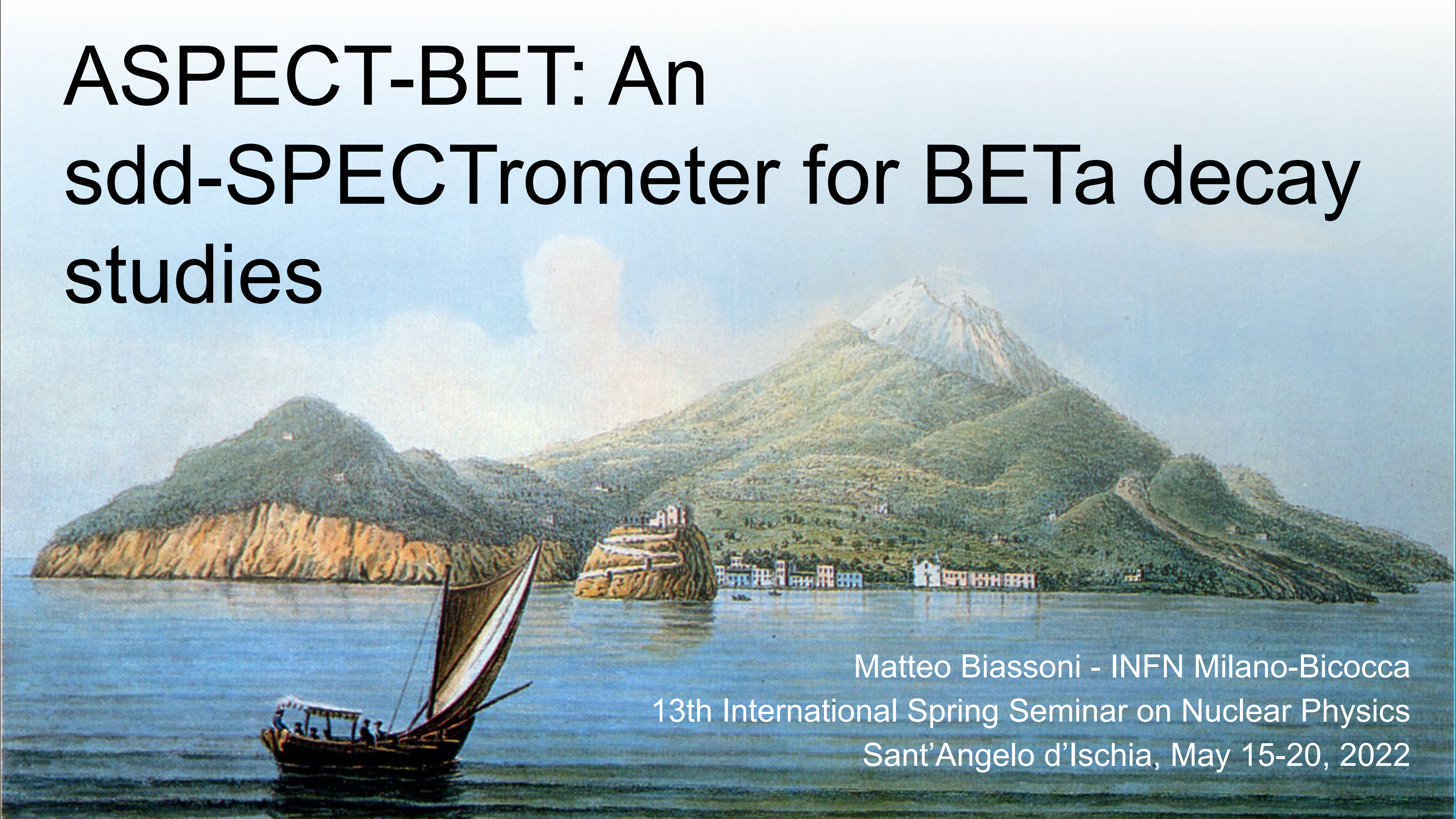
ASPECT-BET: An sdd-SPECTrometer for BETa decay studies



Matteo Biassoni - INFN Milano-Bicocca

13th International Spring Seminar on Nuclear Physics
Sant’Angelo d’Ischia, May 15-20, 2022

Science case - nuclear models

Original motivation: double-beta decay **experimental effort and strategies** strongly depends on nuclear theory predictions on NME and g_A.

Goal: provide nuclear theory with relevant datasets to compare predictions with and constraint models in order to improve predictive power:

- precise and accurate reconstruction of energy spectra of multiple-forbidden and non-unique beta decays → refinement and down-selection of existing nuclear models
- correlate spectral shape with renormalization of g_A
- nuclear structure calculations have evidenced a sensitivity on the renormalization of the parameters which characterize the beta-decay operators

Simultaneous comparison of multiple beta spectra with theoretical predictions to constraint parameters of the models

Science case - neutrino physics

Reactor neutrino fluxes used as source for oscillation experiments:

- data analysis and interpretation used neutrino fluxes and energies as input to extract neutrino properties
- experimental sensitivity to oscillation parameters depends on knowledge of neutrino spectra
- ignorance of neutrino spectral shapes can lead to strong biases in the analysis
- “anomalies” could be reconducted to inaccurate assumptions on spectral shapes

Geo-neutrinos as messengers for earth studies:

- **spectral shape** uncertainty translates into systematic errors on neutrino fluxes onces convolved with detection cross sections and energy resolution
- complicated decay schemes, direct measurement preferable over theoretical calculations

Direct measurement of electrons from selected short-lived fission products and U and Th natural chains translate into knowledge of neutrino spectra

Science case - summary

SDD-spectrometer: a versatile tool for beta spectra measurements

High-precision measurements of beta spectra

Nuclear Physics

- g_A quenching
- Nuclear Matrix Element → Majorana neutrino mass

Astroparticle Physics

- Majorana neutrino mass
- Background modeling in DM and NLDBD experiments
- Reactor antineutrino anomaly

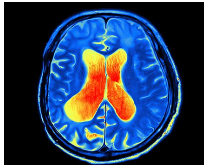
GeoPhysics

- Geo-neutrinos → Earth studies

Technological applications

FOOD SAFETY
Measurements of pure beta-emitters in food

NUCLEAR MEDICINE
Measurement of the dose injected



METROLOGY
Precise measurement of β-source activity

NUCLEAR REACTORS
Characterization of nuclear waste and emitted power

Science case - state of the art

Electron-matter interaction in the beta decays energy range is complex:

- continuous energy release by ionization
- secondary electrons production
- bremsstrahlung photons
- material excitation and characteristic X-rays
- back-scattering

with relevant fraction of the energy

Direct measurement of electron energy with solid state detectors is challenging:

- full energy containment after interaction with detector
- detector response (energy-to-signal conversion) linearity and position dependence

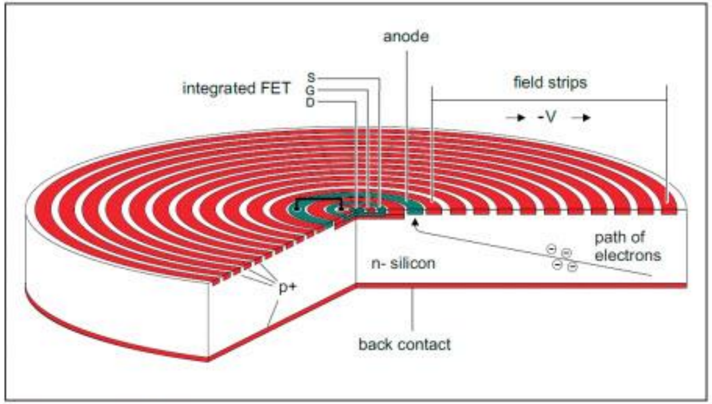
Science case - state of the art

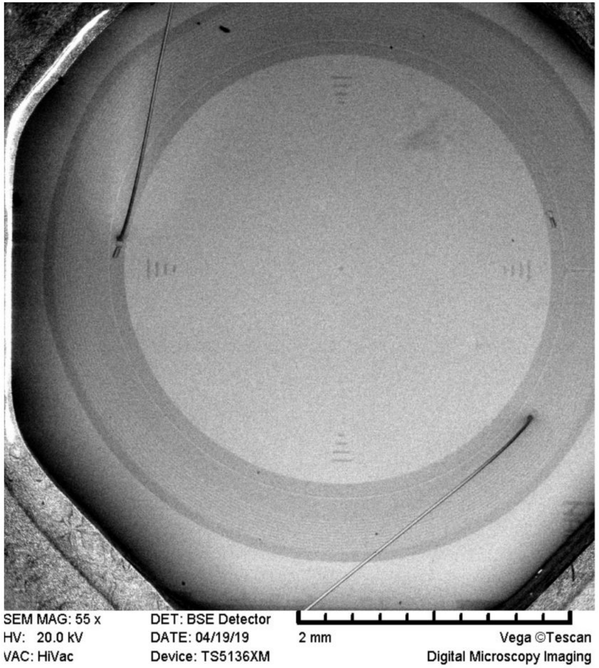
Technique	Energy Range	Strength	Weakness
Magnetic Spectrometer	>50 keV	Versatility in the isotope choice Very low background	High energy threshold Low containment efficiency
Plastic Scintillator	>50 keV		
Semiconductor (embedded source)	>80 keV	Excellent energy resolution Very low background	High threshold Few isotopes can be studied
Cryogenic Calorimeter	>10 keV	Excellent energy resolution Simple response function	Complex operation Few isotopes can be studied
Metallic Magnetic Calorimeter	700 eV - 350 keV	Several isotopes can be studied Very low background Suitable for high counting rate Excellent energy resolution	Containment No back-scattering veto Complex signal readout Low-temperature operation

SDD spectroscopy - working principle

SDD = Silicon Drift Detector

- silicon-based solid state detector
- thin implanted entrance window with O(20nm) dead-layer
- point-like anode for the charge collection
- funnel-like electric field to guide electrons towards the anode
- thick depleted region (up to millimeters)
- integrated first amplification stage

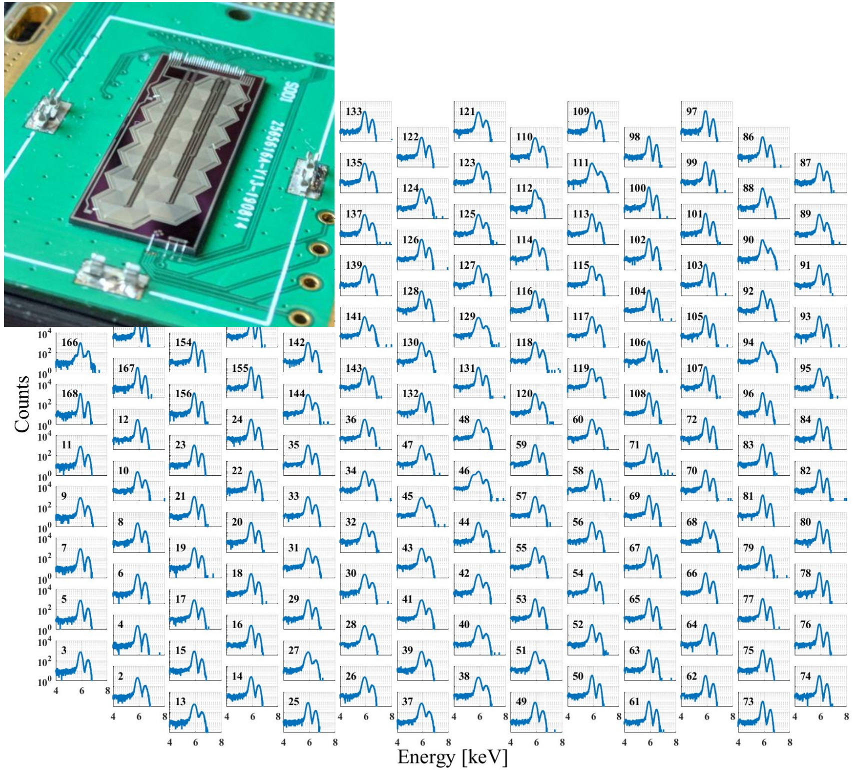




SDD spectroscopy - working principle

SDD = Silicon Drift Detector

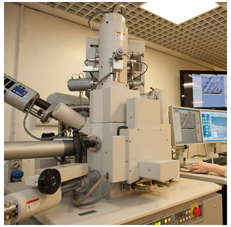
- excellent **energy resolution** (information-carriers statistics limited) already at 5.9 keV ^{55}Fe line (200 eV FWHM routinely achieved on hundreds of pixels)
- low **energy threshold** (<1 keV)
- very good **timing performance** (100 kS/s counting rate achievable)
- **multi-pixel design** possible and demonstrated on large scale to increase total counting rate
- simple, predictable and extensively studied **response** to monoenergetic electrons
- integrated JFET design for low-noise and high speed applications

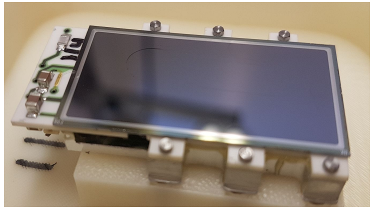


SDD spectroscopy - state of the art

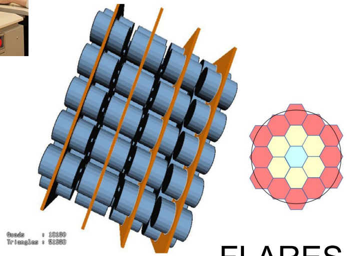
X-ray spectroscopy:

- commercial applications, SEM microanalysis
- X-rays from kaonic atoms, monolithic large area detectors with low dead margins, radiation hardness, high counting rates
- soft X-ray spectroscopy (down to C-K$_\alpha$ 277 eV)
- scintillation light detection with large coupling surface



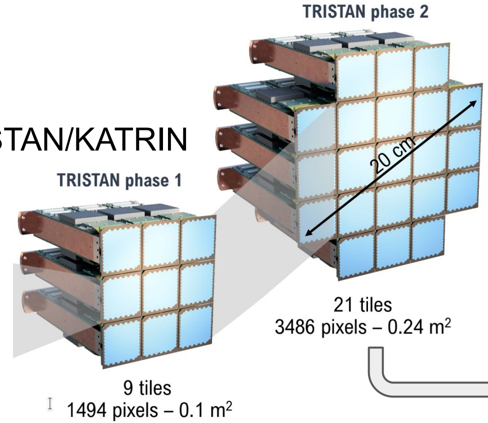


SIDDHARTA



FLARES

TRISTAN/KATRIN



Electron spectroscopy:

- Tristan, 166 pixel matrices with 100 kHz counting rate for T spectroscopy and sterile neutrino search, fast and low-noise readout with integrated JFET

Extensive program of SDD-electron response characterization

SDD-based spectrometer

Basic concept:

- measure electrons kinetic energy with a primary SDD
- consider only events where all energy is contained in primary SDD
- tag and discard all events where a fraction of the energy is lost
- correct (deconvolve) measured energy spectrum with the primary SDD response function

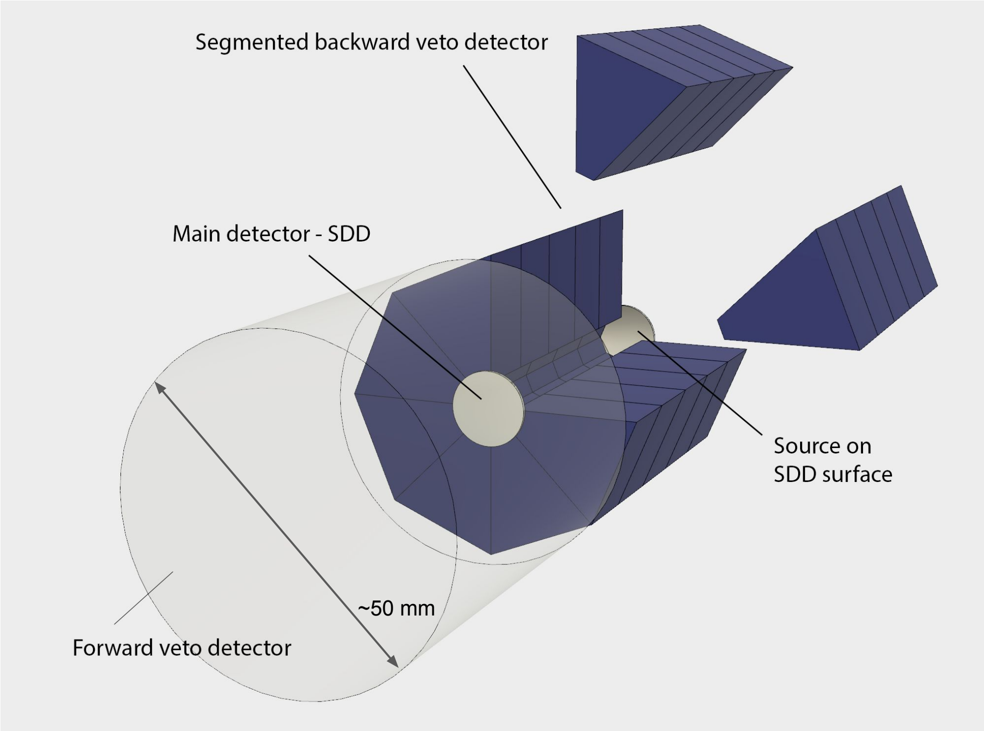
Reconstruct original beta spectrum with high precision and accuracy

SDD-based spectrometer - conceptual design

Main detector: primary SDD, should fully contain electron energy

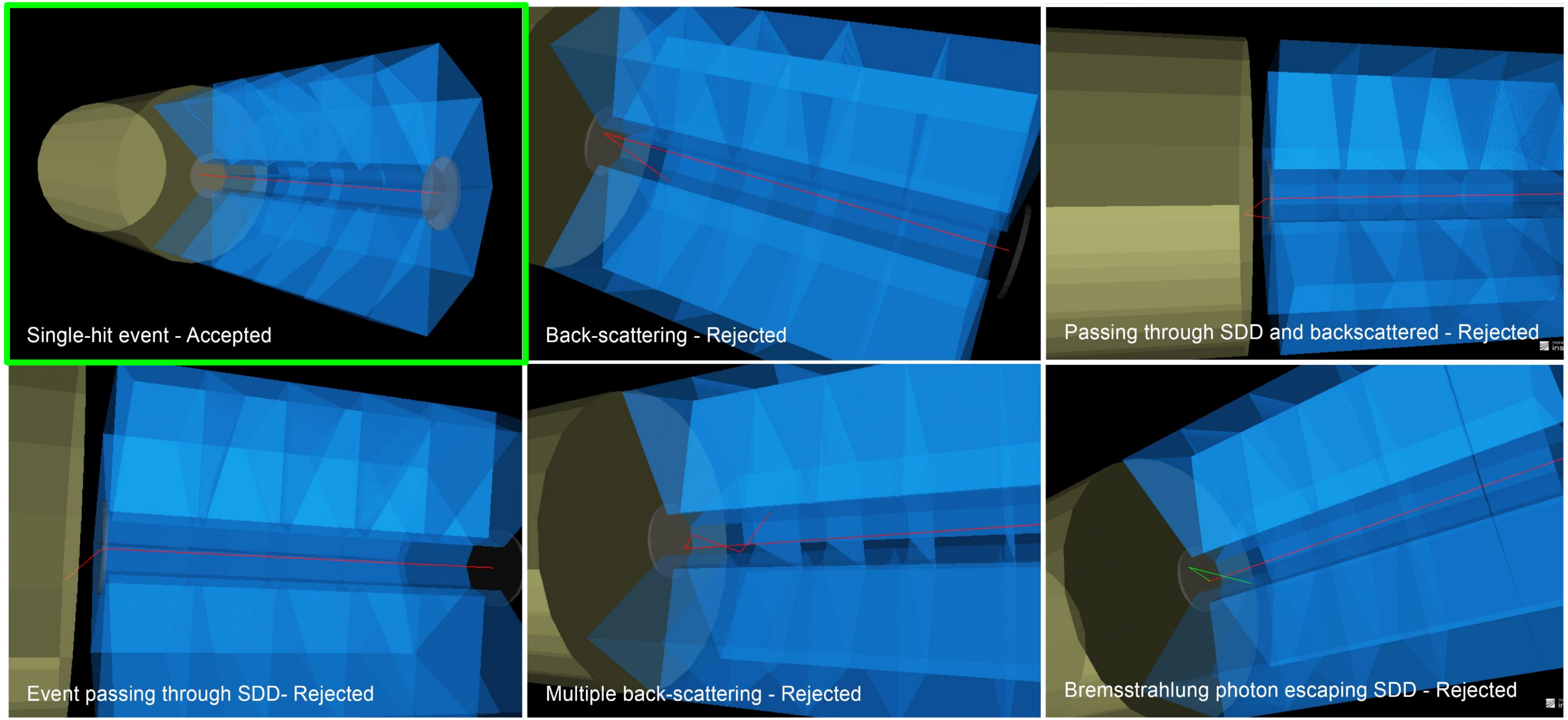
Ancillary detectors:

- ~4π veto with segmented scintillator to contain escaping energy
- additional SDD with surface deposited source
- active collimator integrated in backward veto to reduce angular spread and dead layer effect



SDD-based spectrometer - conceptual design

Selection of events: only single hit events on primary SDD are golden dataset



Integrated spectrometer design - sources

The spectrometer should be able to operate with two types of sources:

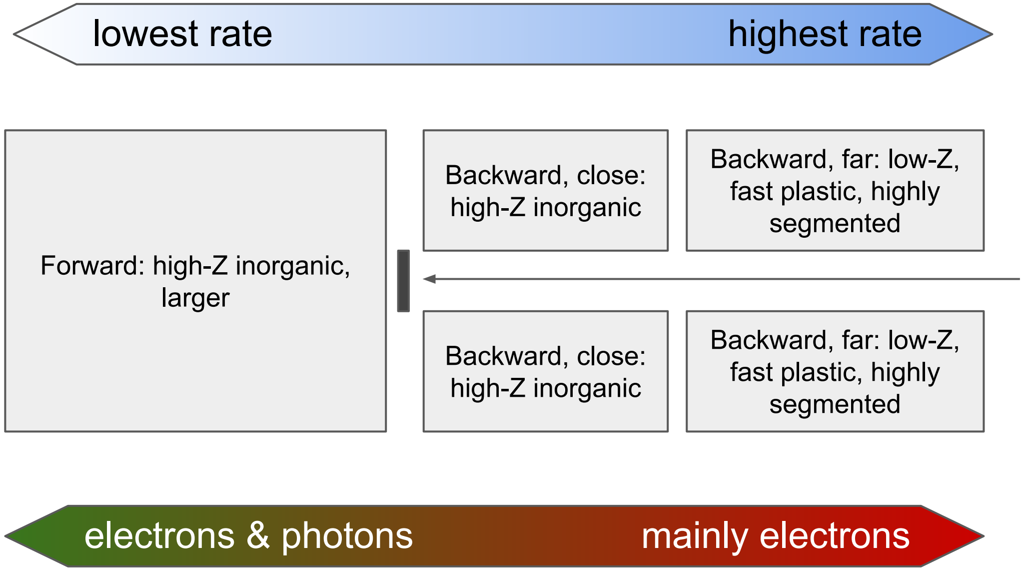
- long or medium lived isotopes:
  - collection with mass-spectrometer or electro-chemical deposition
  - collected on active element (secondary SDD) to reject back-emitted electrons
  - secondary SDD likely multi-pixel to handle highest rate in the system
  - table-top experiment
- short lived isotopes from Radioactive Ion Beams:
  - simply remove secondary SDD
  - self contained system to easily integrate on beam-line infrastructure
  - material selection taking into account compatibility with RIBs

Integrated spectrometer design - veto detectors

Exact configuration of veto detectors will result from extensive campaign of simulation to optimize geometry, segmentation and material.

Guidelines:

- fast
- high photo-peak efficiency for ~100keV photons
- low Z, low density to minimize backscattering
- single-photon sensitive compact light readout for low threshold (SiPM)
- largest possible angular coverage



SDD response function

Eventually only SDD response function is relevant for the spectral shape reconstruction.

Effects that need to be modelled:

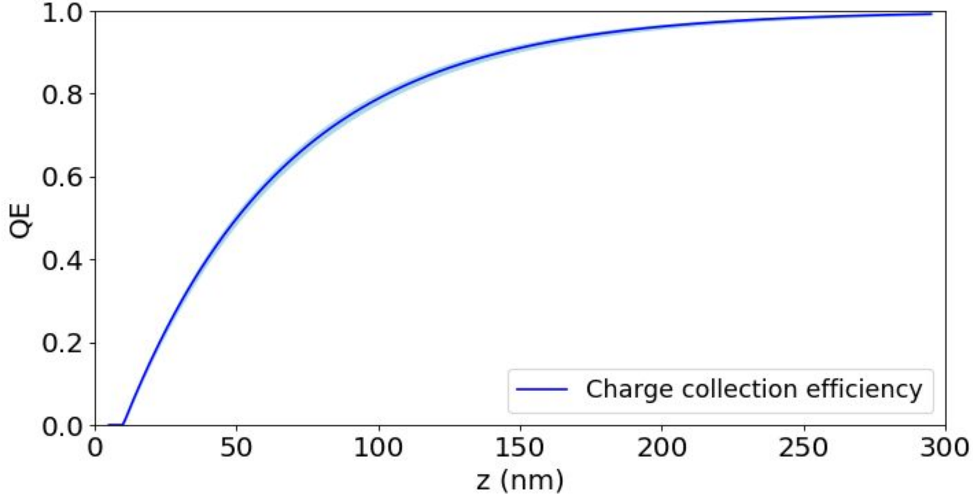
- dead-layer
- “quantum-efficiency”, probability of collecting information-carriers produced in implanted region
- charge sharing
- back-scattering

SDD response function - entrance window and quantum efficiency

Electrons deposit energy continuously in the silicon.
Probability of an electron-hole pair actually contributing to signal formation (Q.E.) depends on production depth:

$$f_{\mathrm{QE}}(z; t, p_0, p_1, \lambda) = \begin{cases} p_0 & z < t \\ 1 + (p_1 - 1)\exp\left(-\frac{z-t}{\lambda}\right) & z > t \end{cases}$$

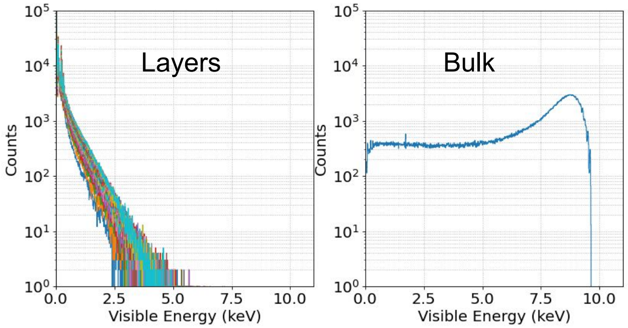
- no charge collection in the dead-layer
- partial charge collection in the superficial implanted structures (entrance window)
- full charge collection in the depleted bulk



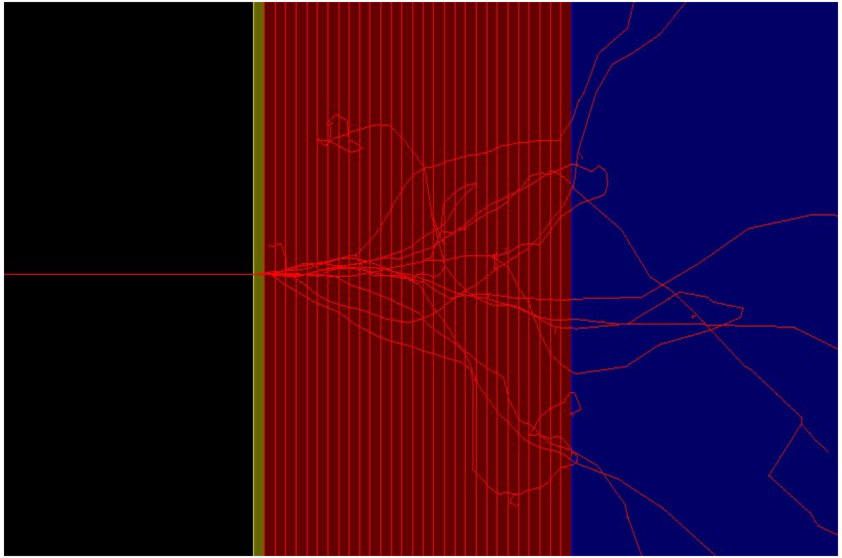
SDD response function - entrance window and quantum efficiency

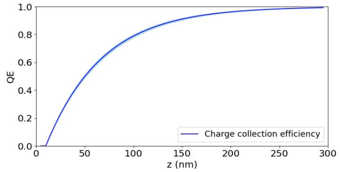
Particle interaction with silicon is simulated with Geant4-based Montecarlo:

- divide the detector in 31 regions:
  - 30 layers 10 nm thick
  - bulk
- record energy deposited in each region



- build the total measured energy by weighting each region for the corresponding Q.E.

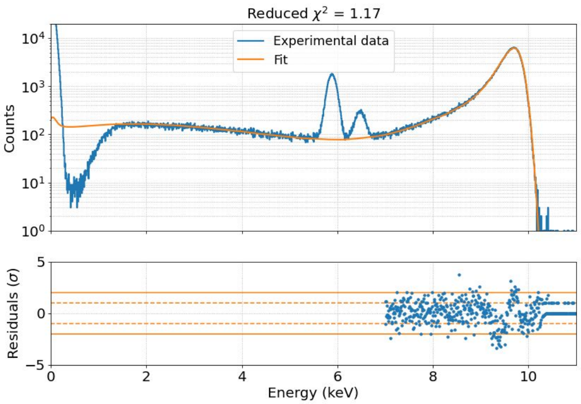


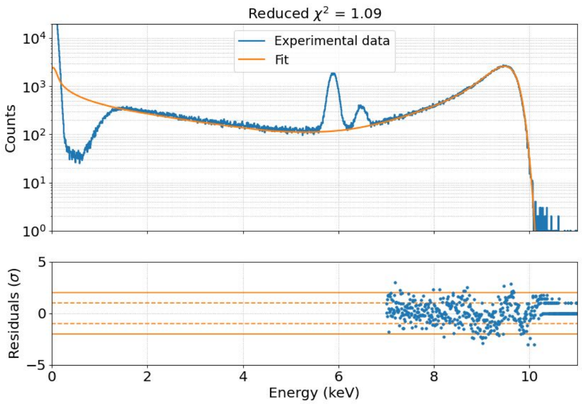


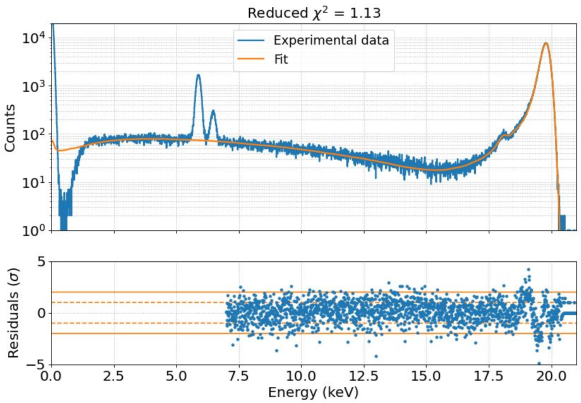
SDD response function - entrance window and quantum efficiency

Q.E. is not known a priori → fit to data to constraint free parameters (dead-layer thickness, characteristic length of exponential region, starting efficiency at the dead-layer boundary). Two sets of data:

- Scanning Electron Microscope: fine angular scan, only 10 and 20 keV



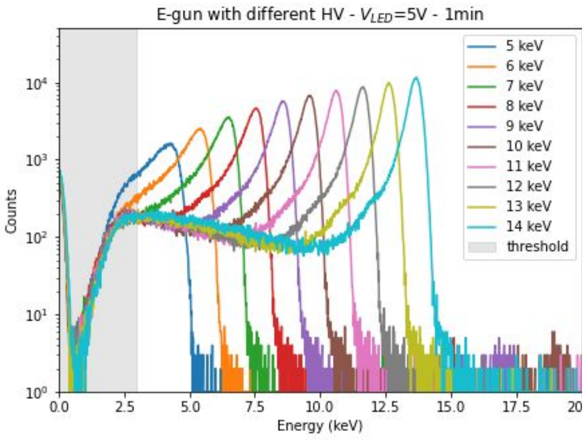


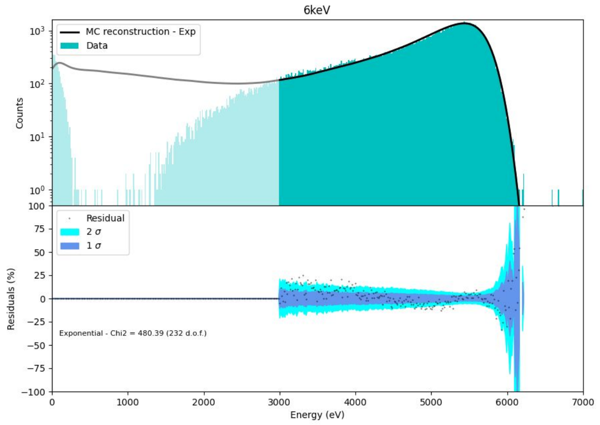


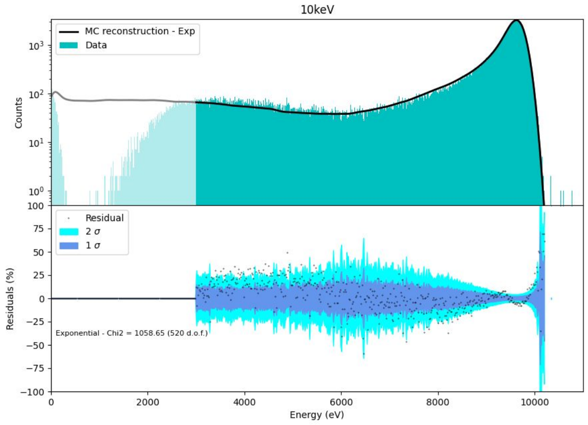
SDD response function - entrance window and quantum efficiency

Q.E. is not known a priori → fit to data to constraint free parameters (dead-layer thickness, characteristic length of exponential region, starting efficiency at the dead-layer boundary). Two sets of data:

- Custom-built electron gun (slide 24): 90° incident angle, fine energy scan in 6-15 keV







SDD response function - back scattering

Back-scattering → electrons deposit only a fraction of energy and leave the detector from entrance window

- primary electron: high momentum transfer scattering can change drastically the electron direction
- secondaries production: low energy electrons are ejected from the detector surface as a consequence of momentum transfer from the primary

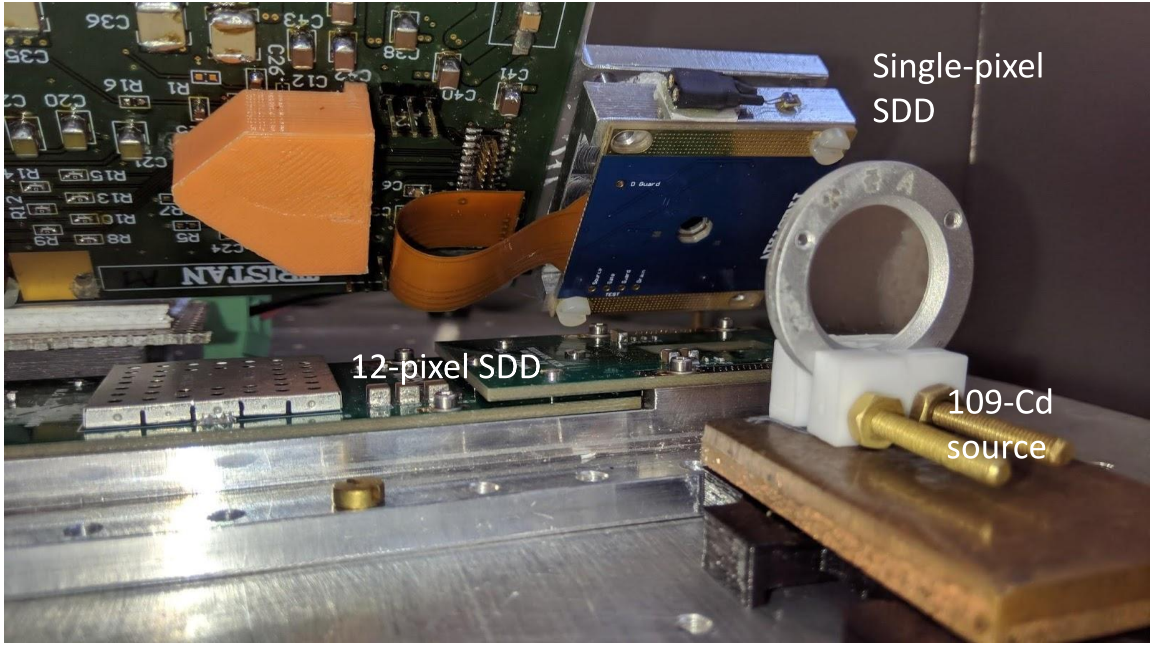
Must be included in the detector response model.

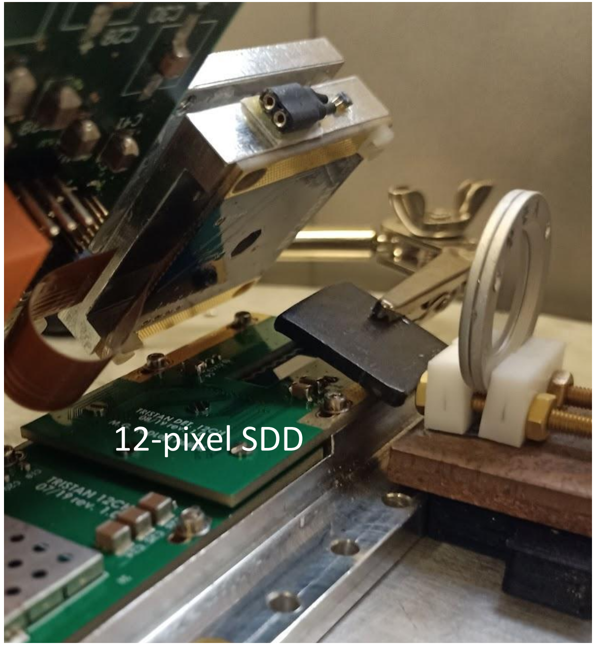
→ Geant4 simulations can model this effect but results (yield, energy spectrum and angular distribution) strongly depend on physics list and simulation parameters

→ Need dedicated measurements to constraint Geant4-based model

SDD response function - back scattering

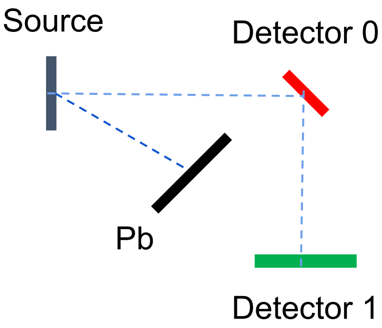
Back-scattering measurements: **internal conversion source**

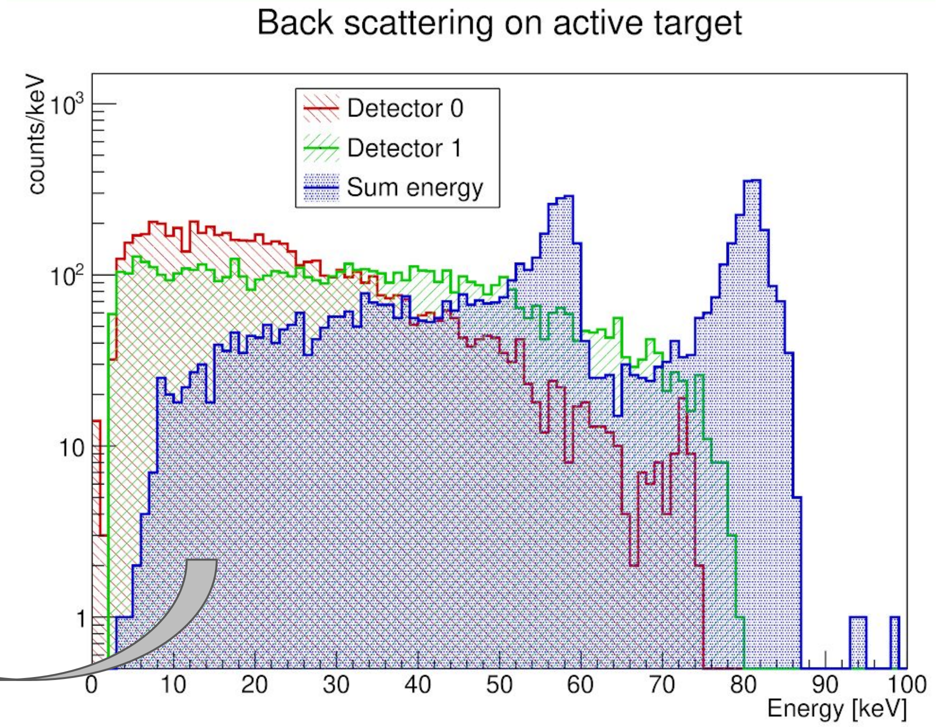




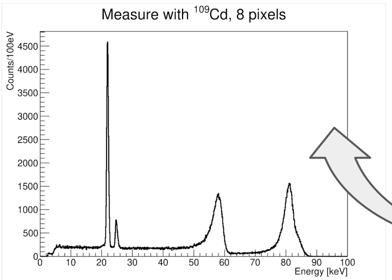
SDD response function - back scattering

Back-scattering measurements: **internal conversion source**





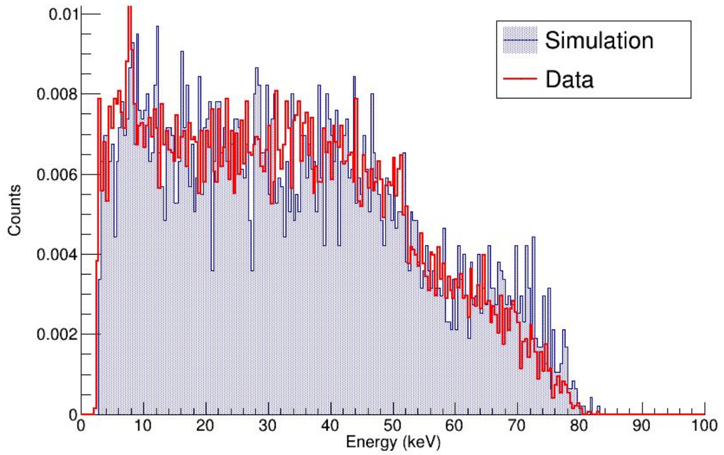
Single-hit reference spectrum



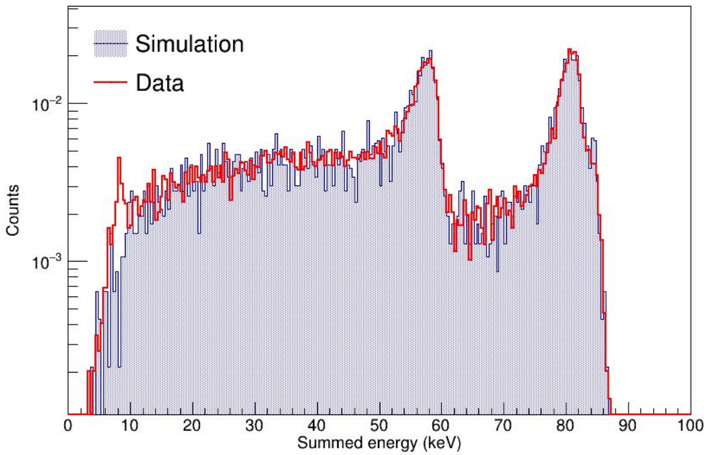
SDD response function - back scattering

Back-scattering measurements: **internal conversion source**

Detector 1



Sum energy



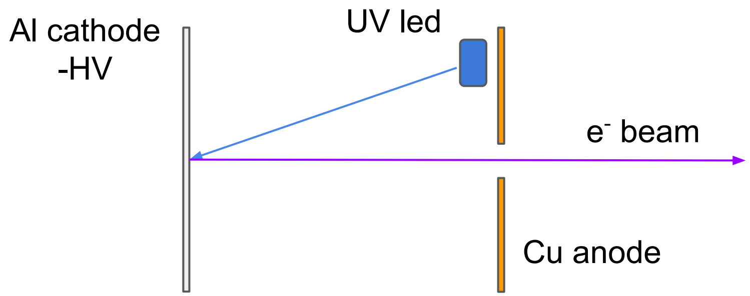
Very good agreement between data and simulation, but **source self-absorption** and **low geometrical efficiency** is limiting the sensitivity

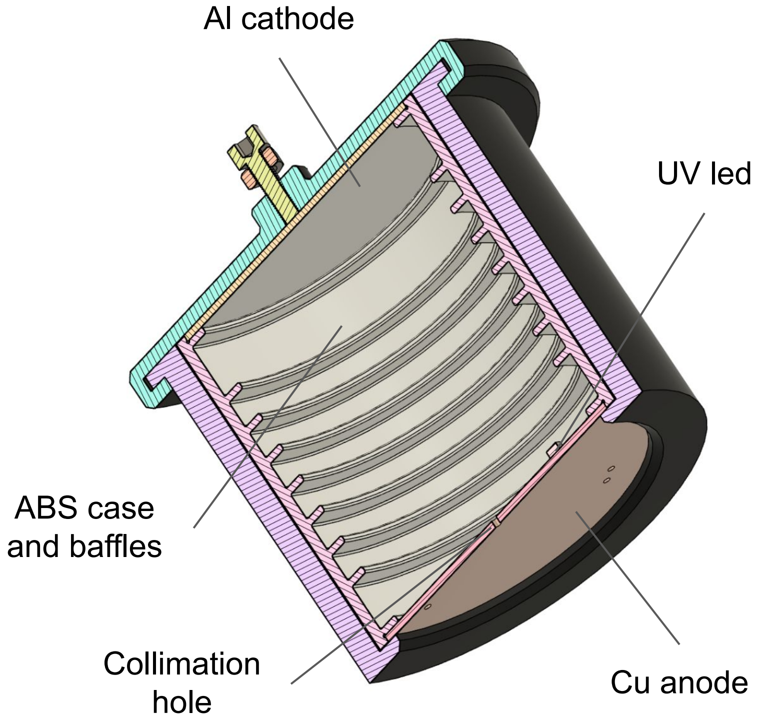
Need a better source
Electron gun

SDD response function - back scattering

Back-scattering measurements: **electron gun**

- versatile source
- collimated beam
- arbitrary energy in the relevant range, 0-15(30) keV
- controlled direction
- passive target → multiple materials
- higher geometric efficiency with much smaller activity → higher statistics

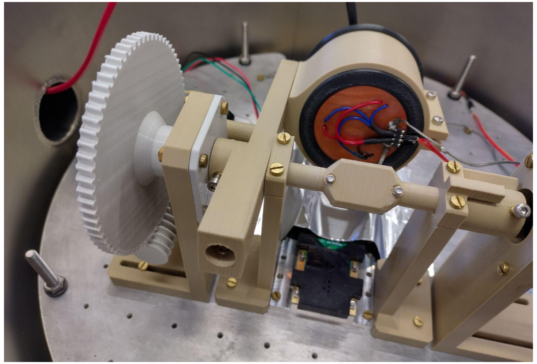


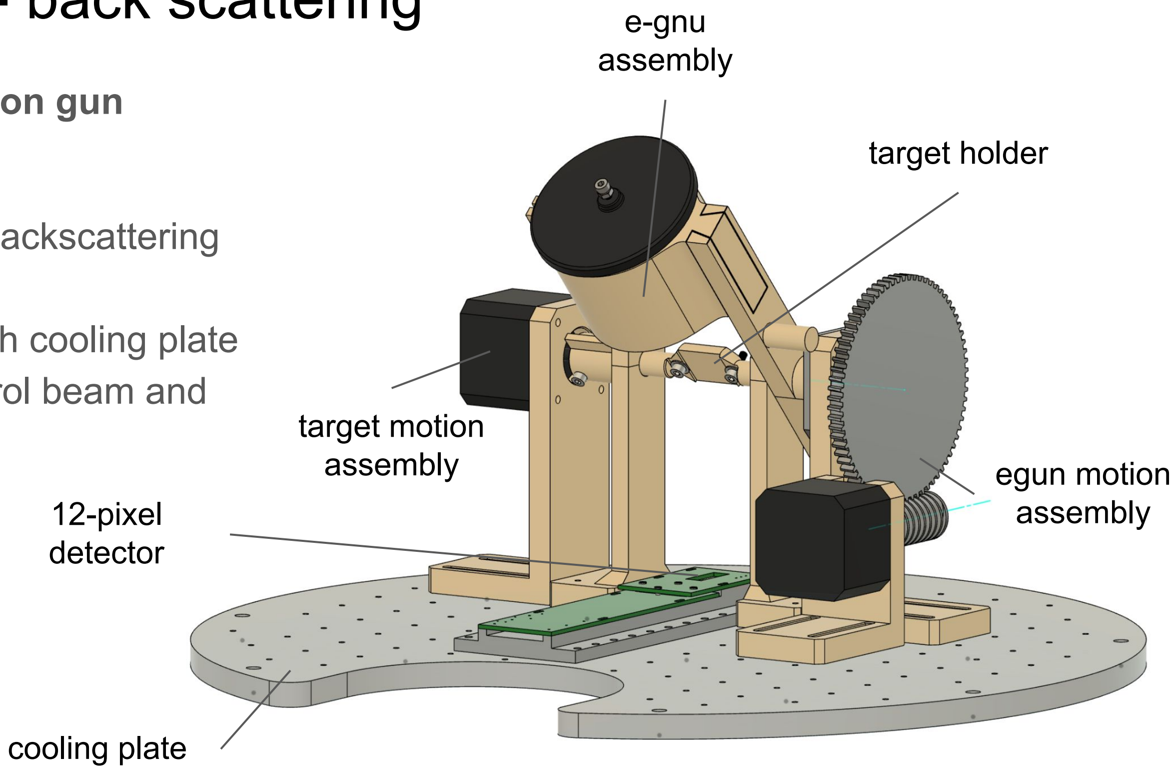


SDD response function - back scattering

Back-scattering measurements: **electron gun**

- different material targets
- 12 pixel sdd matrix to measure backscattering spetrum
- mounted in vacuum chamber with cooling plate
- stepper motors to precisely control beam and target angle w.r.t. detectors



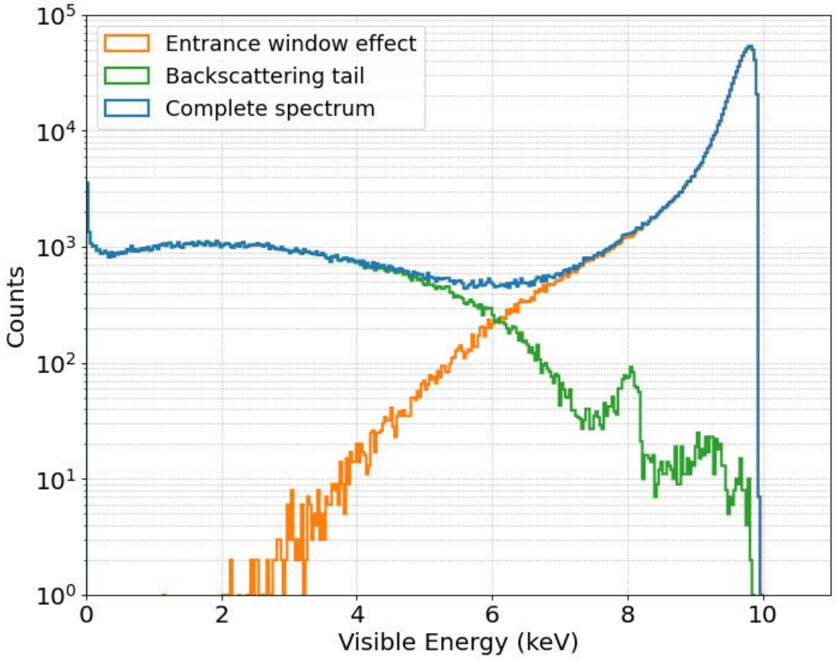


First data in backscattering configuration with Al target being collected now

SDD response function - combined effect

Entrance window quantum efficiency and back-scattering effect can be disentangled only with simulations (that also model x-rays and bremsstrahlung):

Back scattering (and X-ray production) dominates low energy tail



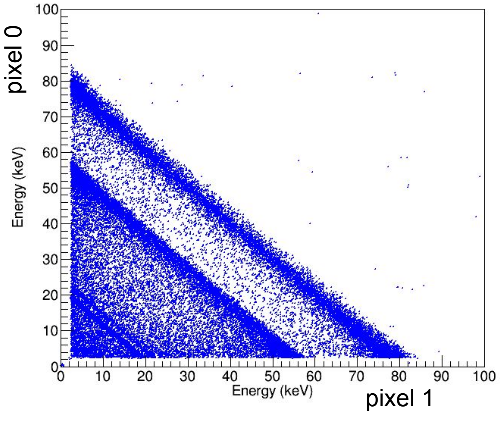
Quantum efficiency mainly affects region close to the full absorption peak

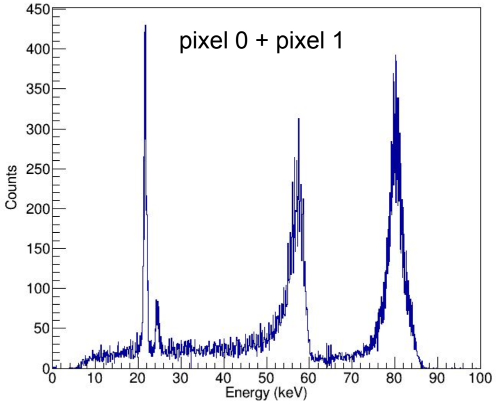
SDD response function - charge sharing

Electron-hole pairs produced close to the boundary of an SDD can be partially collected in adjacent element (if multi-pixel device) or get lost → deformation of energy spectrum

Accurate knowledge of CS probability as a function of energy must be included in the detector response function

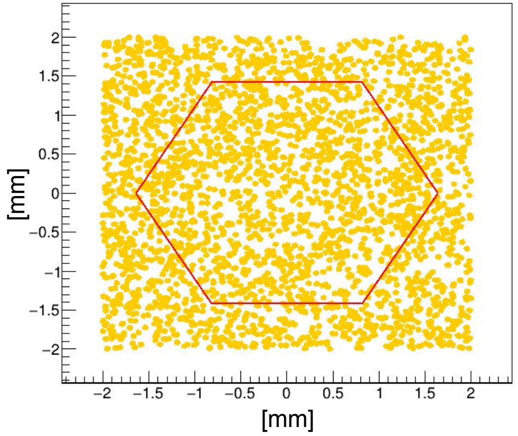
Collect 2-pixel (adjacent) coincidence data with electron conversion source ^{109}Cd





Select events with total energy in a specific peak

Compare with toy MCs with **charge cloud size** as free parameter



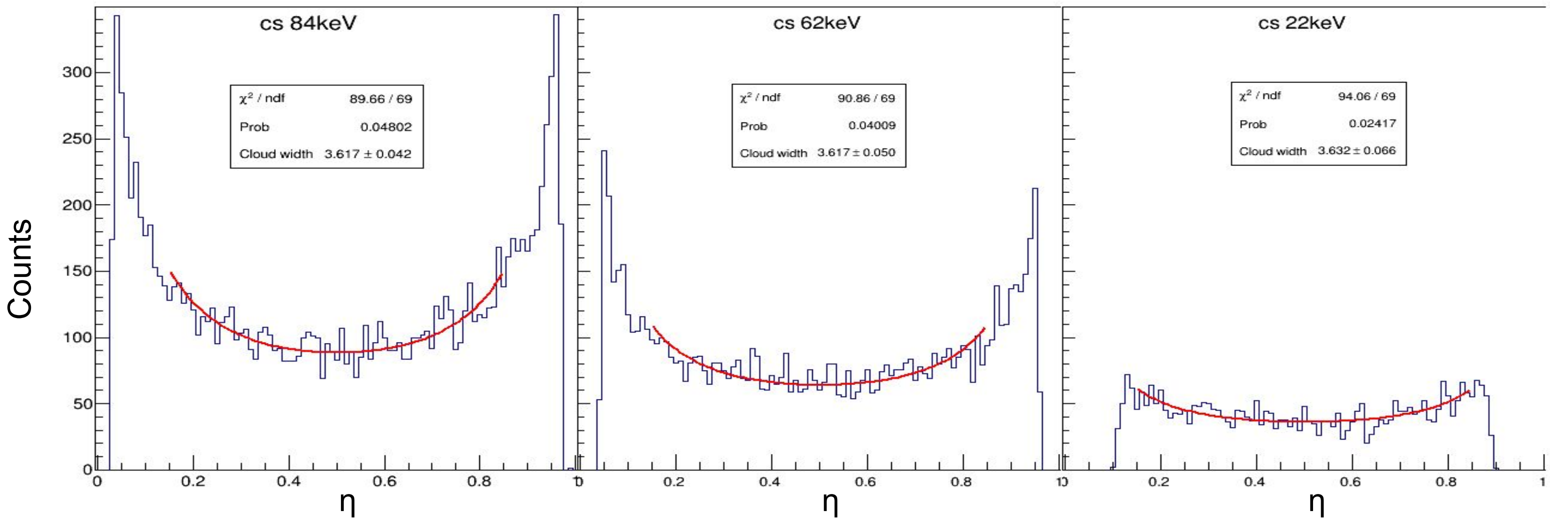
SDD response function - charge sharing

Build distributions of parameter

$$\eta = E_0/(E_0+E_1)$$

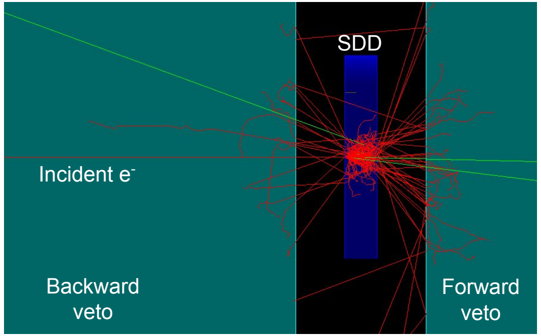
and find value of **charge cloud size** that best fit the data

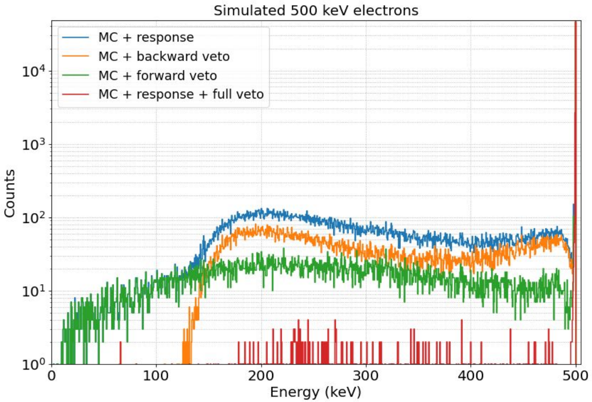
Data driven model for Charge Sharing to be included in the response function of the SDD



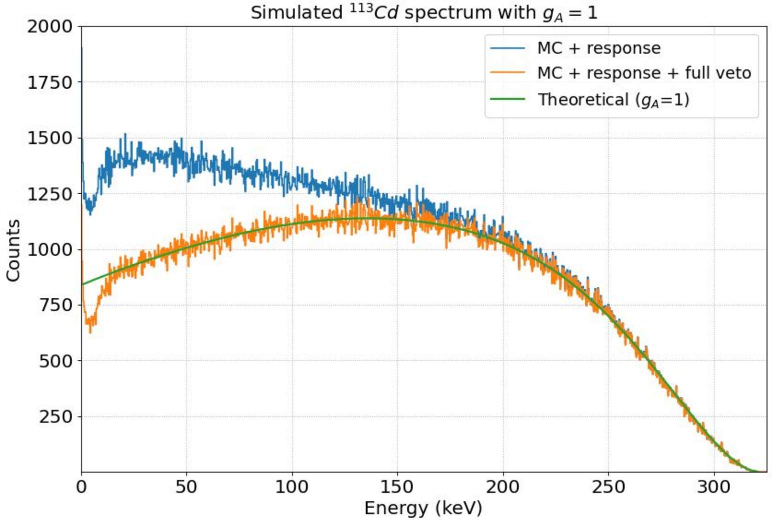
Global spectrometer response function

Combining SDD response function and simulations of full spectrometer



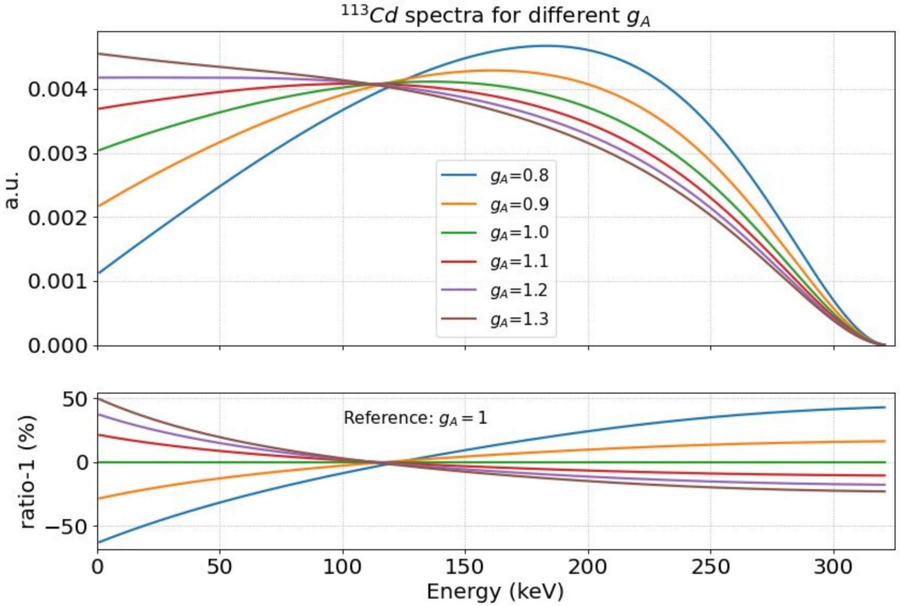


Simulate beta spectrum



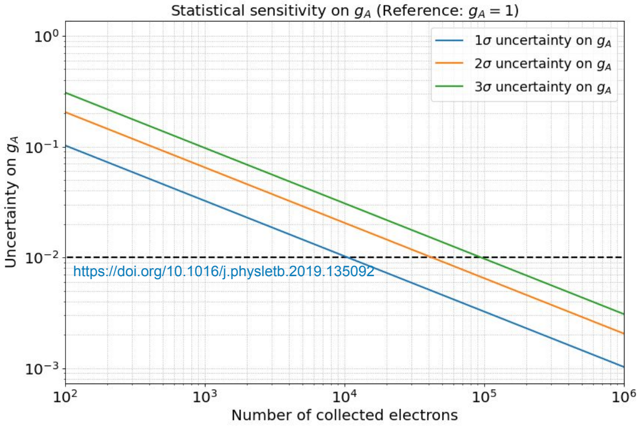
Sensitivity studies

Forbidden beta decays and g_A parameter: ^{113}Cd



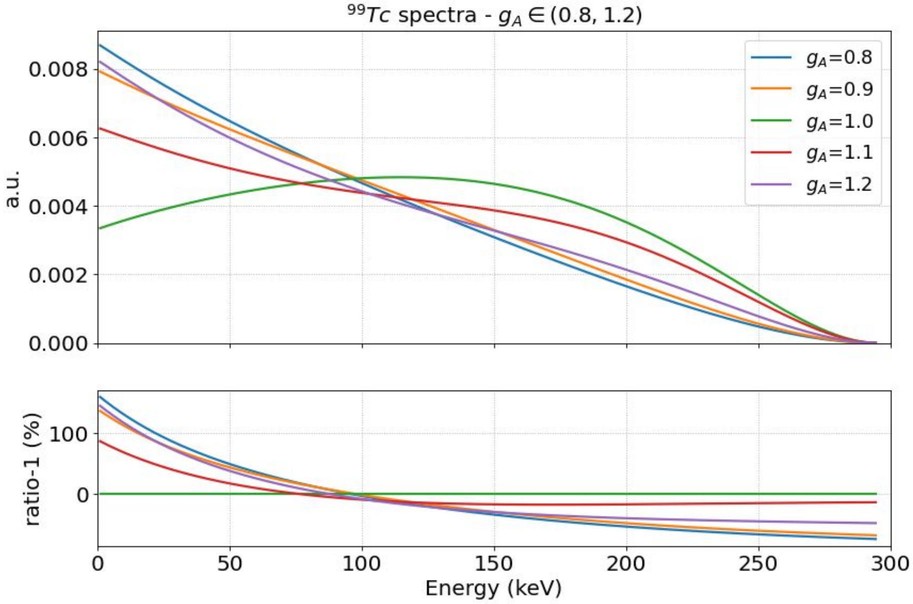
Theoretical spectra from J. Suhonen, Frontiers in Physics Vol. 5 (2017) 55

- spectral shape strongly depends on g_A quenching
- thanks to high rate, high statistics and zero background are possible
- with quasi-monochromatic spectrometer response function and 10^4 events the current sensitivity (calorimetric experiments) can be surpassed



Sensitivity studies

Forbidden beta decays and g_A parameter: ^{99}Tc



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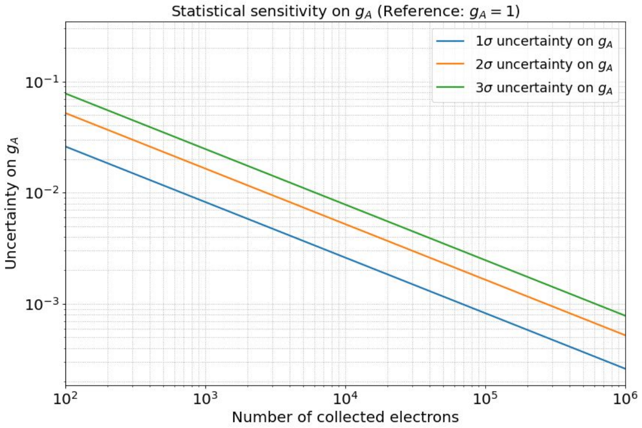

Group of interest

Groups that showed interest in the project at some point of history

Milano-Bicocca INFN & Università:
Matteo Biassoni
Chiara Brofferio
Silvia Capelli
Oliviero Cremonesi
Stefano Pozzi

Politecnico di Milano
Marco Carminati
Carlo Fiorini

GSSI:
Lorenzo Pagnanini

Università degli Studi della Campania:
Luigi Coraggio

LNS INFN & Università di Catania:
Francesco Cappuzzello
Manuela Cavallaro

Ready for new Collaborations!

Conclusions

- Accurate and precise measurement of beta spectra from many isotopes of interest as input to theoretical calculations
- Leverage **deep understanding of the detector response** of SDDs to electrons coming from preparation of TRISTAN upgrade for KATRIN
- Leverage high-count rate capabilities and flexibility of SDDs to achieve high statistics with table-top experiment
- **Multiple sources**: isotopes collected on active target or radioactive ion beams
- Multi-detector system with 4π veto to select events with **full energy containment**
- Currently at the proposal level with **core technology already very mature**

THANKS FOR THE ATTENTION!