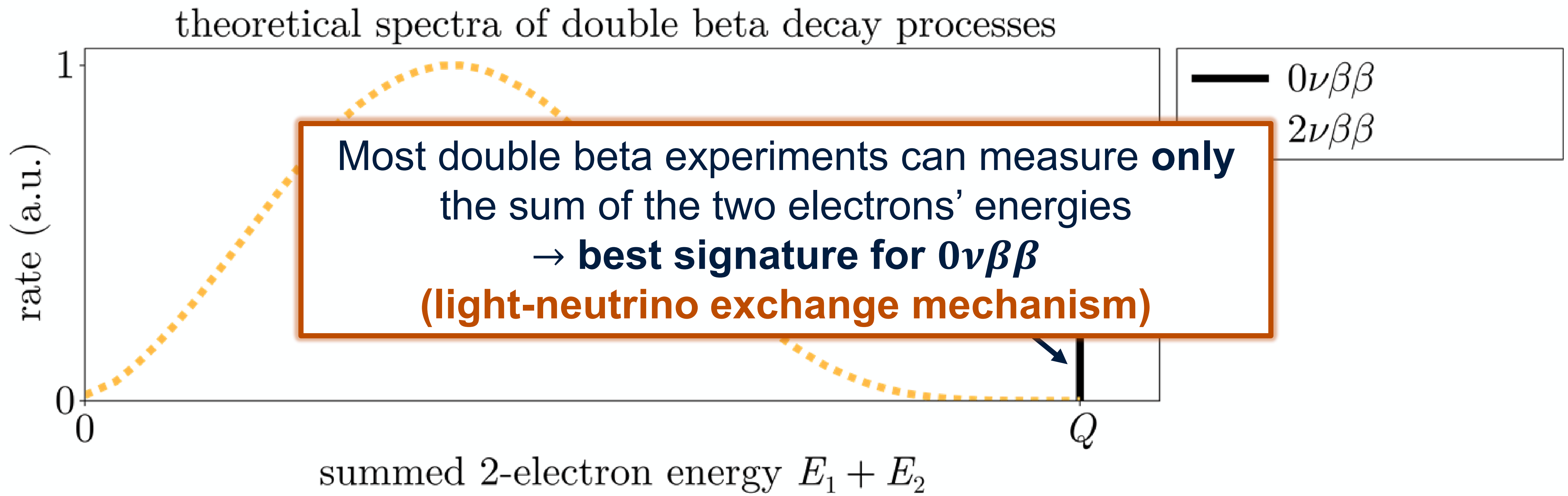


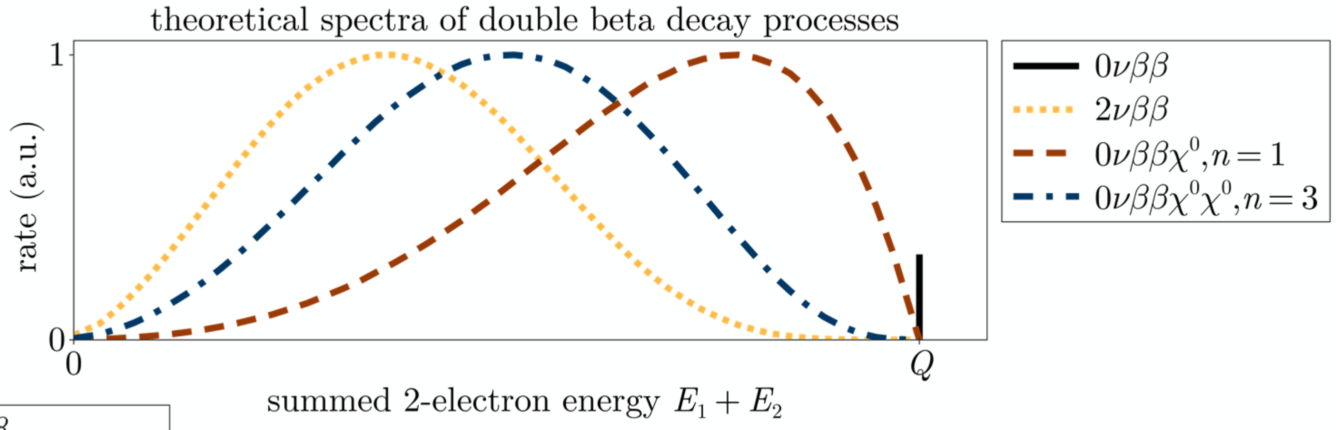
Most double beta experiments can measure **only** the sum of the two electrons' energies
→ **best signature for $0\nu\beta\beta$**
(light-neutrino exchange mechanism)

BSM Double beta decay

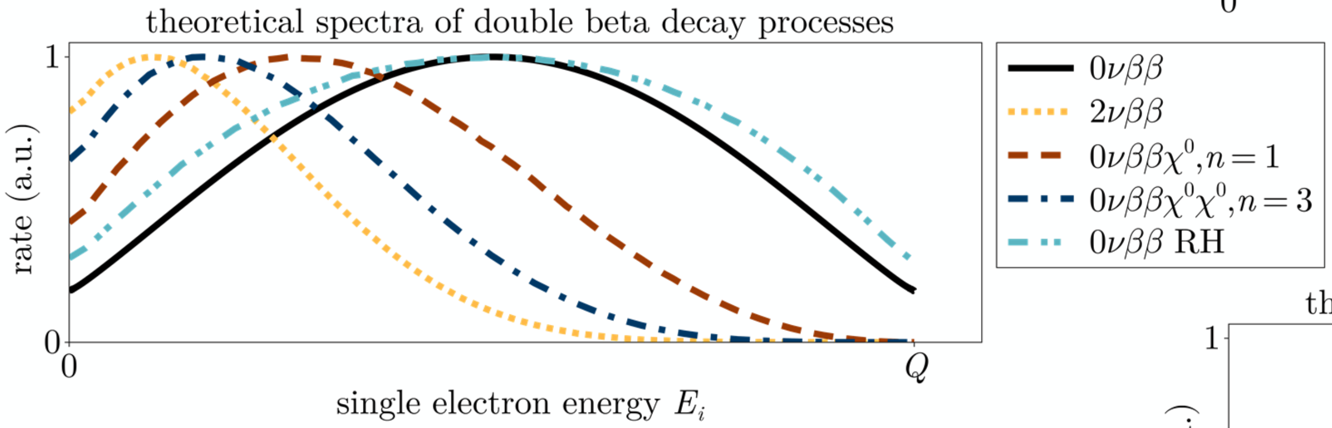
For different mechanisms, different ways to measure may be more optimal…

BSM Double beta decay

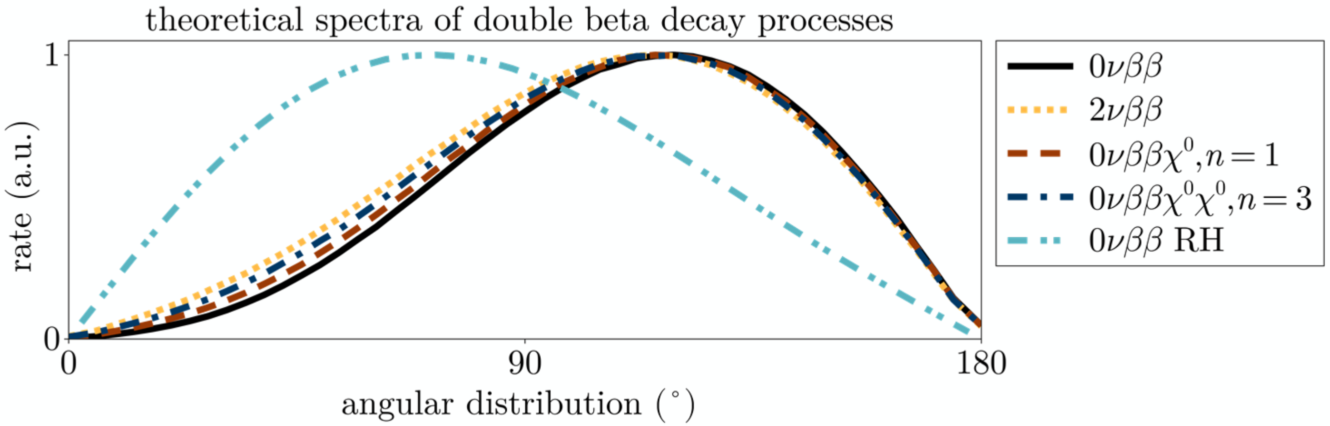
E_sum channel



E_i channel



φ channel



BSM Double beta decay

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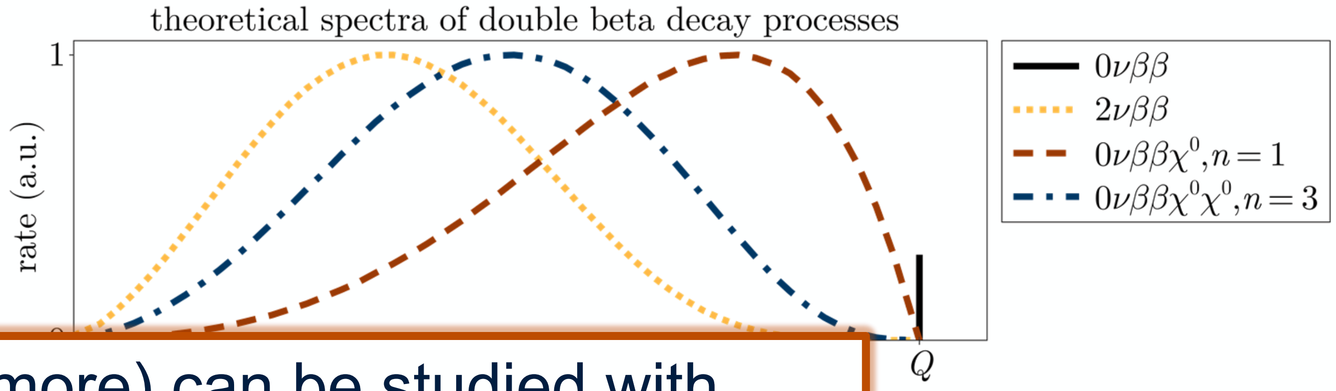

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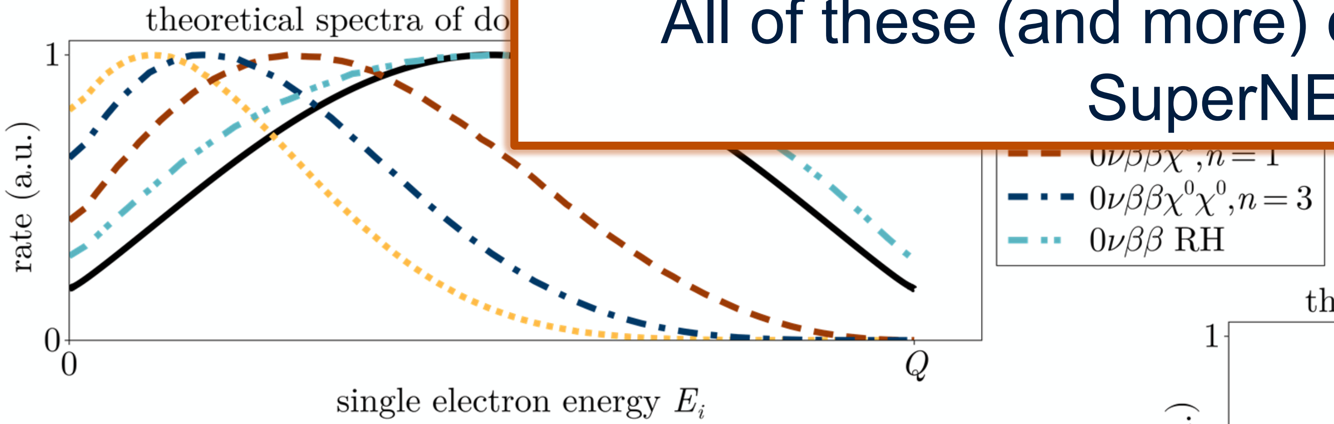
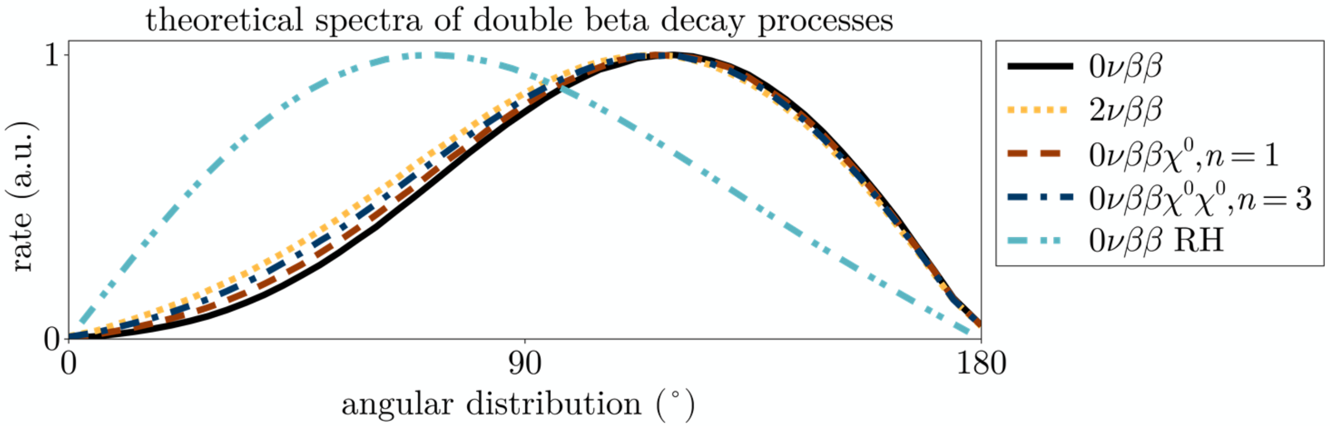


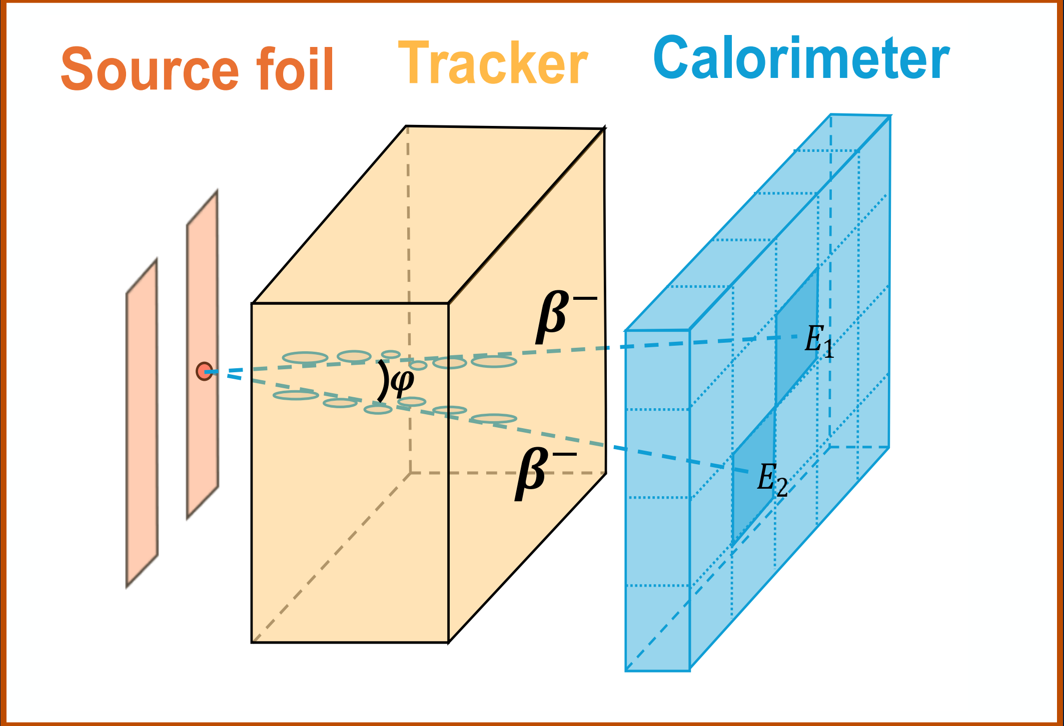
All of these (and more) can be studied with SuperNEMO

φ channel

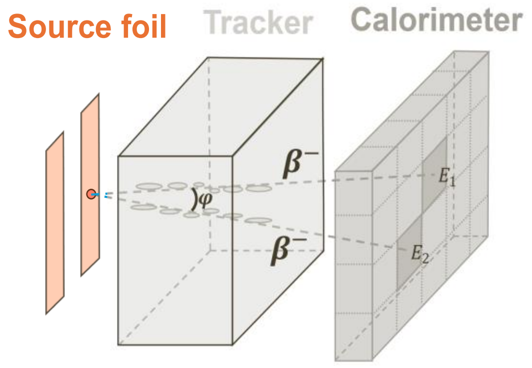


OUTLINE

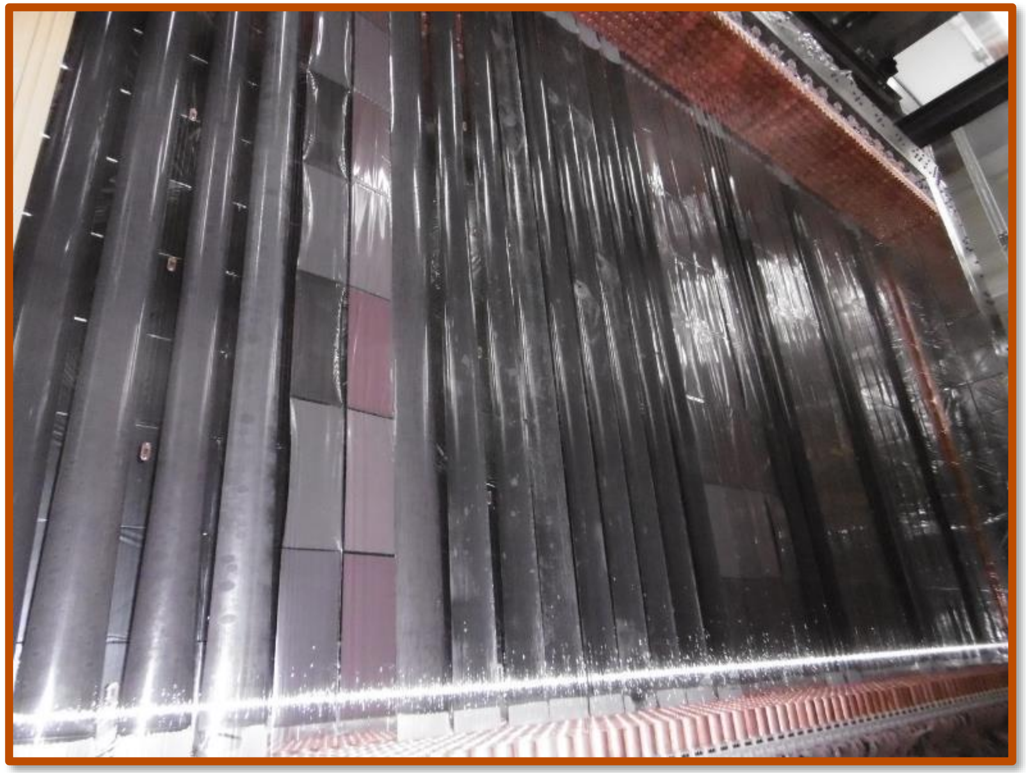
- Double beta decay
- **SuperNEMO Demonstrator**
- Background
- Sensitivity to new physics



SuperNEMO Demonstrator – source foil

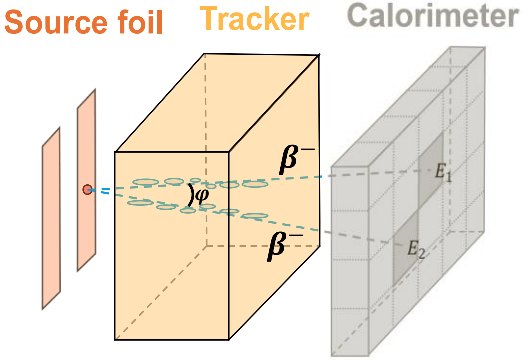


- Free choice of isotope
- 34 strips of ^{82}Se
- 6.11kg mass, $\sim 50\ mg/cm^2$
- 96-99.9% enrichment
- Q ≈ 3 MeV
- **If $0\nu\beta\beta$ discovered - measure isotope**



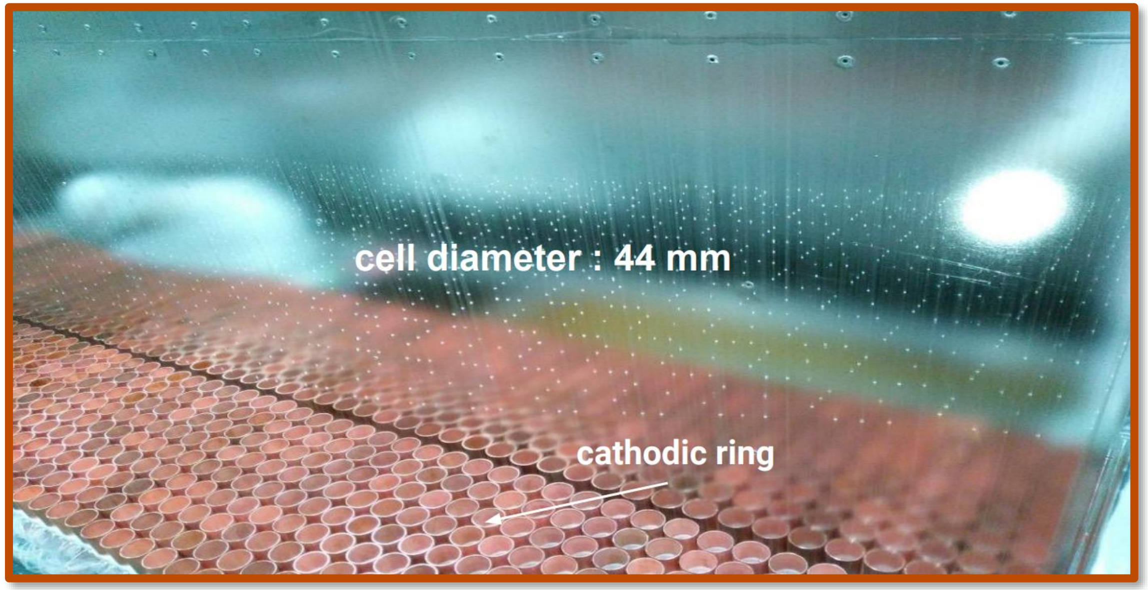
Picture of installed source foils

SuperNEMO Demonstrator - tracker

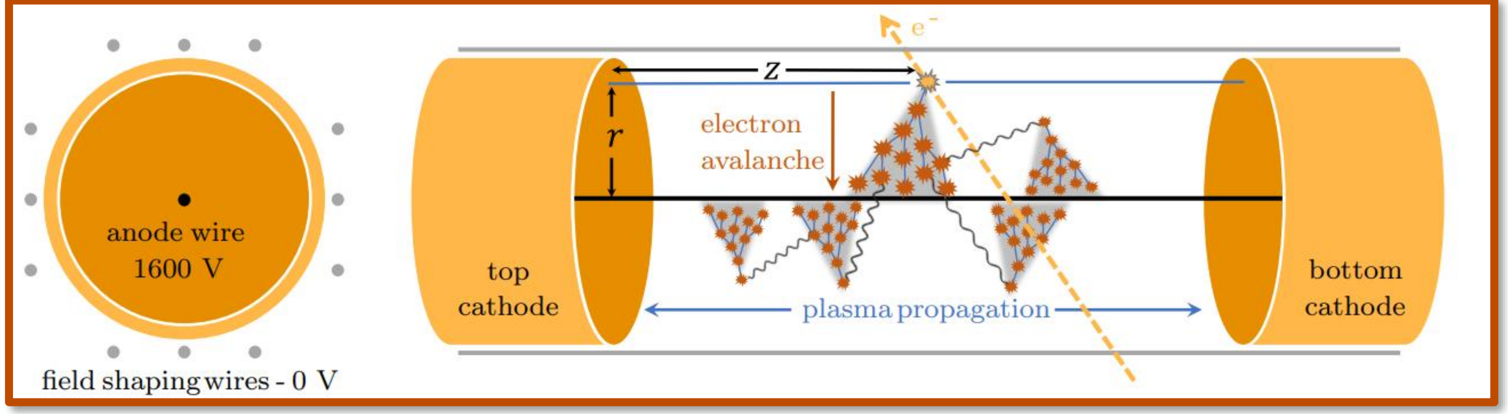


- 2034 drift cells (Geiger mode)
- Allows particle identification
- Full electron topology
- Single-electron spectra
- Angular distribution
- Status: **working (98.4%)!**

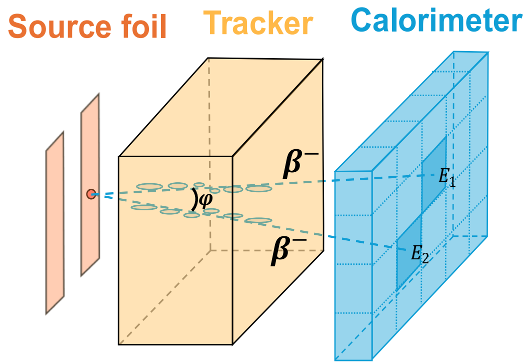
Tracker section



Tracker cell working principle



SuperNEMO Demonstrator - calorimeter



- 712 Optical Modules (OM)
- Target ~ 8% FWHM @ 1 MeV
- 8'' + 5'' PMTs
- Time-resolution ~200 ps @ 1 MeV
- Automatic calibration system
- Status: **working (97.4%)!**

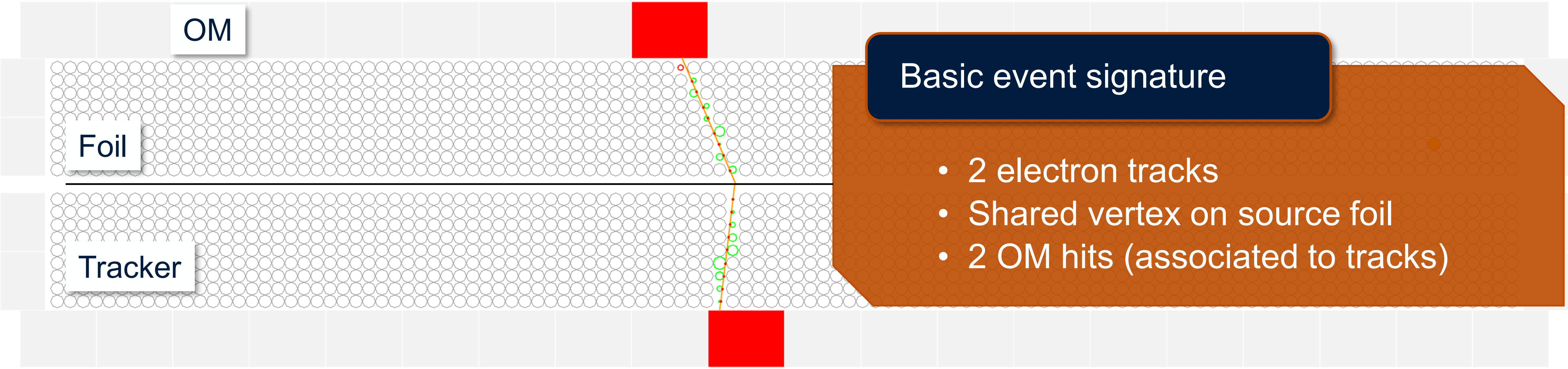
Optical Module

Calorimeter main wall ($6 \times 4\ \mathrm{m}^2$)

SuperNEMO Demonstrator - taking data

Candidate double beta event.

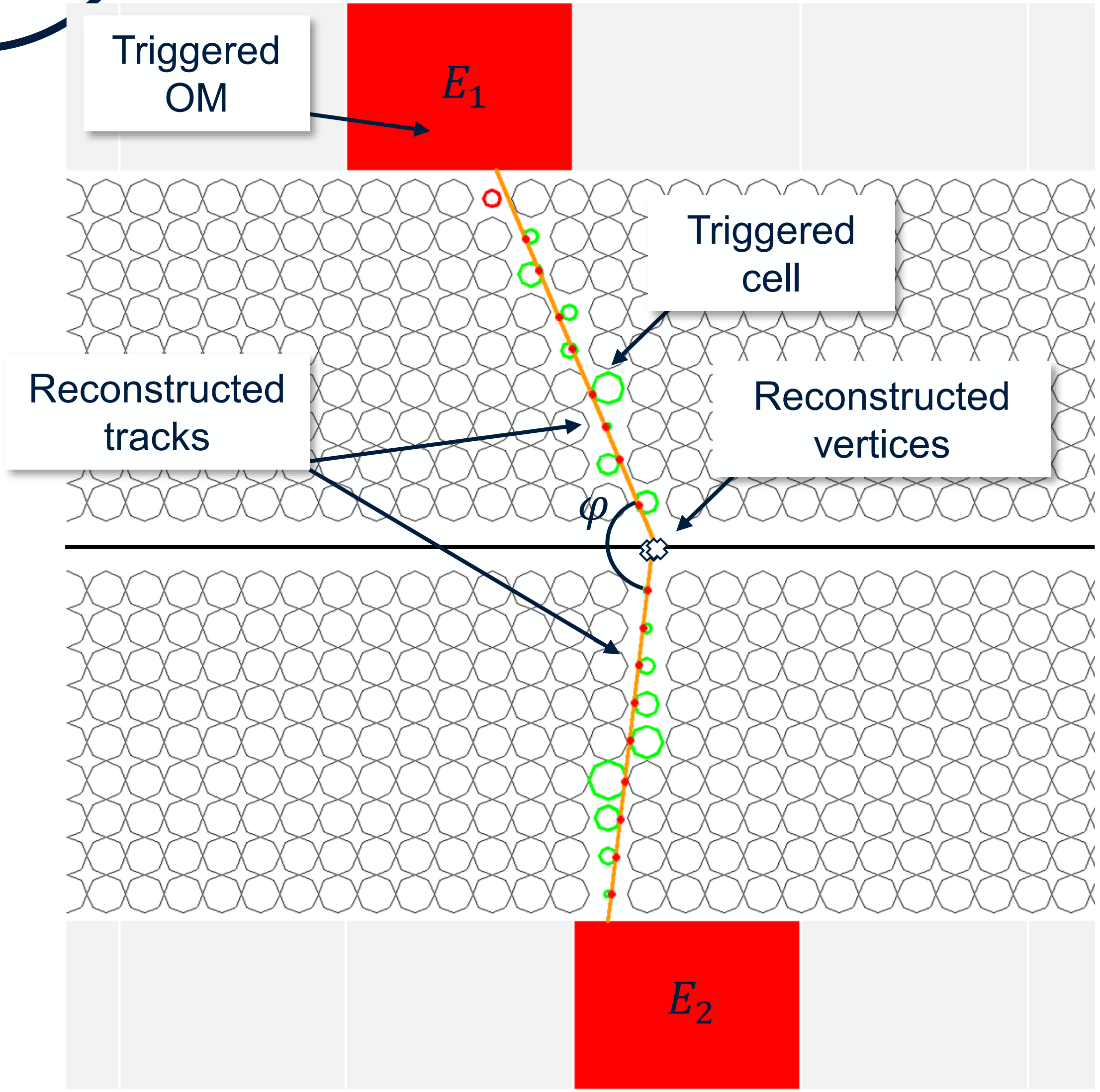
Run 974 | Event 634 **TOP VIEW**



Basic event signature

- 2 electron tracks
- Shared vertex on source foil
- 2 OM hits (associated to tracks)

SuperNEMO Demonstrator - taking data



For each event we measure

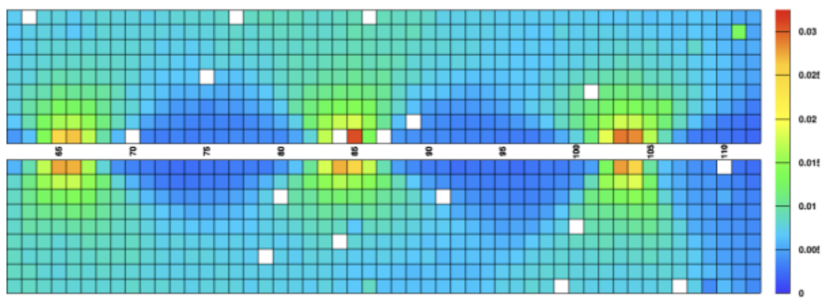
- Individual energy in OMs: E_i
- 3D angle between tracks: φ
- Vertex separation
- ToF
- Track length
- Etc.

SuperNEMO current status

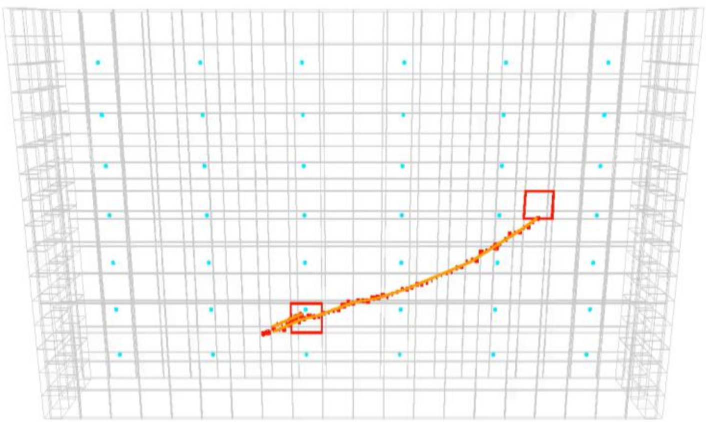
SuperNEMO Status

- Detector placed in LSM
- **Running in $\beta\beta$ mode since 10th April!**
- Average duty cycle 92%
- Background data being assessed

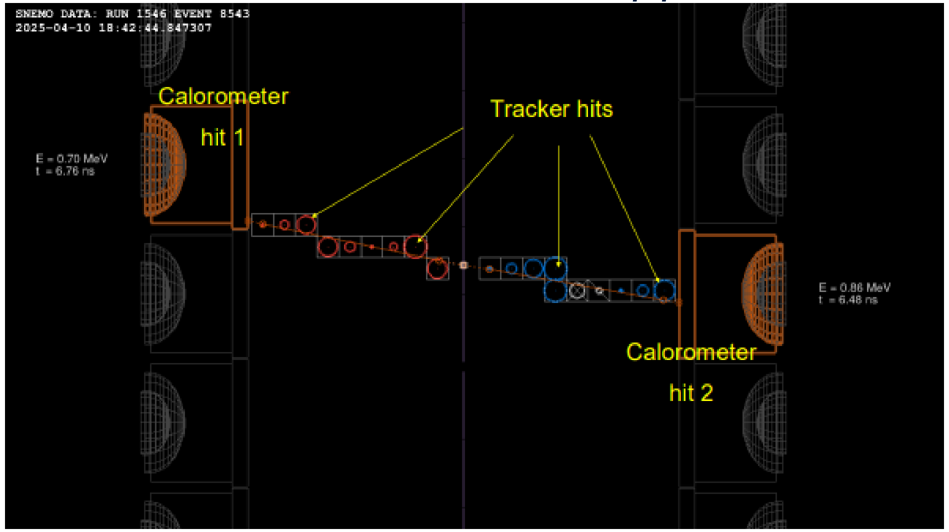
Bi207 calibration **tracker hit** map (Top view)



3D event visualization



10 April 2025 18:42:44
First $\beta\beta$ candidate



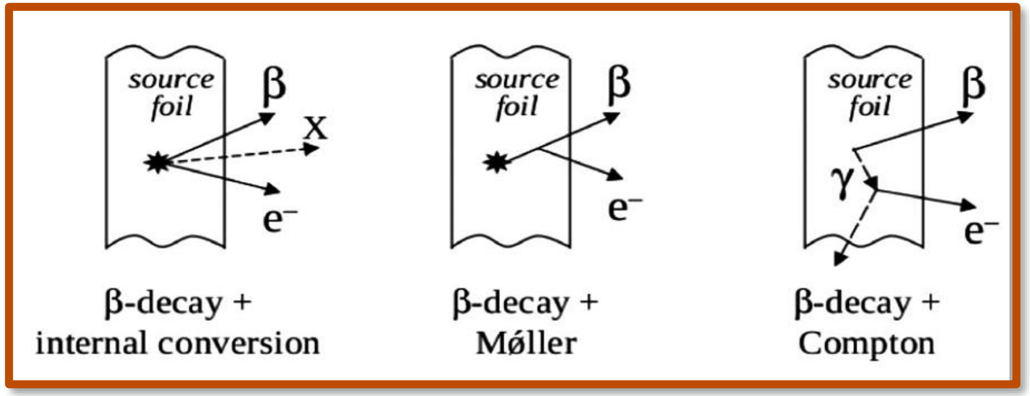
OUTLINE

- Double beta decay
- SuperNEMO Demonstrator
- **Background**
- Sensitivity to new physics

Background - sources

Internal background

- $2\nu\beta\beta$
- Foil contamination



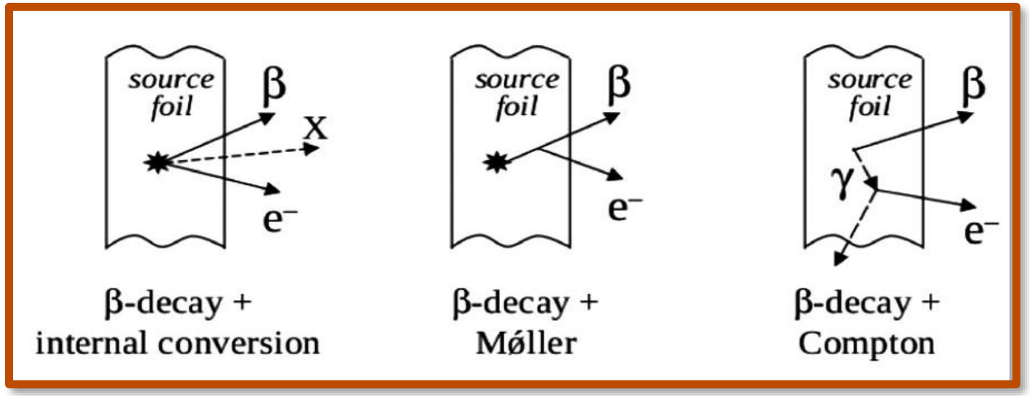
Background - sources

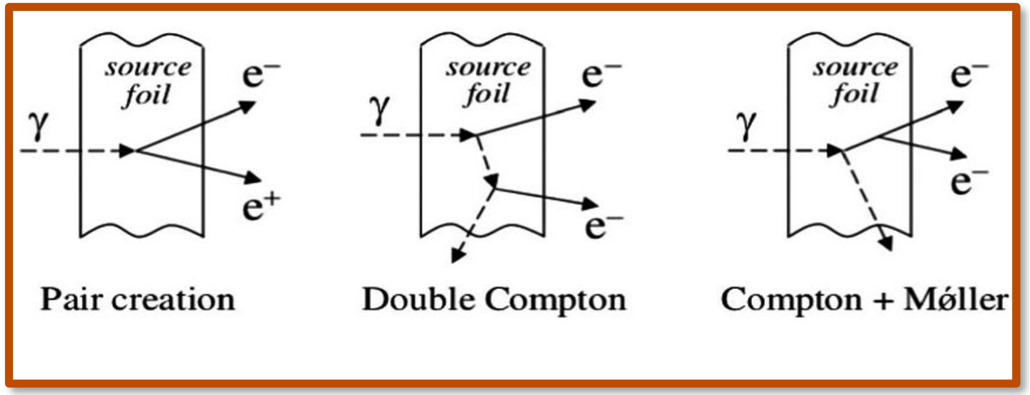
Internal background

- $2\nu\beta\beta$
- Foil contamination

External background

- Detector contamination
- Ambient (neutrons and gamma)
- Radon gas





Background - SuperNEMO shielding

Anti-radon tent

aim $\sim 0.25\ cts$
in ROI @ $17.5\ \mathrm{kg} \cdot \mathrm{yr}$

Iron gamma shield

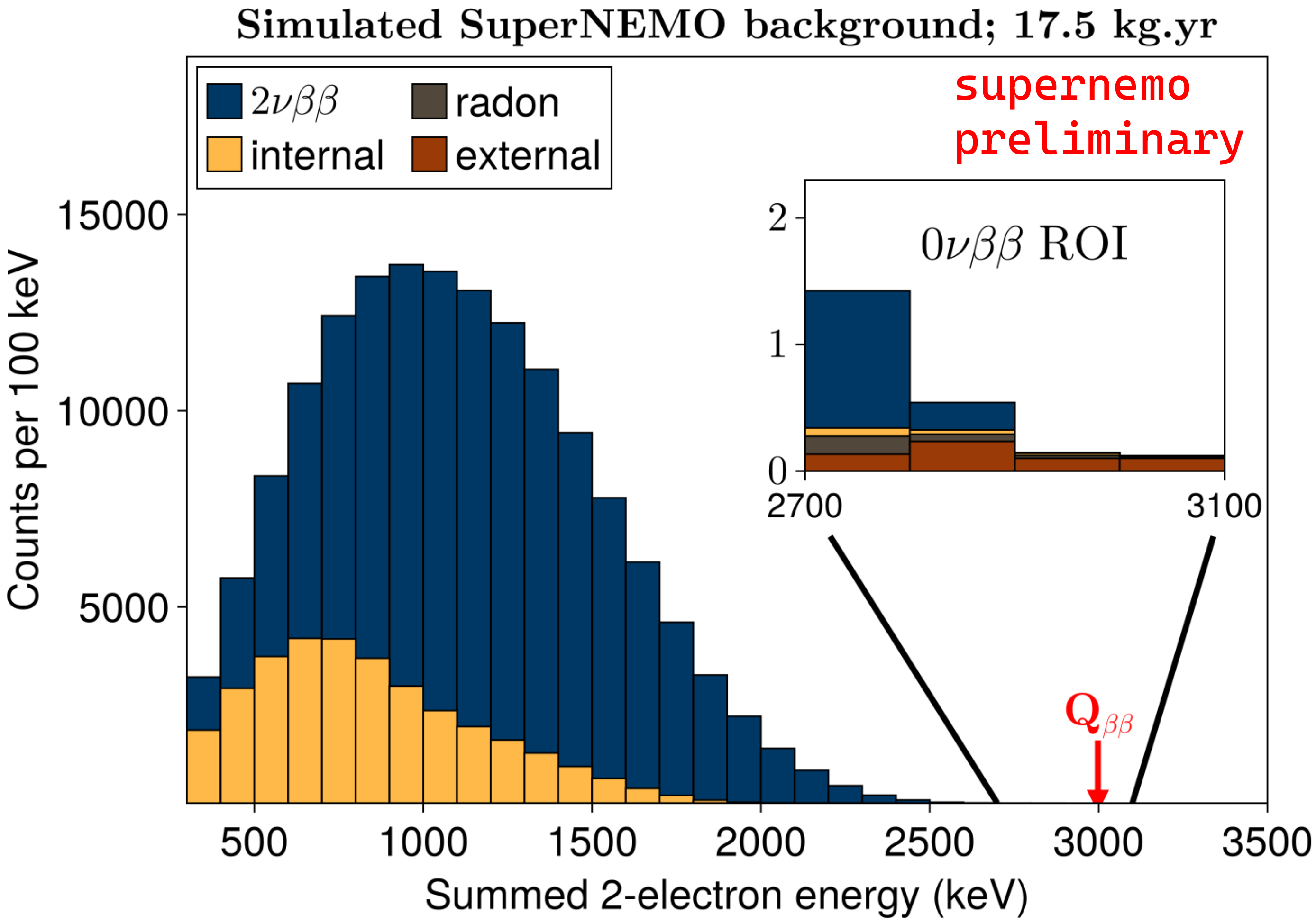
negligible

PE neutron shield

aim $\sim 0.65\ cts$
in ROI @ $17.5\ \mathrm{kg} \cdot \mathrm{yr}$

Background - expectation

- Expected 100k – 200k $2\nu\beta\beta$ events
- Wide ROI for $0\nu\beta\beta$ (2700 - 3100) keV
- Largest bkg. $2\nu\beta\beta$ and neutrons
- **Bkg. index $\sim 2 \times 10^{-4}$ cts/(keV · yr · kg)**



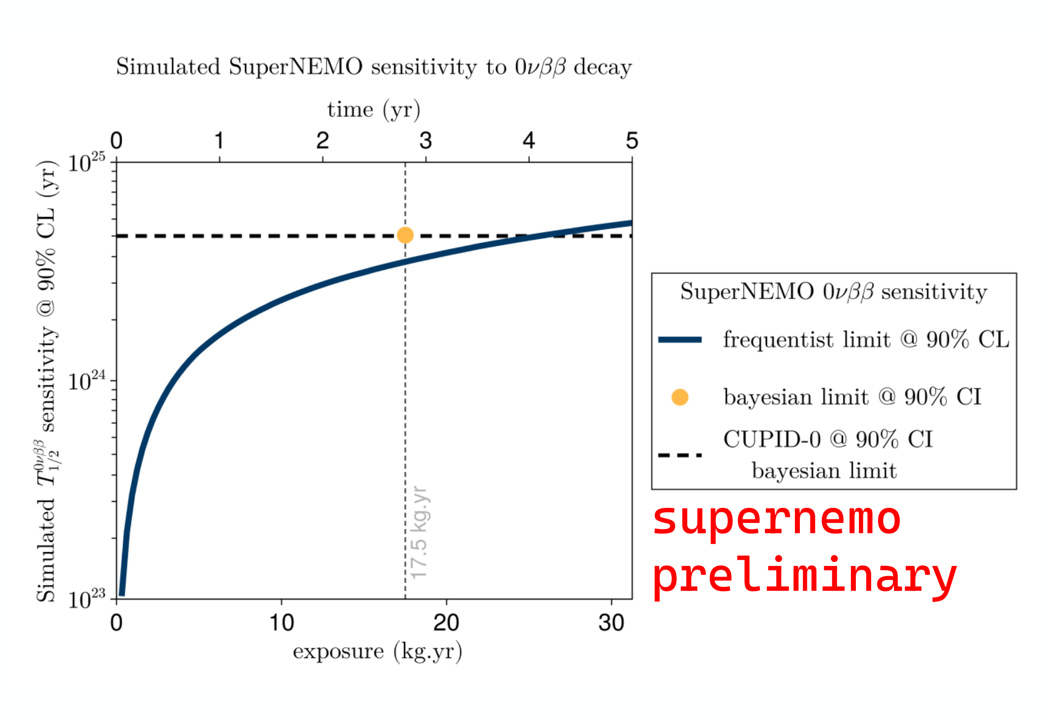
OUTLINE

Double beta decay

SuperNEMO Demonstrator

Background

Sensitivity to new physics



Sensitivity to new physics

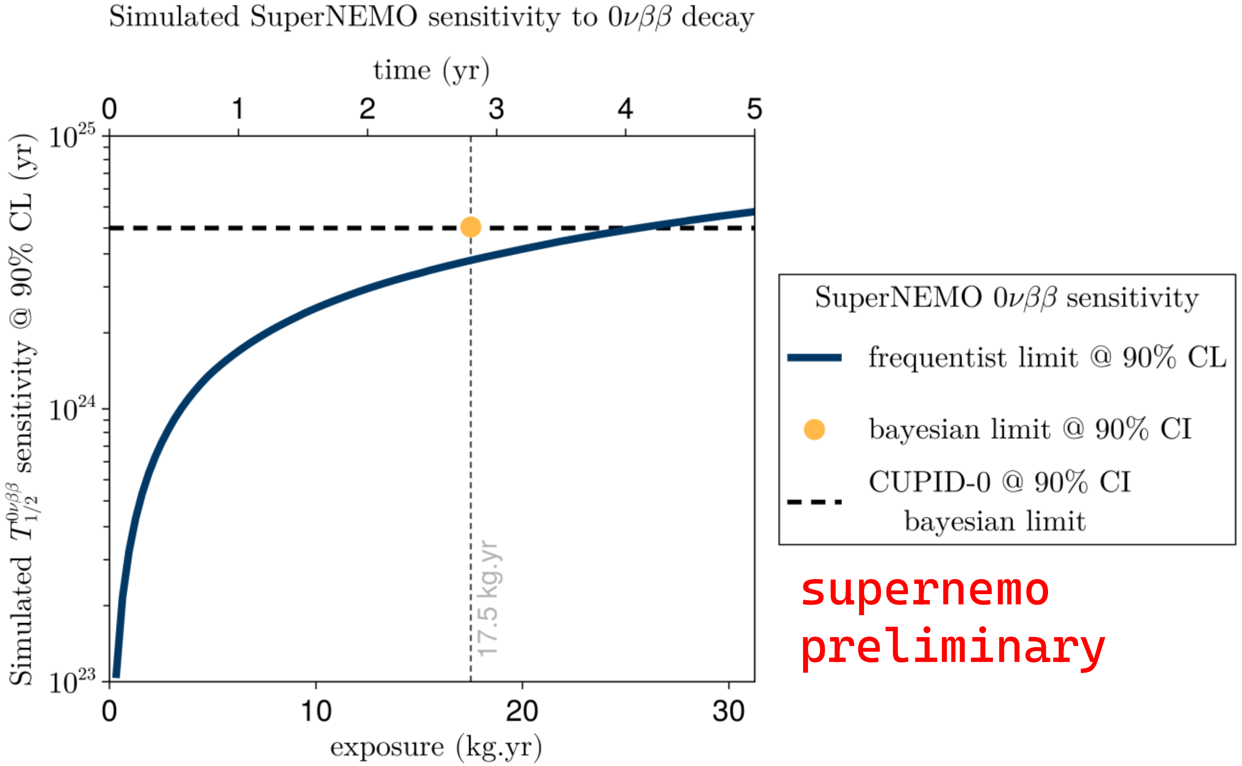
E_{sum} spectrum: The traditional approach.

$$T_{1/2}(ROI) = T_{1/2}(E^{l}_{sum}, E^{u}_{sum}) \propto \frac{\varepsilon}{f(b)}$$

l, u – lower and upper ROI boundary

Goal is to find ROI that maximizes sensitivity

1. Determine best data-cuts **individually**
2. Estimate the background in ROI
3. Estimate signal efficiency in ROI
4. **Calculate sensitivity**



supernemo preliminary

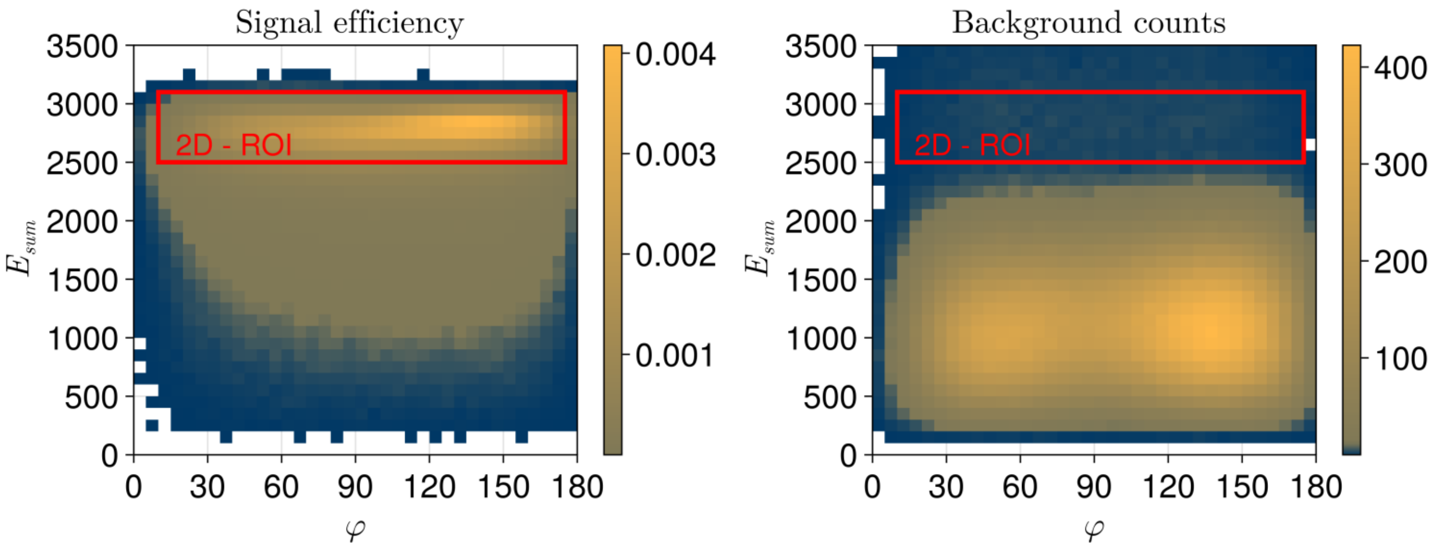
Sensitivity to new physics - results

N-dimensional ROI optimization!

$$T_{1/2}(ROI) = T_{1/2}(\theta_1^l, \theta_1^u, \theta_2^l, \theta_2^u, \ldots) \propto \frac{\varepsilon(\theta_1^l, \theta_1^u, \theta_2^l, \theta_2^u, \ldots)}{b(\theta_1^l, \theta_1^u, \theta_2^l, \theta_2^u, \ldots)}$$

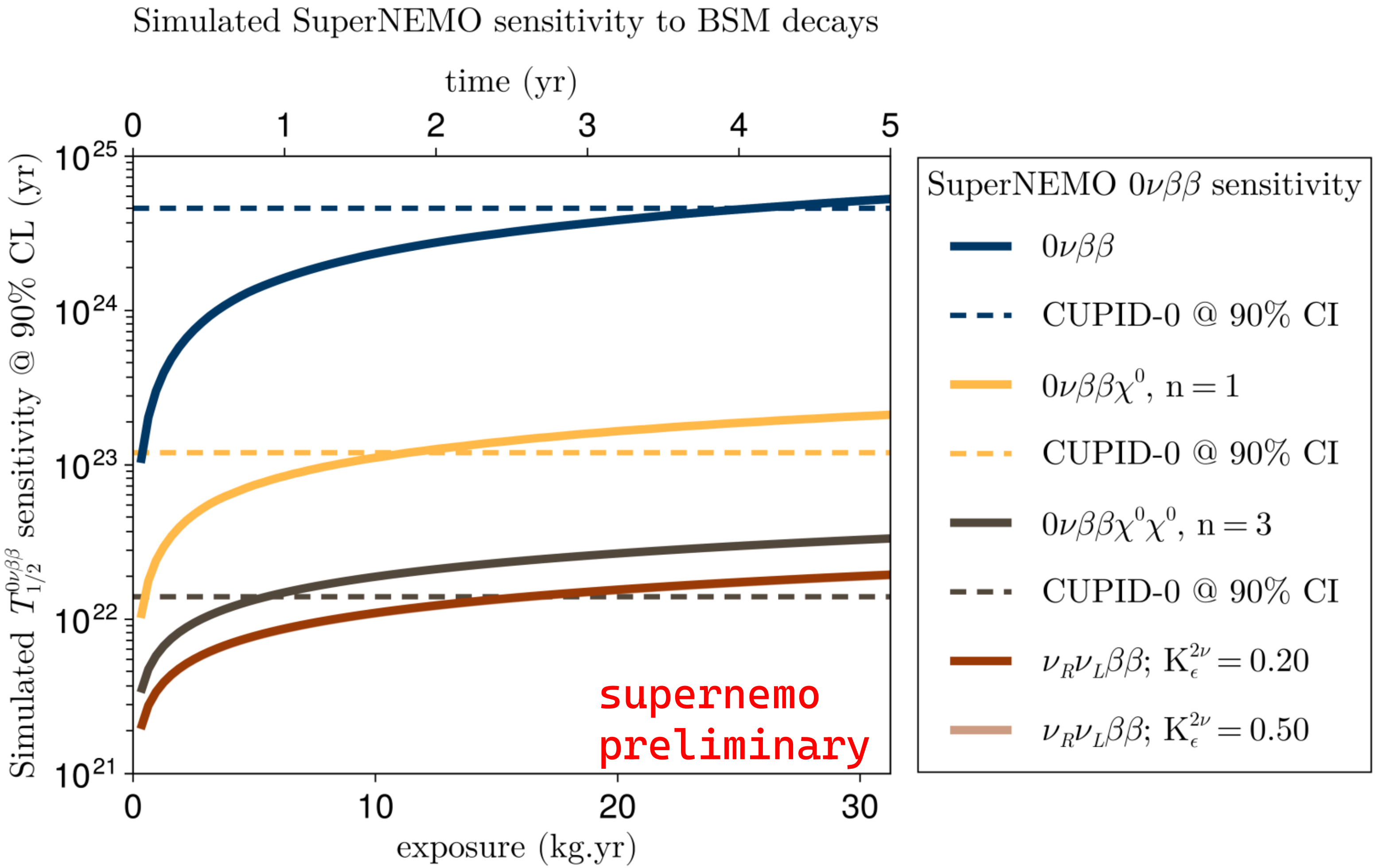
Find maximum

- Maximize signal-to-background ratio
- Across multiple variables simultaneously!
- i.e. $E_{sum}, E_i, \varphi, r, P(ToF)^* \rightarrow \theta_i$
- **Obtain an optimized set of data-cuts!**



Sensitivity to new physics - results

- With enough time world best $0\nu\beta\beta$
- Can achieve best for majoron (1-2 yr)
- World first $\nu_R\nu_L\beta\beta$
- **And many more…**



Conclusion

SuperNEMO Status

- **Detector running in $\beta\beta$ mode!**
- Background data being assessed
- **Data-taking ~2.3 $\mathbf{kg \cdot yr}$**

Background

- Simulation **expected $< \mathbf{2 \times 10^{-4}}$ $\mathbf{cts/(keV \cdot yr \cdot kg)}$**
- Background model to be reevaluated with measured activities

Sensitivity

- Estimated $0\nu\beta\beta$ sensitivity **$\geq \mathbf{4.6 \times 10^{24}}$ yr (Bayes, 90%)**
- Possible world best for limits for $0\nu\beta\beta\chi^0, 0\nu\beta\beta\chi^0\chi^0$ (^{82}Se)
- Possible world first limits for $2\nu\beta\beta$ RHC

Collaboration meeting in Marseille
February 2024

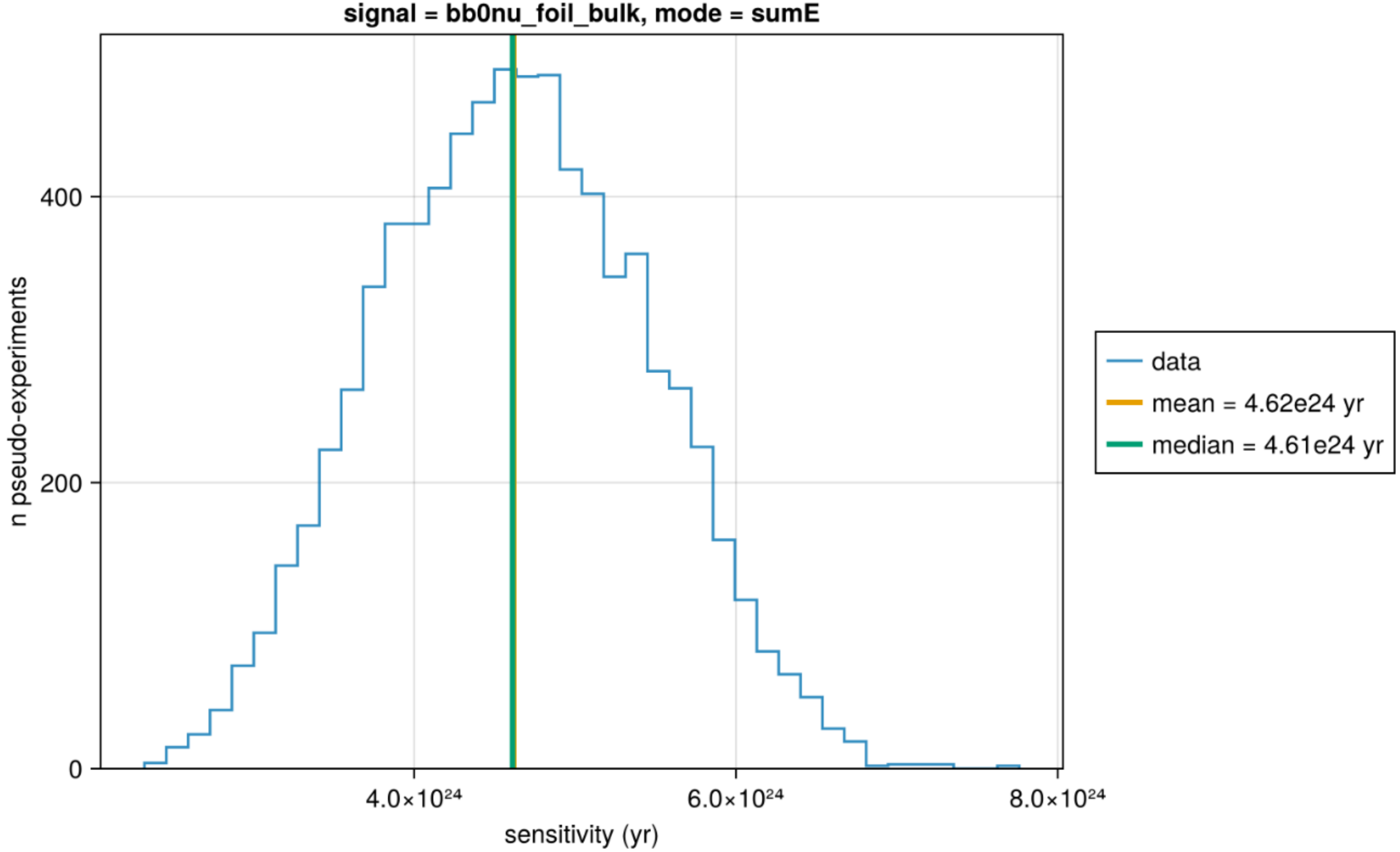
THANK YOU!

Acknowledgments:
I would like to thank the Modane Underground Laboratory and its staff for support through underground space, logistical and technical services. LSM operations are supported by the CNRS, with underground access facilitated by the Société Française du Tunnel Routier du Fréjus.
This work was supported by the Czech Science Foundation (GAČR), project No. 24-10180S.

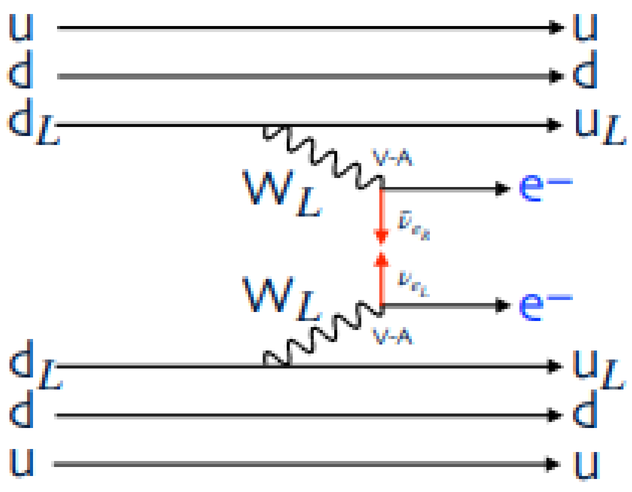
BACKUP – bkg composition

source	counts in ROI	activitiies
$2\nu\beta\beta$	0.98±0.13	0.00185935
^{214}Bi	0.089±0.004	1.0e-5
Radon	0.233±0.039	0.00015
^{208}Tl	0.039±0.001	2.0e-6
external	0.57±0.27	--
total	1.9±0.3	--

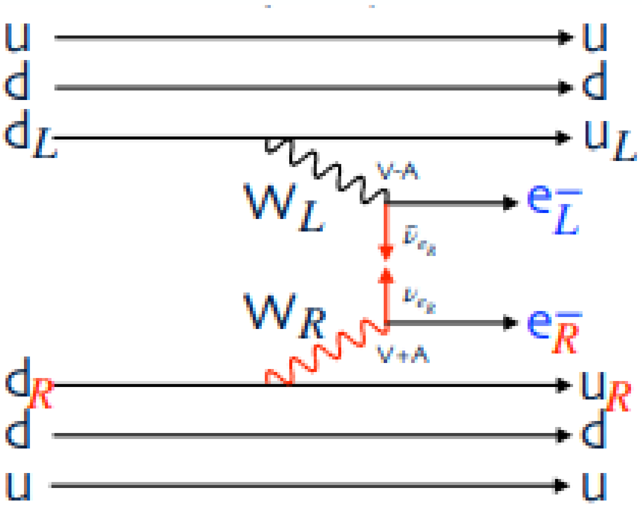
BACKUP – Bayesian analysis (work in progress)



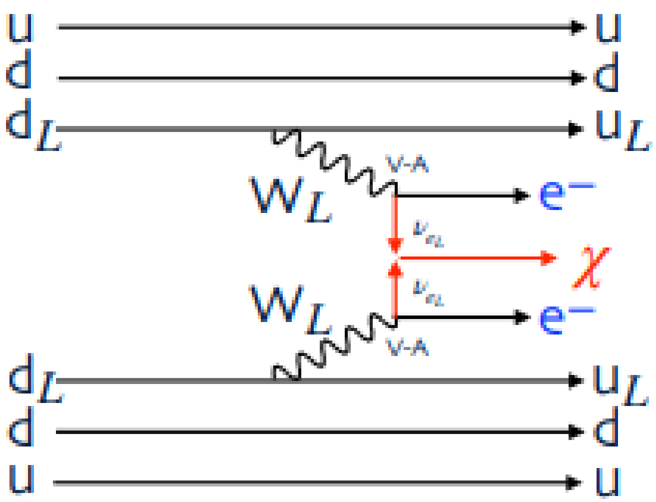
Modes of DBD



Light Neutrino Exchange (V-A)



Left-Right Symmetric (V+A)



Majoron Emmission

Sensitivity to new physics

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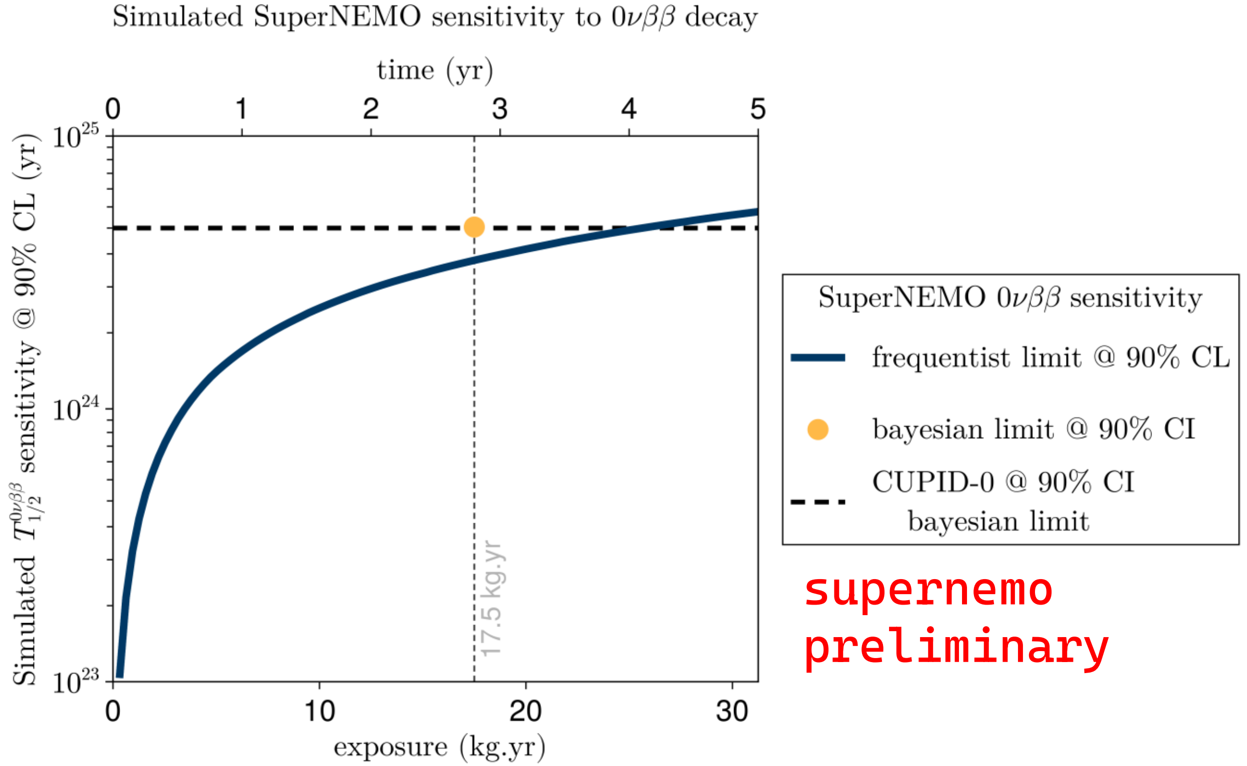


Sensitivity to new physics

Thanks to the ability of SuperNEMO to measure full decay topology, we can **study BSM decays in various ways!**

Single-electron spectra

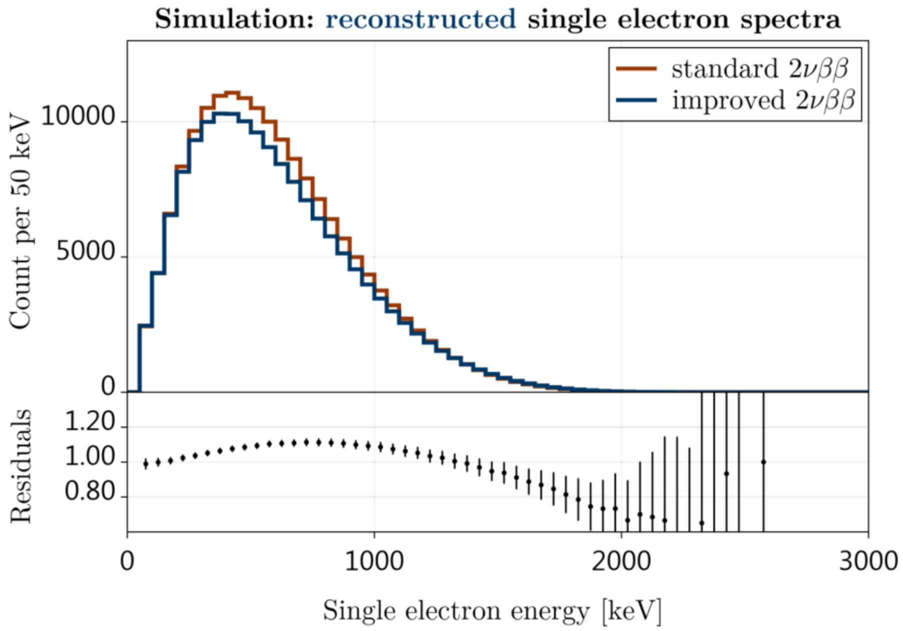
- SSD vs HSD
- g_A analysis via ξ_{31}, ξ_{51} [1]

Angular distribution

- g_A analysis via $K(\xi_{31}, \xi_{51})$ [2]
- $\nu_R \nu_L \beta\beta$ constraints [3]

Multivariate

- Combining all variables



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[2] O. Nitescu et al, Universe 2021, 7, 147
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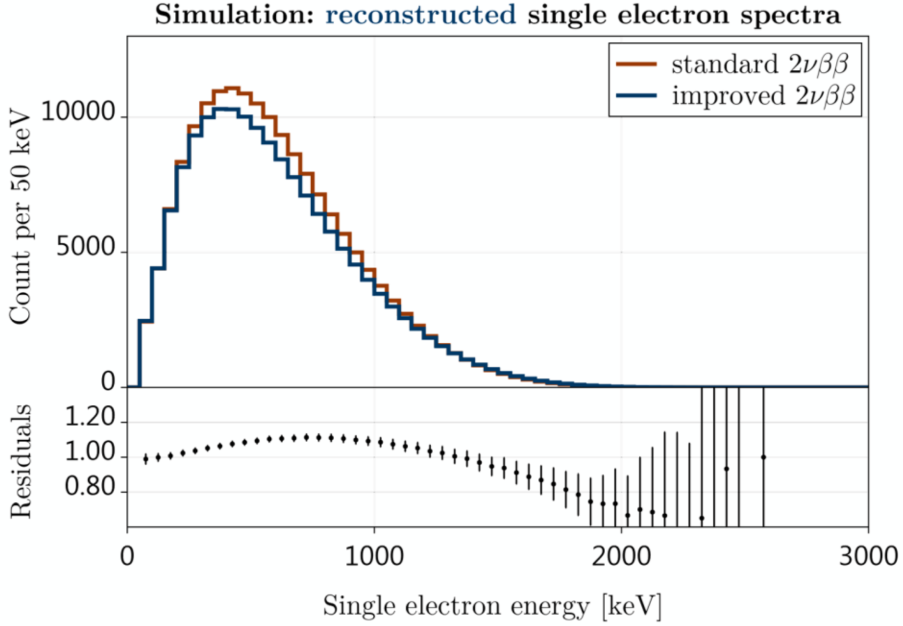

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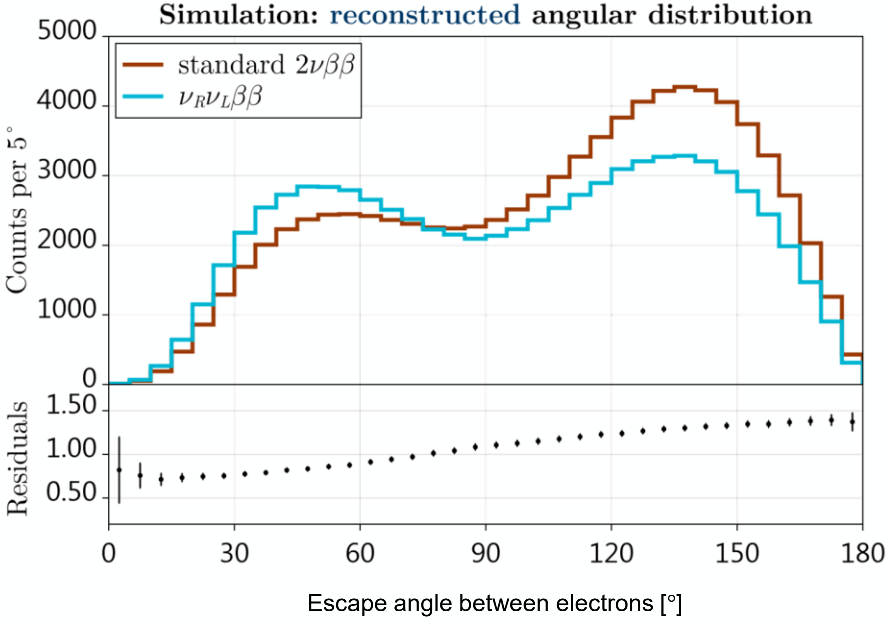

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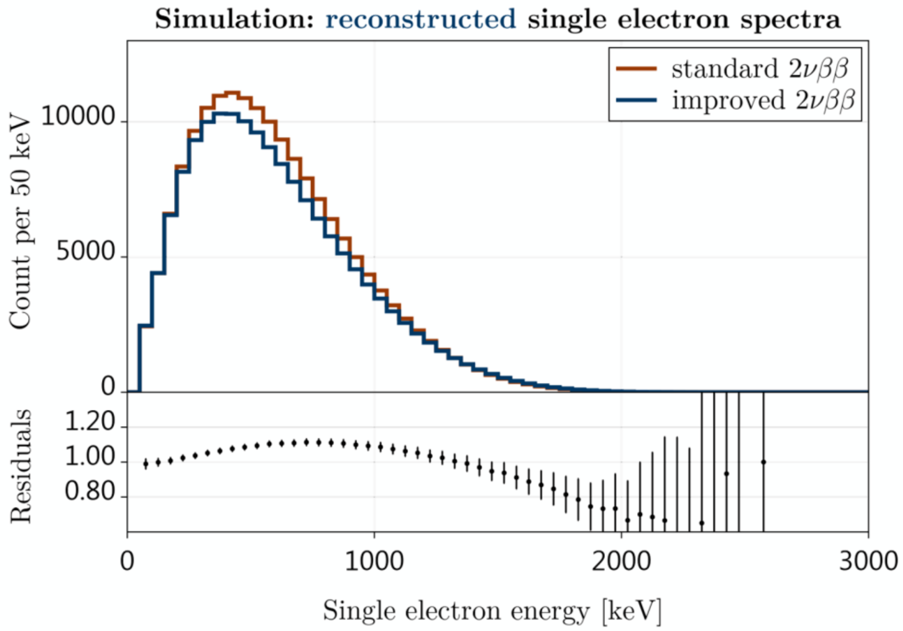

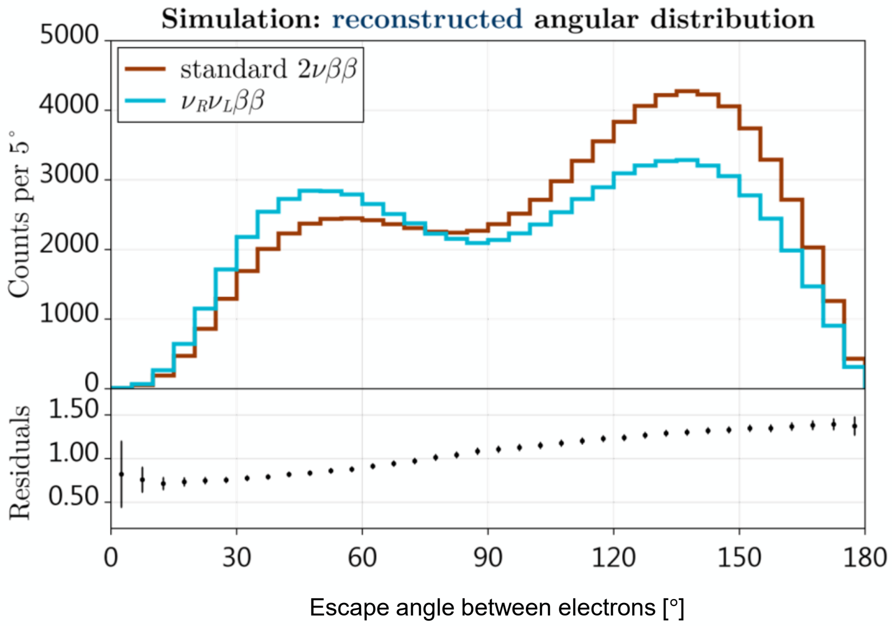

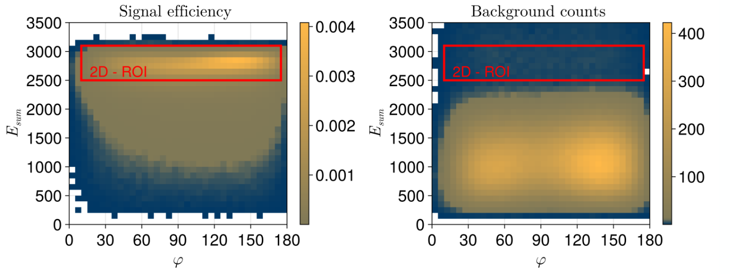

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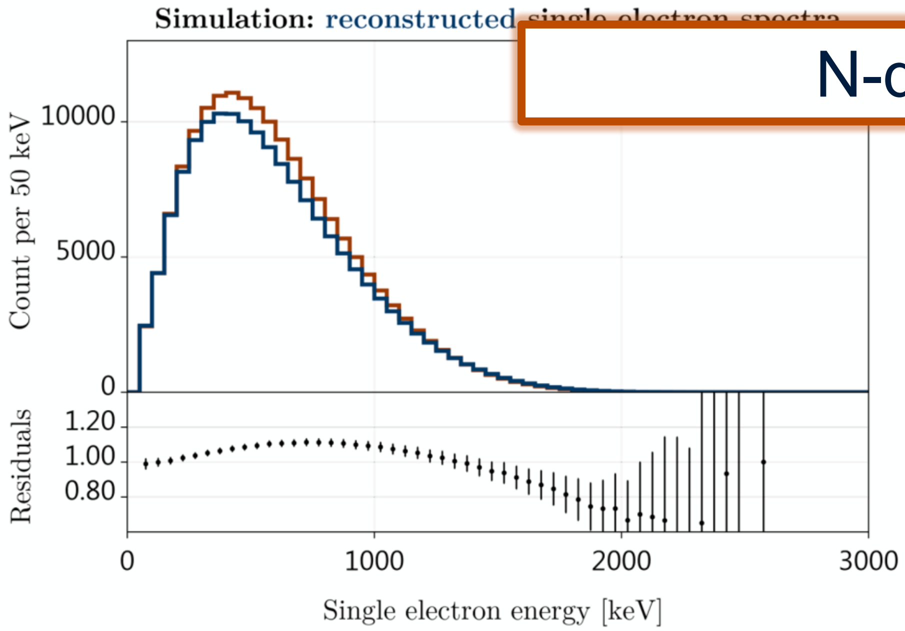

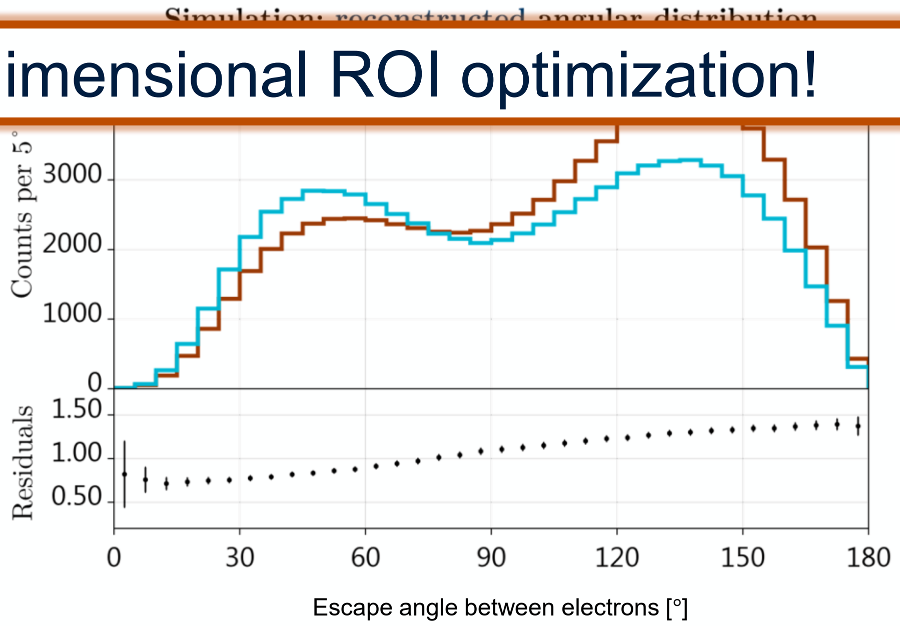

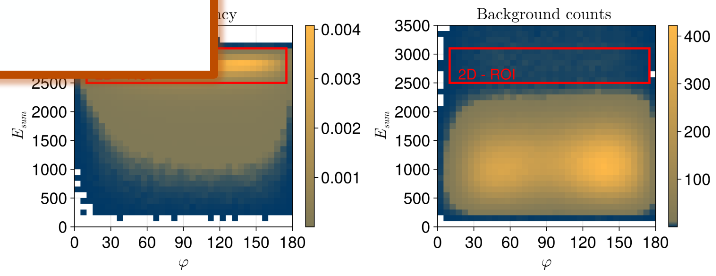

N-dimensional ROI optimization!

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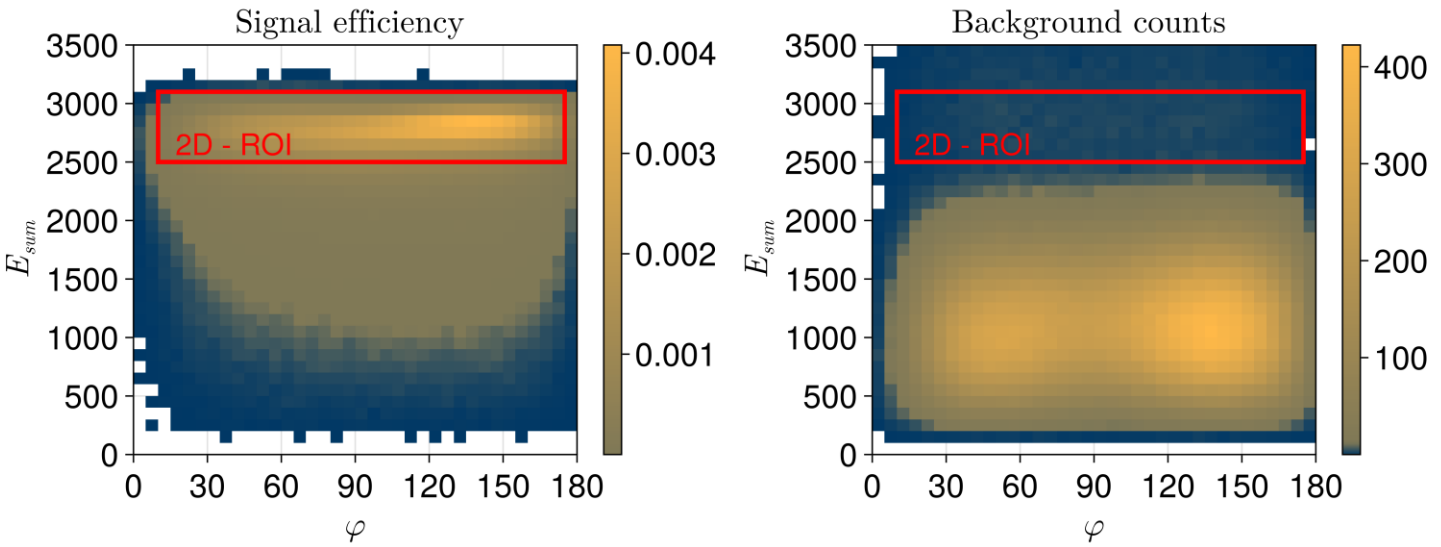
- i.e. $E_{sum}, E_i, \varphi, r, P(ToF)^* \rightarrow \theta_i$
- **Obtain an optimized set of data-cuts!**



Sensitivity to new physics - results

N-dimensional ROI optimization!

- Possible ~16% increase
- Depends on the process
- The goal is to optimize for each process individually