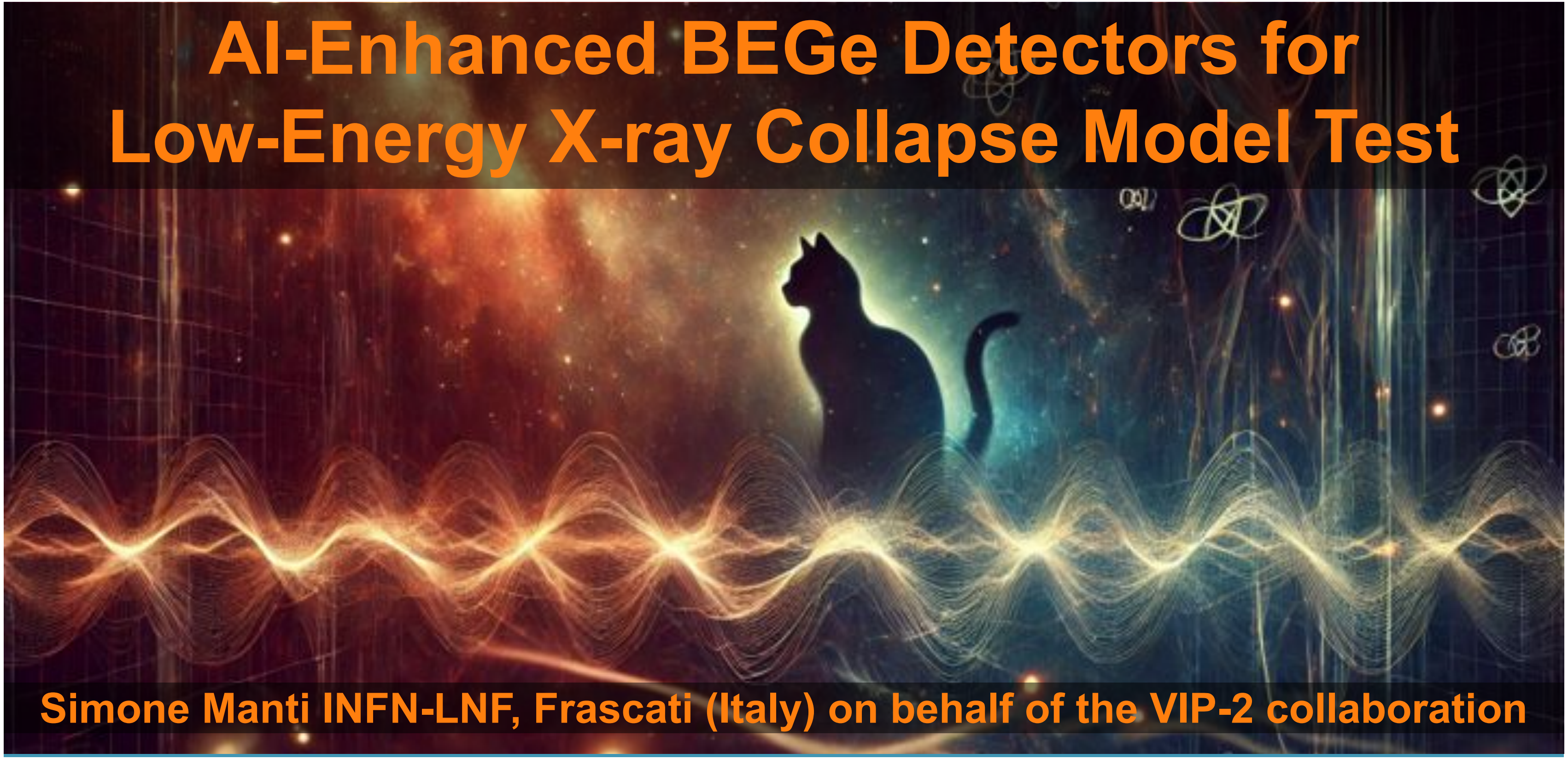
AI-Enhanced BEGe Detectors for Low-Energy X-ray Collapse Model Test



Simone Manti INFN-LNF, Frascati (Italy) on behalf of the VIP-2 collaboration

Content

- **Testing Collapse Models through Spontaneous Emission**
- **Emission Rate in the Low-Energy Regime:**
  - **Rate Calculations and Cancelation Effects**
  - **AI-assisted BEGe detector for low-energy analysis**

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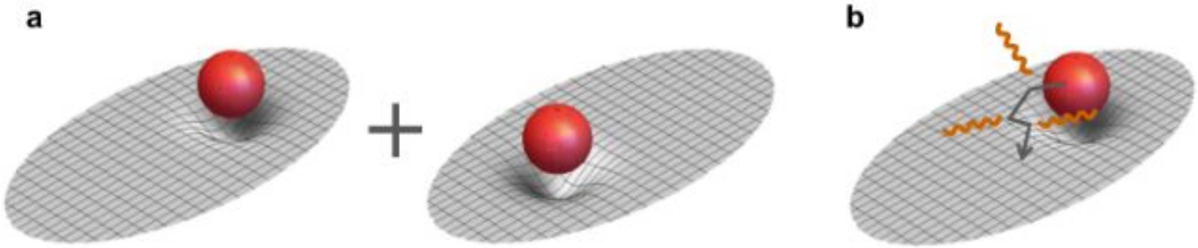
The Measurement Problem and Collapse Models

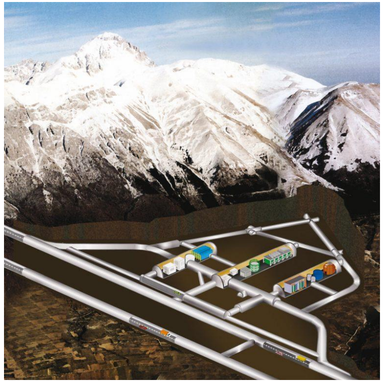
- **Quantum Mechanics:** Allows precise predictions, but superposition principle is not observed in macroscopic systems.
- **Collapse Models:** Propose that quantum mechanics' linearity breaks down at a certain scale to solve the measurement problem (GRW,DP,CSL,Károlyházy,...)
  - **Continuous Spontaneous Localization (CSL)**
  - **Diósi-Penrose (DP)**

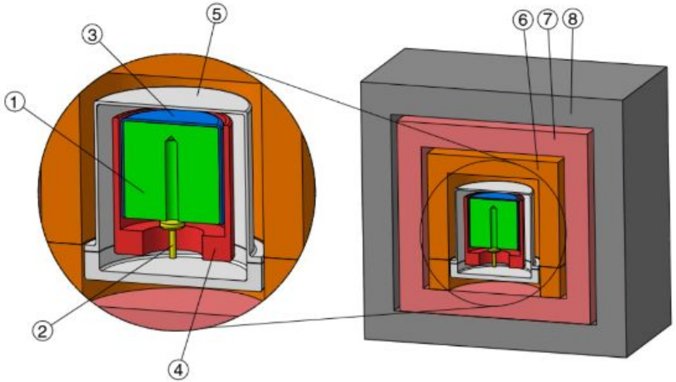


How to test Collapse Models?

- Unavoidable side effect of the **Stochastic Collapse Dynamics**: Brownian-like diffusion of the system in space
- **Charged particles** emit spontaneous radiation. We search for spontaneous radiation emission from a germanium crystal and the surrounding materials in the experimental apparatus.

Gran Sasso environment (LNGS) low-background enhanced sensitivity 3600 m w.e.

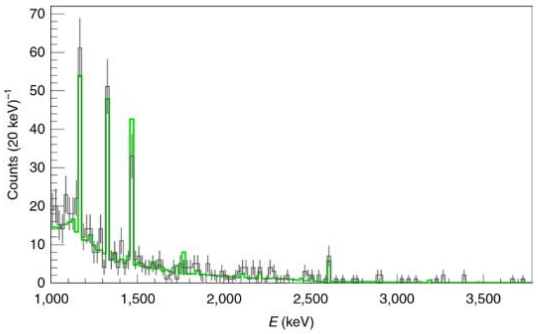


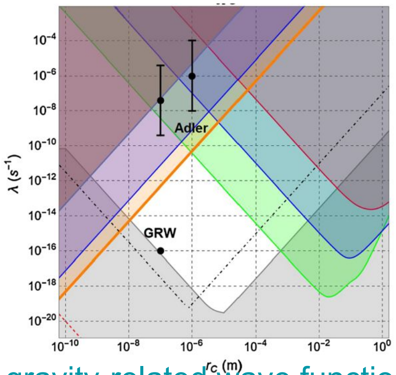


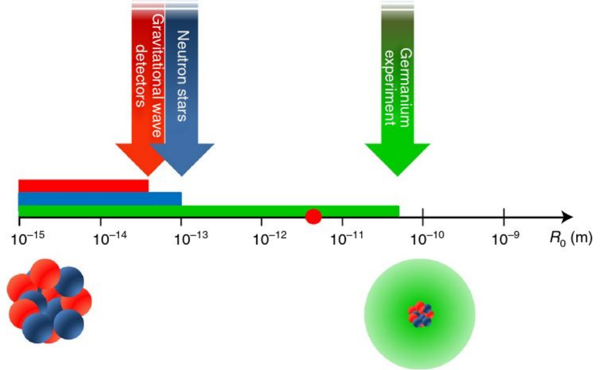
How to test Collapse Models?

Strategy:

- **Simulate the background** from all the known emission processes
- Perform a **Bayesian inference** of the residual spectrum with the theoretical prediction
- Extract the **PDF** of the **Model Parameters**
- **Bound the Parameters**



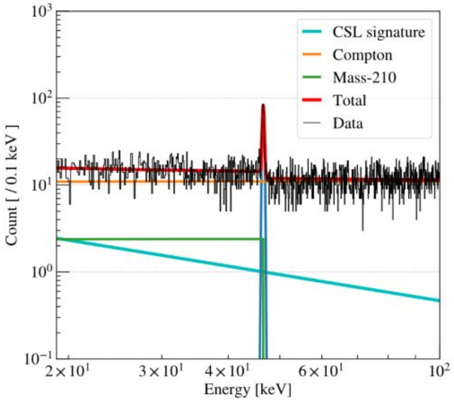


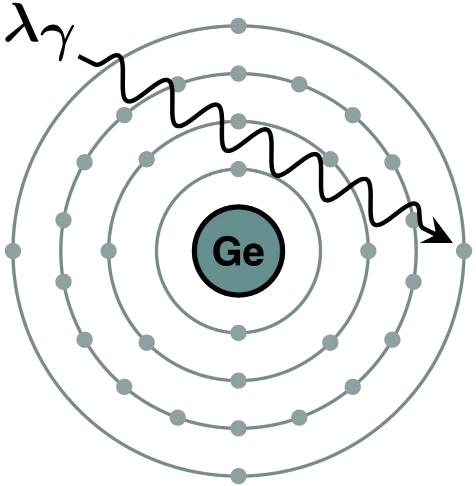


[Donadi, Sandro, et al. "Underground test of gravity-related wave function collapse." *Nature Physics* 17.1 (2021): 74-78.]

Testing Emission Rate at Low-Energy

- Theoretical spectrum follows a **~1 / E dependence**, implying a **diverging rate at low energies**
- **Low-Energy Region** is the most promising to observe or constrain collapse-induced radiation and discriminate different models





Arnquist, I. J., et al. *Physical Review Letters* 129.8 (2022): 080401.

Content

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Atomic Structure Effects on the Emission Rate at Low-Energy

- Dissipative dynamics of collapse models is described by a master equation:

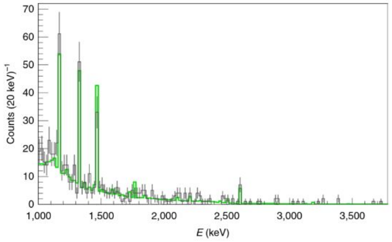
$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{1}{2\hbar^2}\int d^3r d^3r' \mathcal{D}(\boldsymbol{r} - \boldsymbol{r}')[\hat{\varrho}(\boldsymbol{r}), [\hat{\varrho}(\boldsymbol{r}'), \hat{\rho}]] \qquad \hat{\varrho}(\boldsymbol{r}) = \sum_{\iota=1}^{n} m_\iota \sum_s a_\iota^\dagger(\boldsymbol{r}, s) a_\iota(\boldsymbol{r}, s)$$

- The **spontaneous emission rate** is given by:

$$\frac{d\Gamma}{dE} \sim \frac{1}{E}\sum_{ij} q_i q_j \frac{\sin(k r_{ij})}{k r_{ij}}(-\nabla^2 D(r, \omega)) \qquad -\nabla^2 D(r,\omega) = \begin{cases} \dfrac{\hbar G}{2\sqrt{\pi}\sigma^3} e^{-r_{ij}^2/4\sigma^2} & \textbf{(DP)} \\ \dfrac{6\hbar^2\lambda}{4 m_0^2 \sigma^3}\left(1 - \dfrac{r_{ij}^2}{6\sigma^2}\right) e^{-r_{ij}^2/4\sigma^2} & \textbf{(CSL)} \end{cases}$$

- For **Radiation Wavelengths** larger than **Interatomic Distances**, the rate simplifies to:

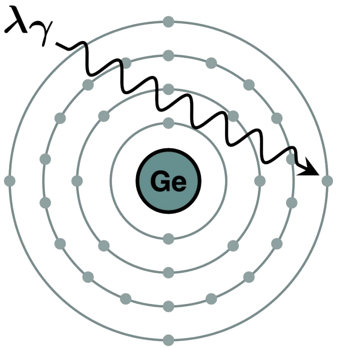
$$\frac{d\Gamma}{dE} \sim \frac{1}{E}(N_p^2 + N_e)$$



[Donadi, Sandro, et al. "Underground test of gravity-related wave function collapse." *Nature Physics* 17.1 (2021): 74-78.]

Low energy limit: Semiclassical Approximation

$$\frac{d\Gamma}{dE} \sim \frac{1}{E} \sum_{ij} q_i q_j \frac{\sin(kr_{ij})}{kr_{ij}} (-\nabla^2 D(r,\omega))$$



- **Proton-Proton term:**

$$|\mathbf{r}_{ip} - \mathbf{r}_{jp}|/\lambda_\gamma \ll 1 \qquad (\mathbf{r}_{ip} - \mathbf{r}_{jp})^2/r_C^2 \ll 1$$

- **Proton-Electron term:**

$$|\mathbf{r}_{ip} - \mathbf{r}_{je}^{(o)}| = \langle \mathbf{r}_{je}^{(o)} \rangle = \rho_o$$

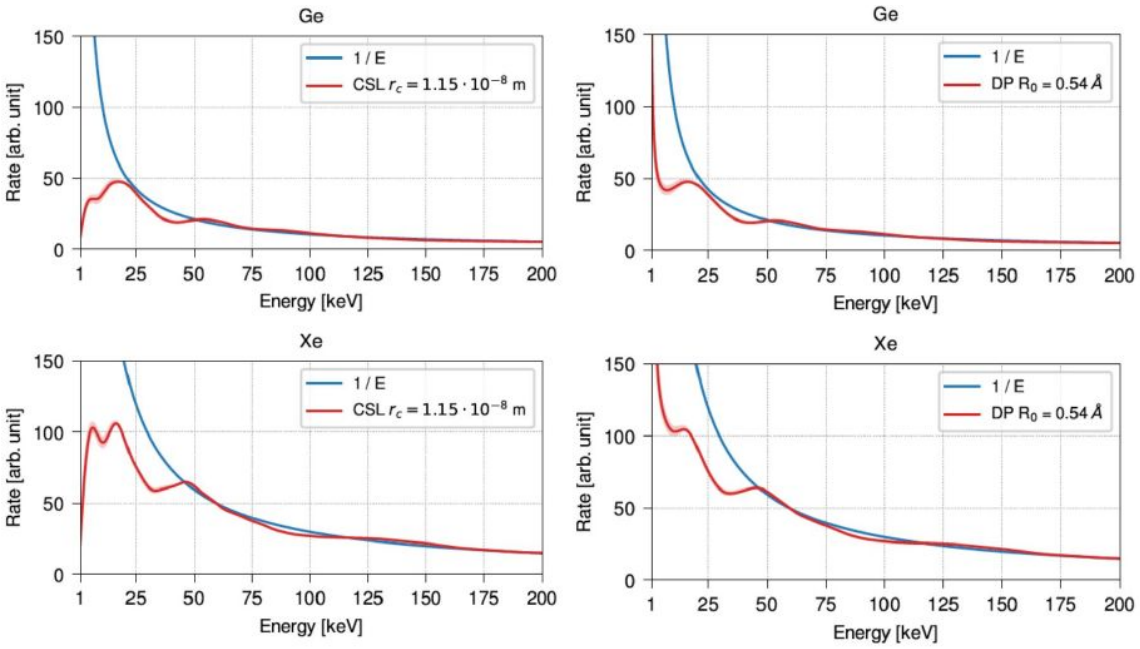
- **Electron-Electron term:**

$$\begin{cases} |\mathbf{r}_{ie}^{(o)} - \mathbf{r}_{je}^{(o')}| = \langle \mathbf{r}_{ie}^{(o)} - \mathbf{r}_{je}^{(o)} \rangle = \alpha\rho_o & if \quad o = o' \\ |\mathbf{r}_{ie}^{(o)} - \mathbf{r}_{je}^{(o')}| = \langle \mathbf{r}_{ie}^{(o)} - \mathbf{r}_{je}^{(o')} \rangle = (1-\beta)|\rho_o - \rho_{o'}| & if \quad o \neq o' \end{cases}$$

state nl	occupation	eigenvalue [Hartree]	[eV]	<r> [Bohr]
1s	2.000	-396.251380	-10782.54926	0.048
2s	2.000	-49.051315	-1334.75427	0.214
2p	6.000	-43.720357	-1189.69150	0.185
3s	2.000	-5.960689	-162.19862	0.636
3p	6.000	-4.194670	-114.14278	0.653
3d	10.000	-1.117153	-30.39929	0.733
4s	2.000	-0.426445	-11.60415	2.142
4p	2.000	-0.149906	-4.07915	2.883

Piscicchia, Kristian, et al. *Physical Review Letters* 132.25 (2024): 250203.

Low energy limit: Semiclassical Approximation



Piscicchia, Kristian, et al. *Physical Review Letters* 132.25 (2024): 250203.

- Differences compared to the **~1/E behaviour**!
- **Different model** (CSL and DP) exhibits **different behaviour** as function of the energy
- **Atomic Cancellation** effect in **CSL** at low energies
- Scheme recently used by **XENON experiment**

Aprile, E., et al. "Challenging Spontaneous Quantum Collapse with XENONnT." *arXiv preprint arXiv:2506.05507* (2025).

Low energy limit: Radial Distribution Functions (RDFs)

Including realistic Radial Distribution in the Emission Rate formula:

$$\frac{d\Gamma}{dE} \sim \frac{1}{E} \sum_{ij} q_i q_j \frac{\sin(kr_{ij})}{kr_{ij}} (-\nabla^2 D(r,\omega))$$

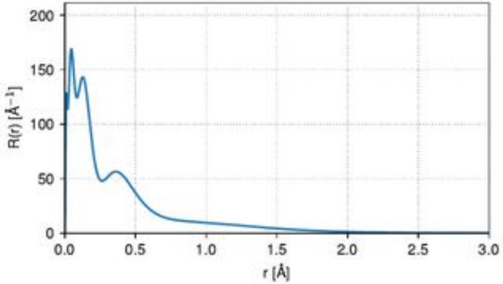
Evaluating the sum with:

$$\frac{d\Gamma}{dE} = \frac{1}{E} \sum_{ij} q_i q_j \int_0^\infty dr\, P_{ij}(r) \frac{\sin(kr)}{kr} f(r)(-\nabla^2 D(r,\omega))$$

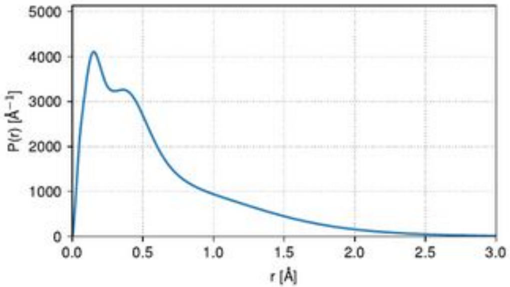
$$P_{ij}(r)dr$$

Probability to find emitters i and j at distance r!

Proton-Electron RDF

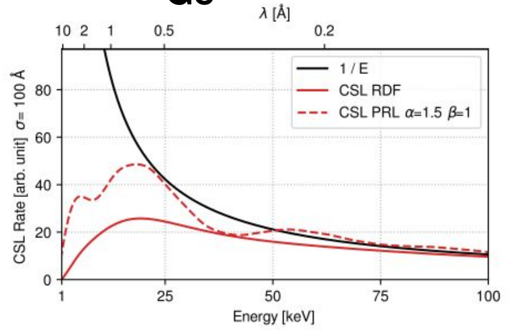


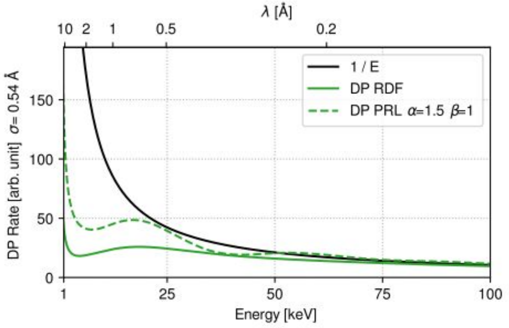
Electron-Electron RDF



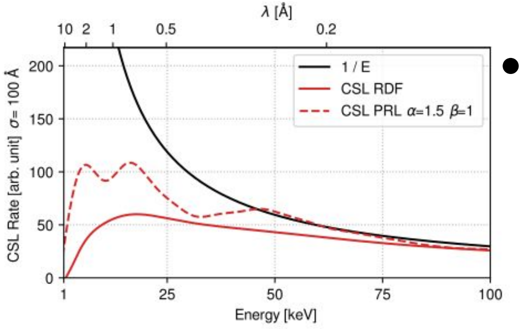
Low energy limit: Radial Distribution Functions

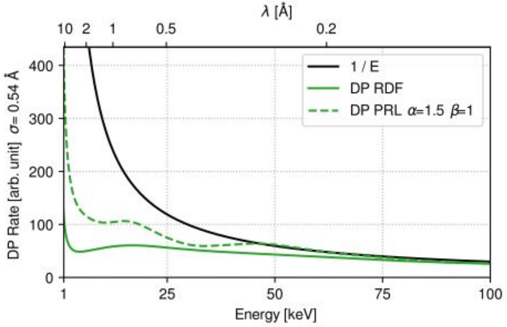
Ge





Xe





- Recovering **former results** with RDF:
  - **Difference ~1/E**
  - **Model dependence**
  - **Cancelation effects**
- **Smoother rates** due to realistic emitters radial density
- **Paper in preparation!**

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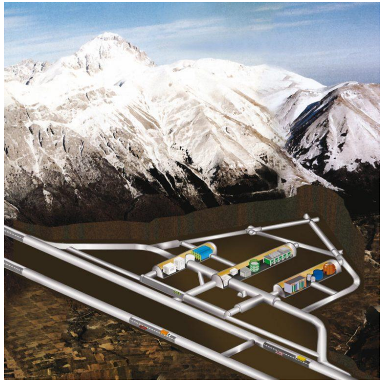
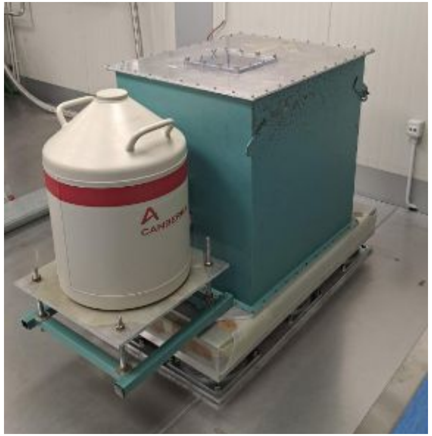
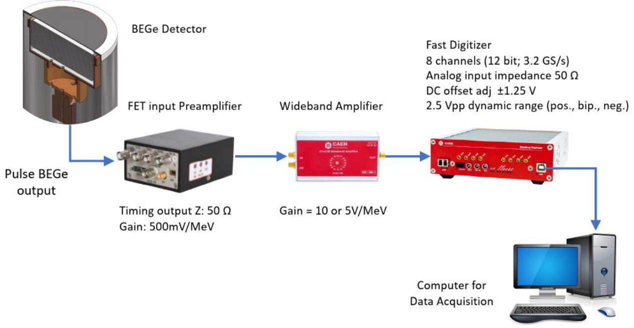
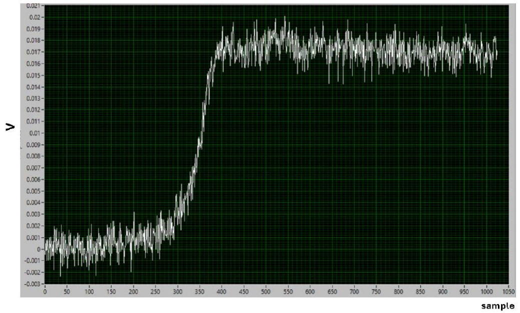
BEGe Detector Emission Rate Measurement at LNGS

- BEGe detector at the ***Laboratori Nazionali del Gran Sasso (LNGS)***
- Spectrum obtained from Waveform acquisition optimized for **Low-Energy (< 20 keV)** events



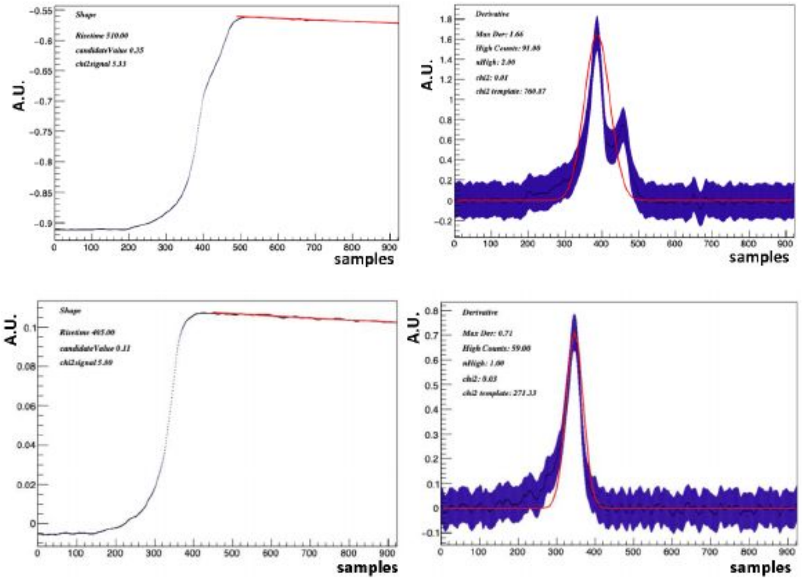






Piscicchia, Kristian, et al. "Optimization of a BEGe Detector Setup for Testing Quantum Foundations in the Underground LNGS Laboratory." *Condensed Matter* 9.2 (2024): 22.

Pulse Shape Analysis of BEGe 2021 Waveforms



Ad-Hoc **Pulse Shape Analysis (PSA)** on 2021 Data Acquisition

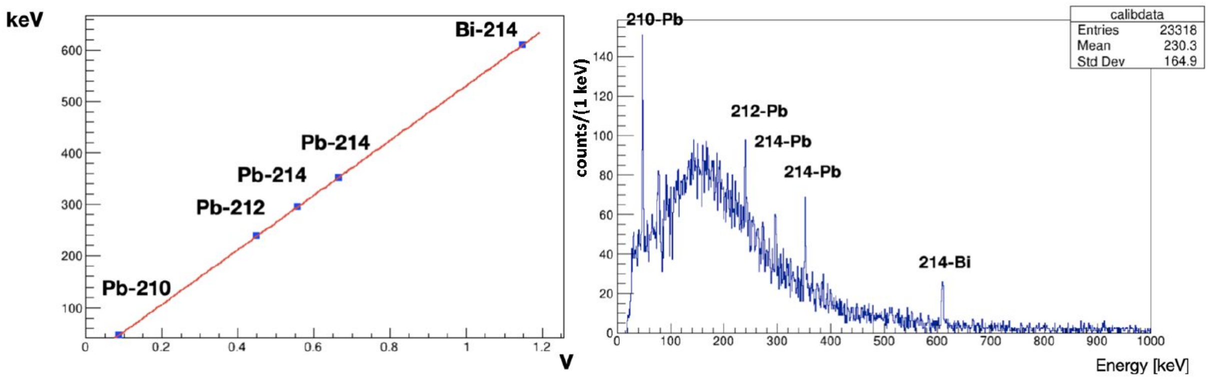
The **PSA** was performed using custom selection criteria:

1. **χ^2-score** from a template-fit to quantify waveform shape agreement.
2. **Number of peaks** identified in the pulse derivative to distinguish multi-site events.
3. **Mean amplitude** at the **start and end** of the waveform to detect slow-rise or flat-top events.

Piscicchia, Kristian, et al. "Optimization of a BEGe Detector Setup for Testing Quantum Foundations in the Underground LNGS Laboratory." *Condensed Matter* 9.2 (2024): 22.

Minimum Energy Threshold for BEGe with PSA

- Validation performed on **2021 spectrum** in the 20–1000 keV range
- Energy calibration using **Pb and Bi reference peaks** (linear response)
  → **Low-energy sensitivity: ~20 keV**
  → **High resolution: 2 keV @ 100 keV**
  → **Linear calibration with Pb/Bi peaks**



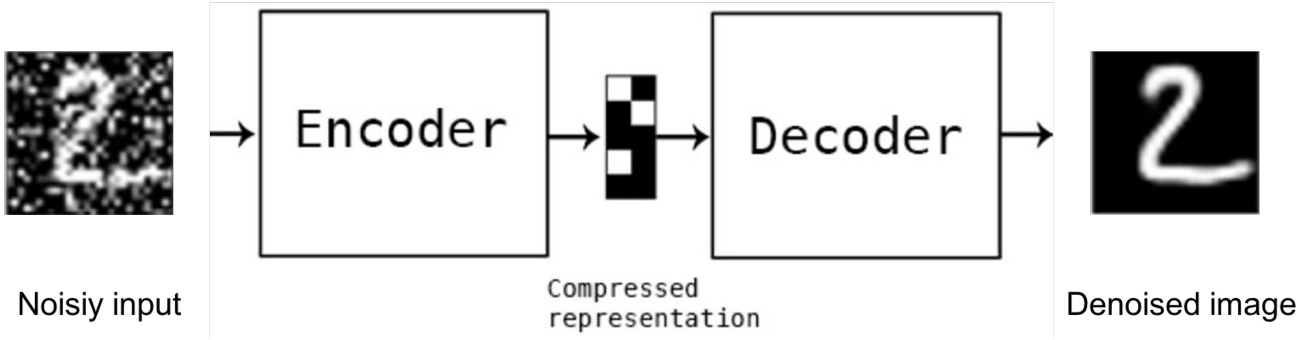
Piscicchia, Kristian, et al. "Optimization of a BEGe Detector Setup for Testing Quantum Foundations in the Underground LNGS Laboratory." *Condensed Matter* 9.2 (2024): 22.

Improving and Automating PSA with Machine Learning

Using a Denoising Autoencoder (DAE) for Pulse Shape Analysis

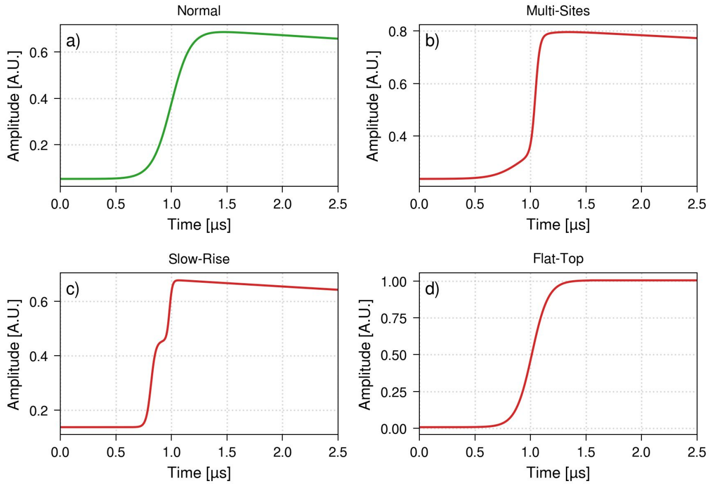
- Enhance waveform quality and automate feature extraction
- **Approach:**
    - **Denoise** waveforms using a trained **Autoencoder**
    - **Extract features** to build a **Labeled Dataset** for *normal* and *anomalous* events.

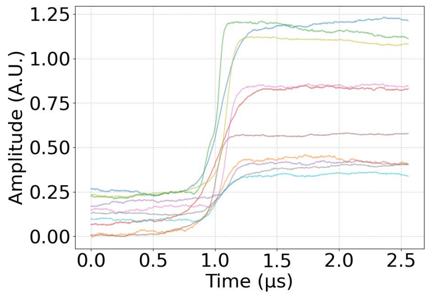
Jason Yip

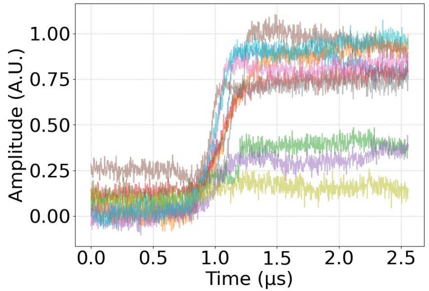


Training the DAE on a Synthetic Dataset

- Synthetic waveforms generated for **Normal**, **Multi-site**, **Slow-rise**, and **Flat-top** events
- Provide controlled inputs for **DAE training and validation**
- Enable robust feature learning before applying to real data

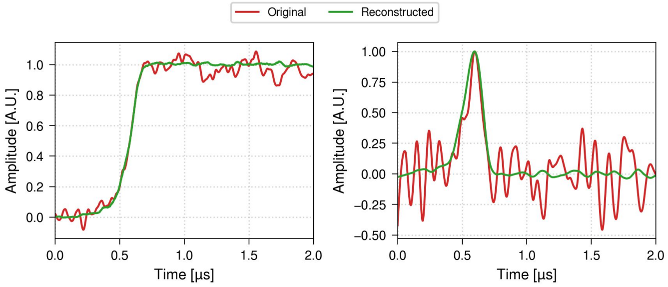




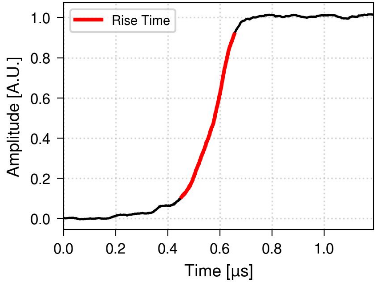


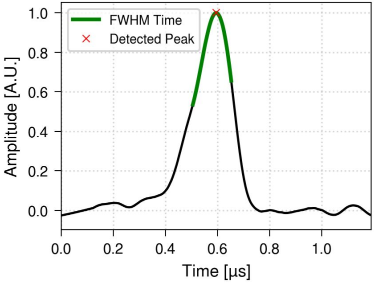
Using DAE on Real BEGe Waveforms

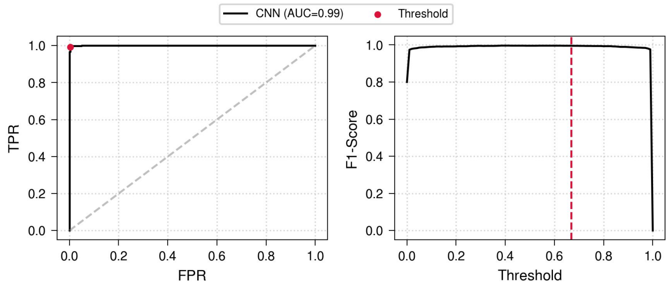
- **Cleaning real BEGe waveforms** with the Denoising Autoencoder (DAE), compared to a **parameter-based filter** (e.g., *Savitzky–Golay*).



- **Extracting features** from denoised signals to build a **labeled waveform dataset**.
- **Attaching a classifier** (e.g., CNN) to distinguish **normal** from **anomalous** events.

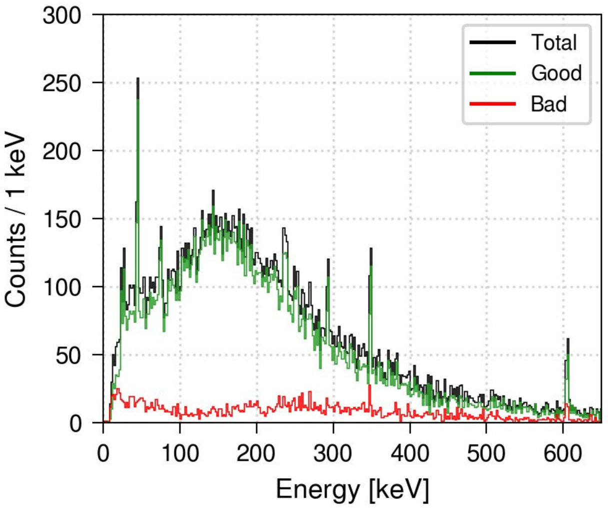


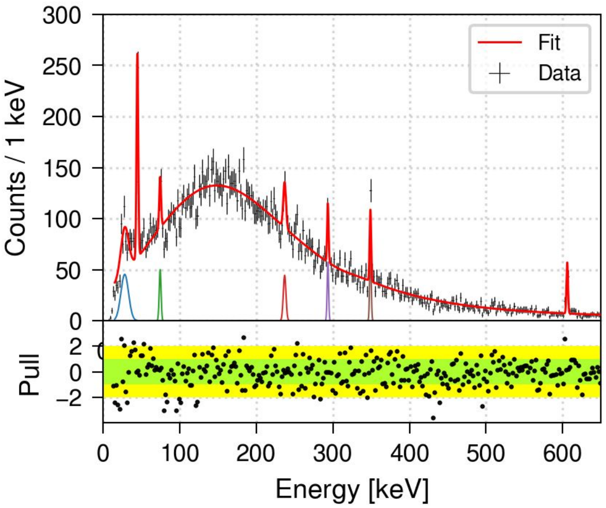




Building Spectrum from DAE Event Selection

- **Spectrum reconstruction** from waveform amplitudes using a **trapezoidal filter**
- **Performance improvement** compared to manual PSA





- **E_{min} ~ 10 keV**
- **FWHM ~ 1 keV@100 keV**
- **S / B improved by 20% over manual PSA**

Conclusion

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- **Emission Rate in the Low-Energy Regime:**
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Thank you for your Attention!