# WEB APPLICATION FOR UNFOLDING THE NEUTRON SPECTRUM MEASURED BY A MULTI-SPHERE SPECTROMETER

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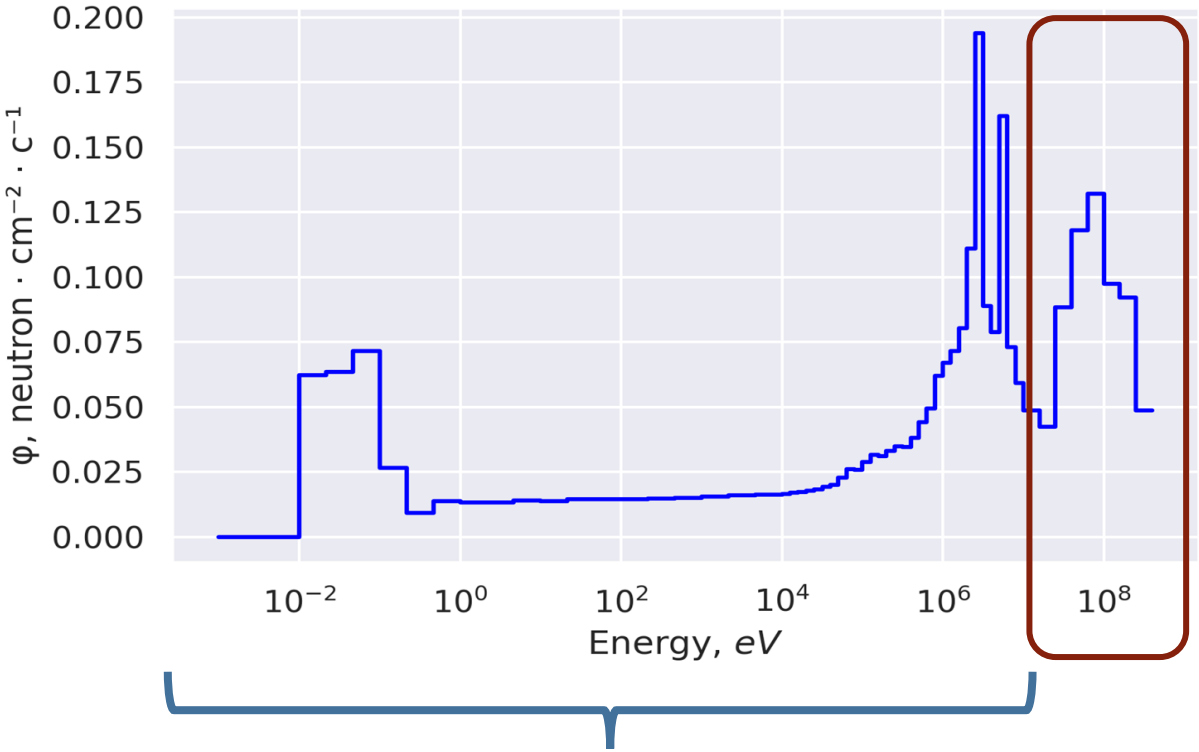
# Introduction

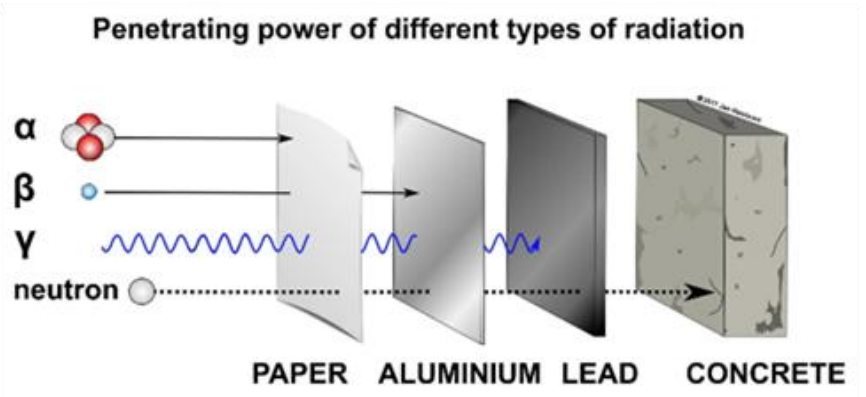
Radiation fields behind the protective shields of nuclear physics facilities (particle accelerators, nuclear reactors) are formed mainly by *neutrons* of a wide energy spectrum.




0.025 eV — 14 MeV



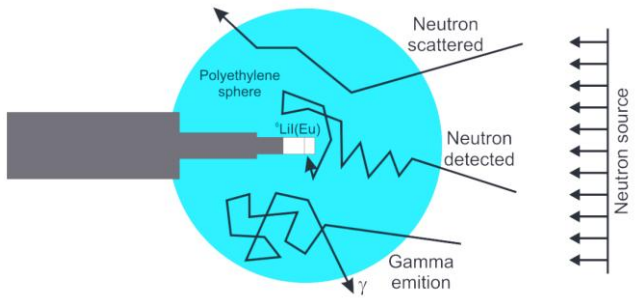
Energy range of neutrons registered by the BDKN-05 detection unit of the MKS-AT6101S spectrometer.




- Nuclear power plants, E ≈ $10^{-9}$ – 20.5 MeV
- Particle accelerators, E ≈ $10^{-9}$ – $10^{3}$ MeV
- Cosmic radiation, E ≈ $10^{-9}$ – $10^{4}$ MeV

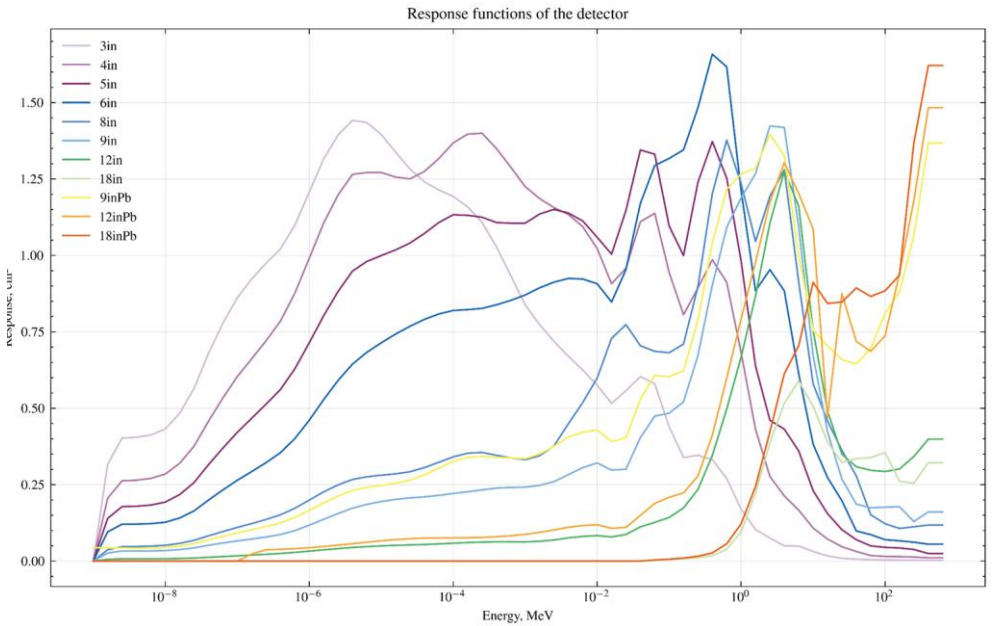


https://atomtex.com/



# Relationship of the spectrum with Bonner spectrometer readings

$$\begin{cases} \int_{E_{\min}}^{E_{\max}} K_1(E)\varphi(E)dE = Q_1, \\ \vdots \\ \int_{E_{\min}}^{E_{\max}} K_M(E)\varphi(E)dE = Q_M, \end{cases}$$




Los Alamos National Laboratory (LANL) BSS, Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes, STI/DOC/010/403

- $\varphi(E)$ is the neutron spectrum;
- $K_j(E)$ is the response function of the detector to neutrons;
- $Q_j$ is the BSS reading for the $j$-th sphere, including the error of measurement;
- $M$ is the number of spheres used;
- The integration limits $E_{\min}$ and $E_{\max}$.

# System of linear equations

1. Integration in lethargy units:

$$u(E) = \lg\left(\frac{E}{E_{\min}}\right), \quad l_E = \lg\left(\frac{E_{\max}}{E_{\min}}\right)$$

$$\ln 10 \times \int_0^{l_E} K_j(u)\,\varphi(u)\,E(u)\,du = Q_j$$

$$\Phi(u) = \varphi(u)\,E(u)$$

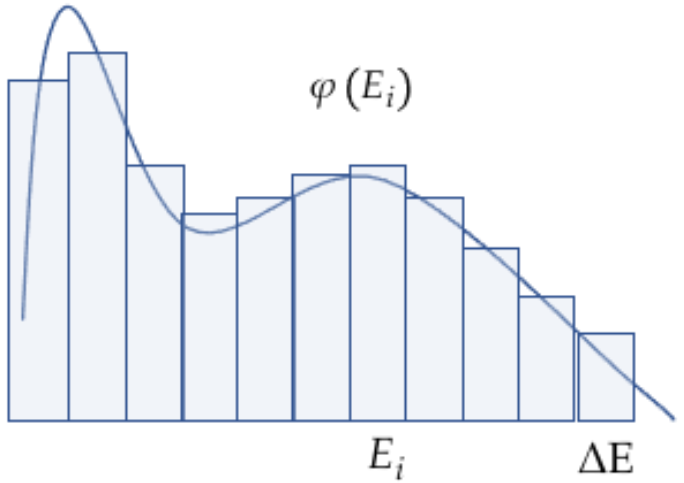
2. Discretization in lethargy units:

$$u_i, \quad i = 1, \ldots, N, \quad \Delta u = \frac{l_E}{N-1}$$

$$\ln 10 \times \sum_{i=1}^{N} K_j(u_i)\,\Phi(u_i)\,\Delta u \approx Q_j$$

$$\Phi_i = \Phi(u_i), \quad K_{ji} = K_j(u_i)$$

$$A_{ji} = \ln 10 \cdot \Delta u \cdot K_{ji}$$




3. SLAE

$$\sum_{i=1}^{N} A_{ji}\Phi_i = Q_j, \quad j = 1, \ldots, M$$

# System of linear equations

**Direct task:** to obtain “effective” readings of the Bonner spectrometer (BSS) based on the given spectra.

**Inverse task:** to obtain the initial spectra based on the measurements (ill-posed inverse task).

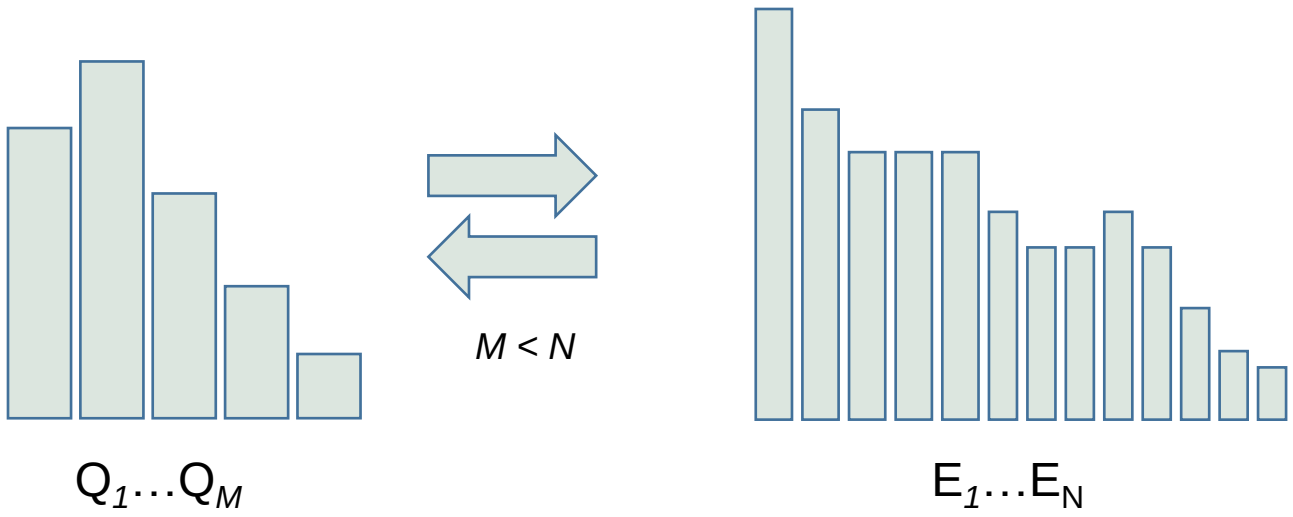
- Hadamard ill-posedness: the solution is not unique.
- Small errors in the measured data lead to large errors in the unfolded function.
- Necessity of regularization: to obtain a physically meaningful solution.

$$\boldsymbol{A\varphi} = Q$$

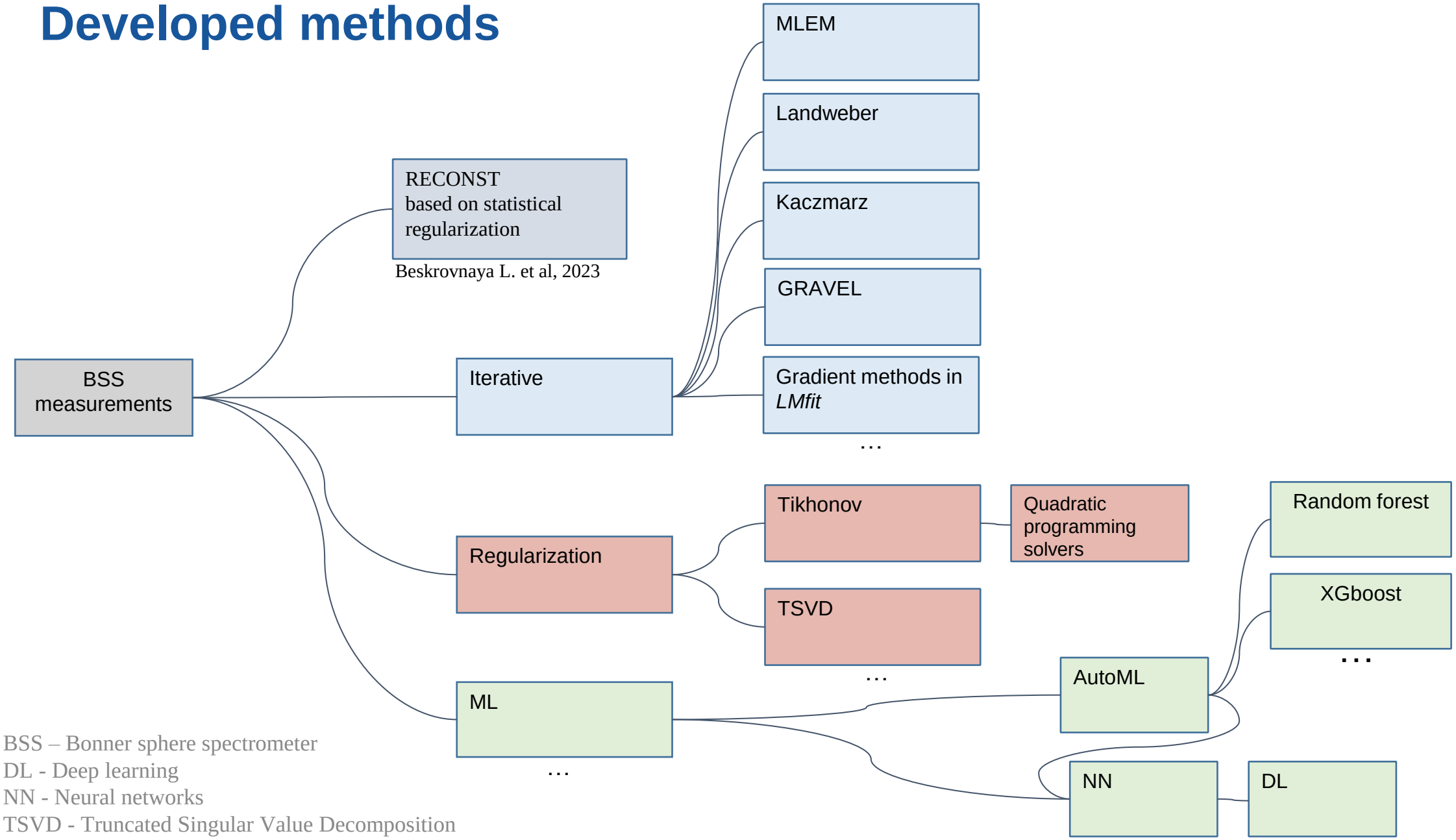
$\boldsymbol{A} \in \mathbb{R}^{MxN}$

$\boldsymbol{\varphi} \in \mathbb{R}^{N}$

$Q \in \mathbb{R}^{M}$



# Developed methods




BSS – Bonner sphere spectrometer
DL - Deep learning
NN - Neural networks
TSVD - Truncated Singular Value Decomposition
MLEM - Maximum likelihood expectation maximization

# Methods

**Landweber iterative**

$$\boldsymbol{\varphi}^{(k+1)} = \boldsymbol{\varphi}^{(k)} + \alpha \mathbf{A}^T(\mathbf{q} - \mathbf{A}\boldsymbol{\varphi}^{(k)}), \quad \alpha = 1/\|\mathbf{A}^T\mathbf{A}\|_2 \qquad \boldsymbol{\varphi}^{(0)} = \boldsymbol{\varphi}_{\mathrm{ML}}$$

**Maximum likelihood expectation maximization (MLEM)**

$$\varphi_i^{(k+1)} = \frac{\varphi_i^{(k)}}{\sum_{j=1}^{M} A_{ji}} \sum_{j=1}^{M} \frac{q_j A_{ji}}{\sum_{l=1}^{N} A_{jl}\varphi_l^{(k)}}, \quad i = 1, \ldots, N, \qquad \boldsymbol{\varphi}^{(0)} = \boldsymbol{\varphi}_{\mathrm{ML}}$$

**Tikhonov regularization**

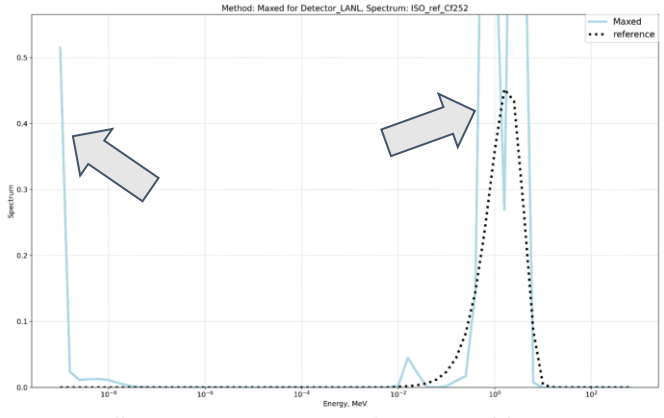
$$\boldsymbol{\varphi}^* = \arg\min_{\boldsymbol{\varphi} \geq 0} \left\{ \|\mathbf{A}\boldsymbol{\varphi} - \mathbf{q}\|_2^2 + \alpha \|\mathbf{L}\boldsymbol{\varphi}\|_2^2 \right\},$$

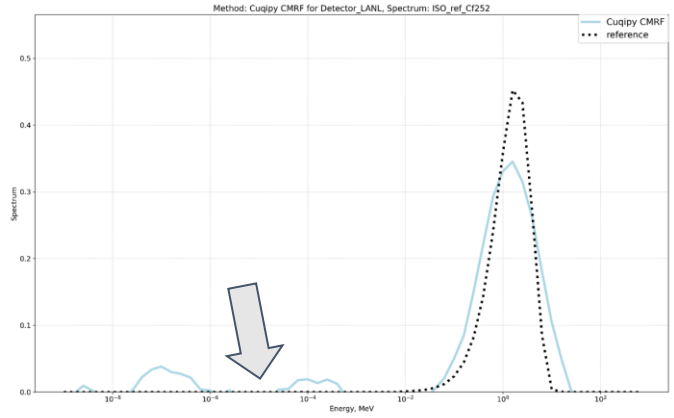
**Truncated Singular Value Decomposition (TSVD)**

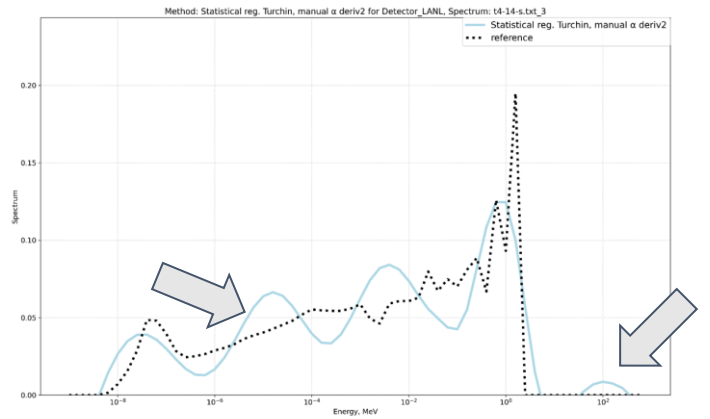
$$\boldsymbol{A} = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^T \qquad \boldsymbol{\varphi} = \sum_{i=1}^{r} \frac{\boldsymbol{u}_i^T \boldsymbol{b}}{\sigma_i} \boldsymbol{v}_i \text{ , select } k \ \sigma, \text{where } k < r$$

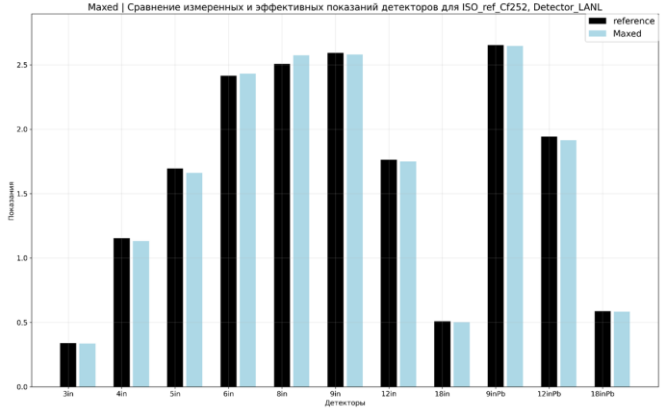
# Solution stabilization methods

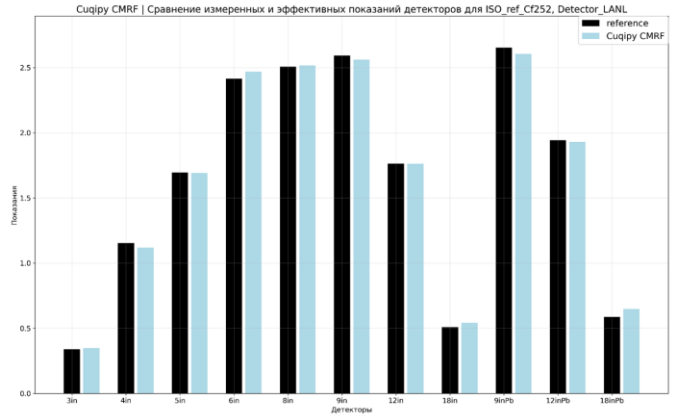
- Small error could give large uncertainty.
- Regularization could make non-physical waves.

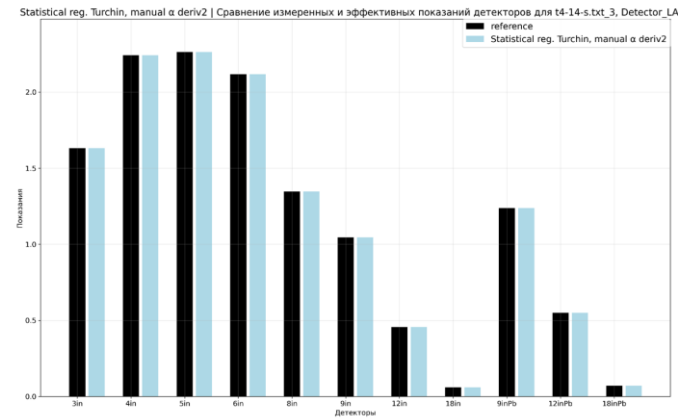


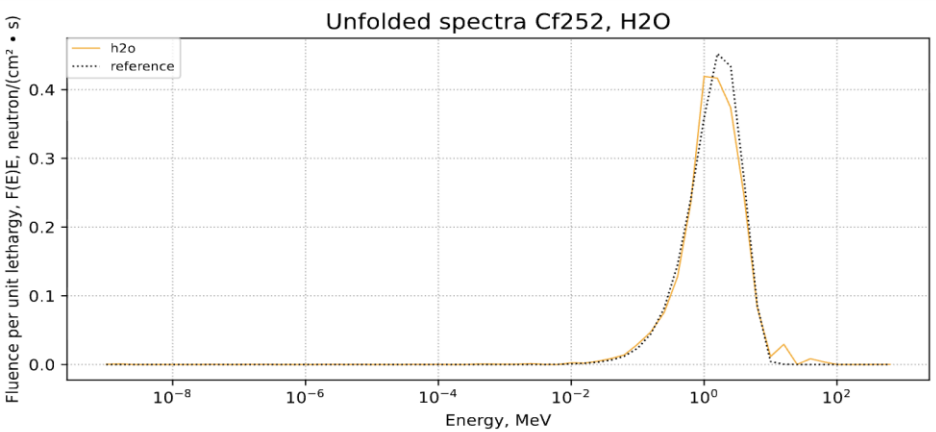



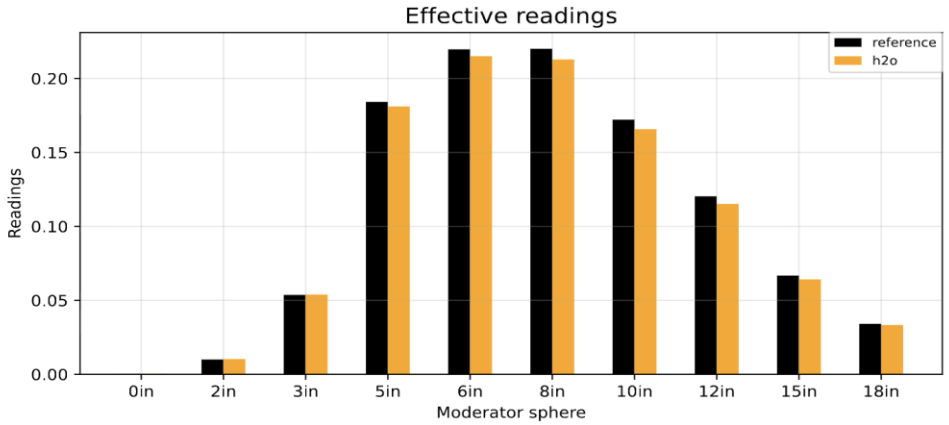



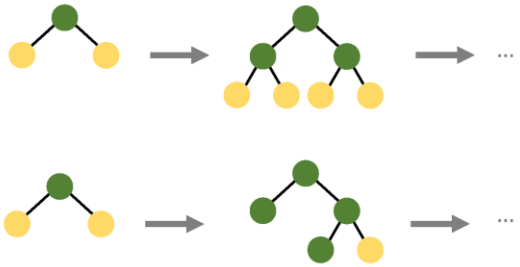
# Machine learning approach

AutoML frameworks provide implementation of many popular algorithms such as Generalized Linear Models (GLM), Gradient Boosting Machines (including XGBoost), Random Forests, Deep Neural Networks, Stacked Ensembles, Naive Bayes, Generalized Additive Models (GAM), Cox Proportional Hazards, K-Means, PCA, Word2Vec, as well as a fully automatic machine learning algorithm.

The best for this task: **GBM & XGBoost.**
Auto ML gives us initial spectrum, based on it we could select regularization parameters.

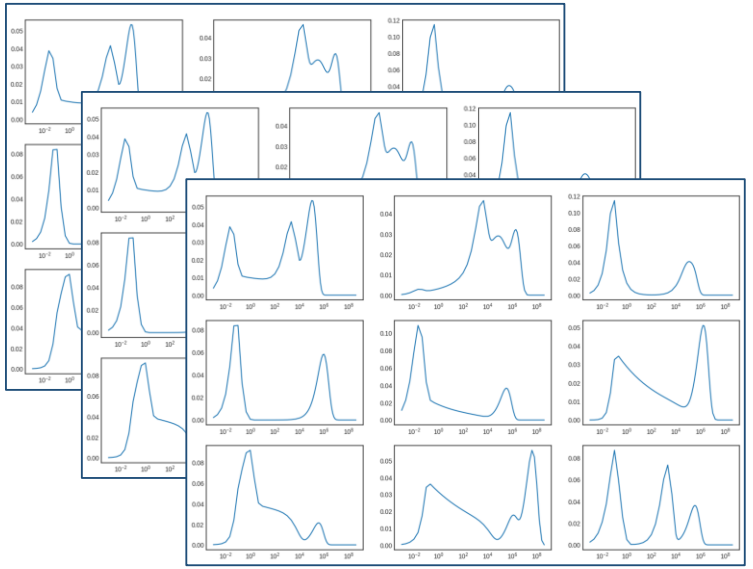


# Machine learning approach. Dataset

- **Synthetic based on parametric method FRUIT[1] ($5 \cdot 10^5$ spectra) for train/validation**
  1. Each spectrum is modeled as a linear combination of four parametric functions representing thermal, epithermal, fast and high-energy components.
  2. Input features: numerical, M measurements.
  3. Output targets: values for N energy bins ($10^{-9}$ – $6.3 \cdot 10^2$ MeV, log scale).
  4. Training / validation: 80 % / 20 % .



| Model | Thermal $\phi_{\text{th}}(E,\dots)$ | Epithermal $\phi_e(E,\dots)$ | Fast $\phi_f(E,\dots)$ | High Energy $\phi_{\text{hi}}(E,\dots)$ |
|---|---|---|---|---|
| Fission | $\left(\frac{E}{T_0^2}\right)e^{-E/T_0}$ | $\left[1-e^{-(E/E_d)^2}\right]E^{b-1}e^{-E/\beta'}$ | $E^{\alpha}e^{-E/\beta}$ | 0 |
| Evaporation | ↓ | ↓ | $\left(\frac{E}{T_{ev}^2}\right)e^{-E/T_{ev}}$ | 0 |
| Gaussian | ↓ | ↓ | $exp\left(-\frac{1}{2}\left(\frac{E-E_m}{\sigma E_m}\right)\right)$ | 0 |
| High Energy | ↓ | ↓ | $\left(\frac{E}{T_{ev}^2}\right)e^{-E/T_{ev}}$ | $\left(\frac{E}{T_{hi}^2}\right)e^{-E/T_{hi}}$ |

- **Spectra by Monte-Carlo simulations** from International Atomic Energy Agency (IAEA) dataset for tests.


1. Frascati Unfolding Interactive Tool, doi: 10.1016/J.NIMA.2007.07.033
2. *Compendium of Neutron Spectra and Detector Response for Radiation Protection Purposes: Technical Report Series. Vienna: IAEA, 2001. No. 403.*

# Unified interface for measurements & spectra processing

**Existing code in JINR:**

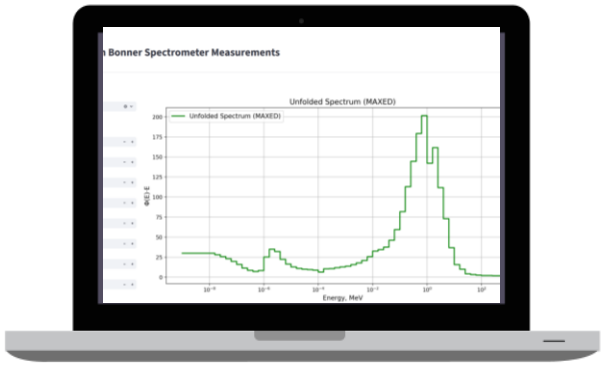
RECONST software based on statistical regularization

Certificate of state registration of computer program No. 2024611064 Russian Federation. Program for reconstruction of neutron spectra based on Bonner spectrometer readings (RECONST): No. 2023689679: declared. 26.12.2023: published. 17.01.2024 / L. G. Beskrovnaya; applicant Joint Institute for Nuclear Research. – EDN SJPKWJ.

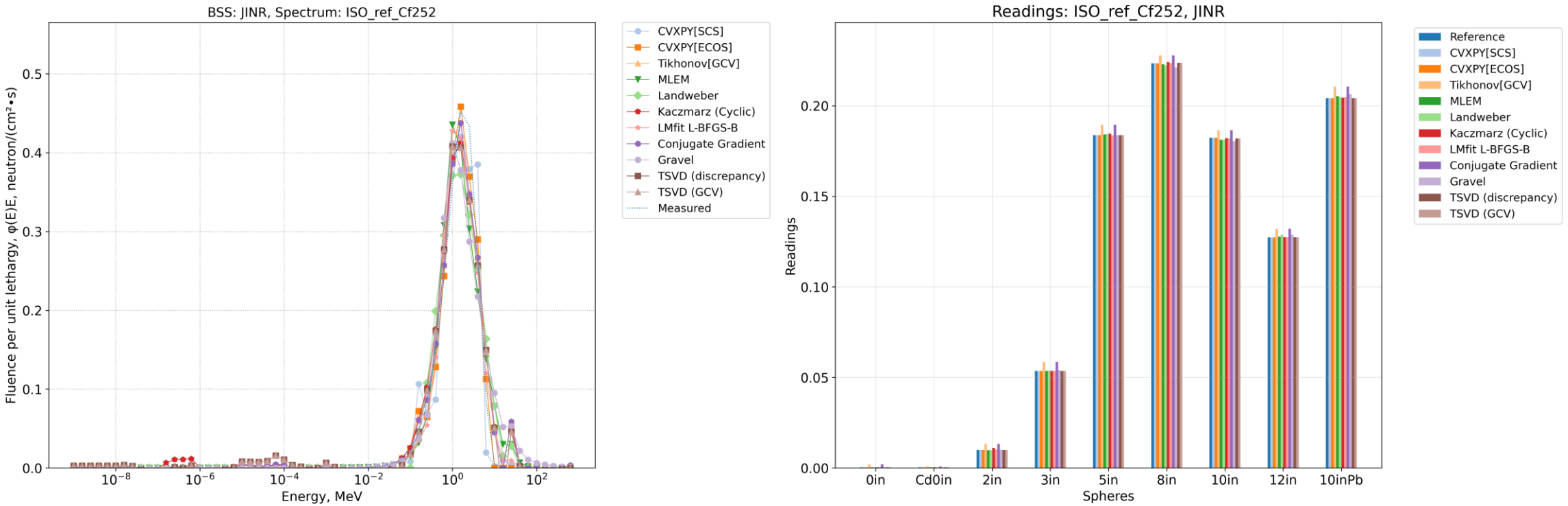



**Our approach:**

- Unified interface for different methods with automatization of selection of the regularization parameters.
- Multi-platform application (web-interface).
- Database of measurements and unfolded spectra.
- Groups of users.
- Authorization.



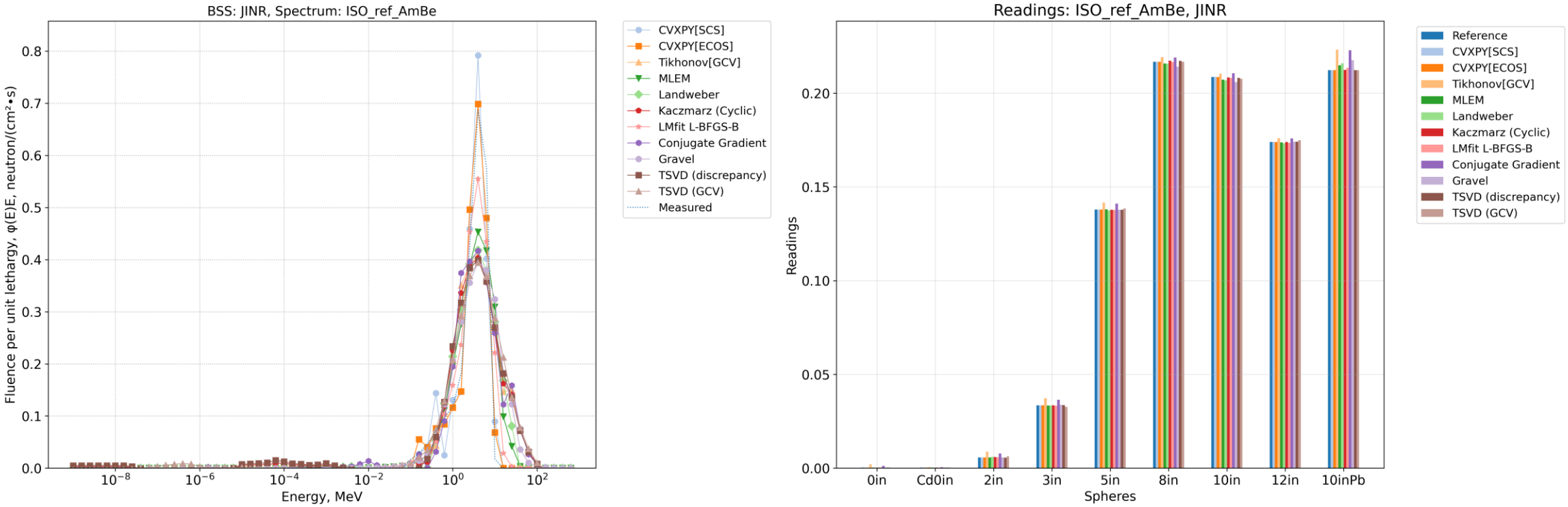
# Results for $^{252}$Cf (ISO reference)




Monte-Carlo calculated spectra for $^{252}$Cf.

*Compendium of Neutron Spectra and Detector Response for Radiation Protection Purposes: Technical Report Series. Vienna: IAEA, 2001. No. 403.*

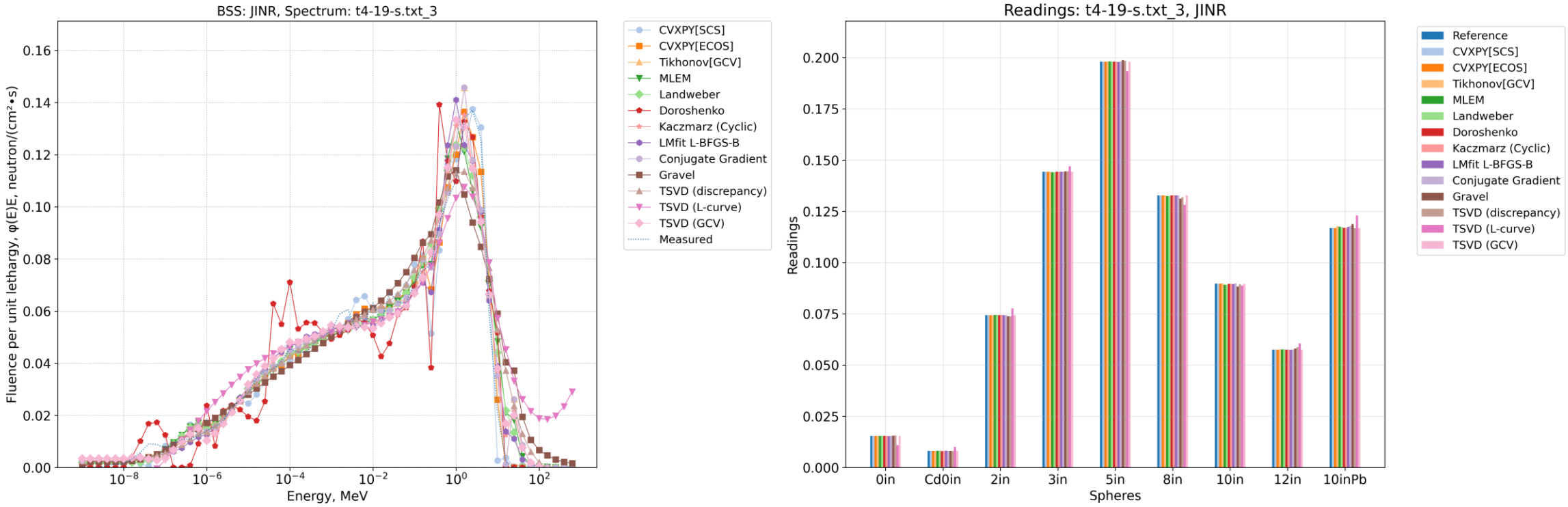
# Results for AmBe (ISO reference)




Monte-Carlo calculated spectra for AmBe.

*Compendium of Neutron Spectra and Detector Response for Radiation Protection Purposes: Technical Report Series. Vienna: IAEA, 2001. No. 403.*

# Results for GRENF (C)

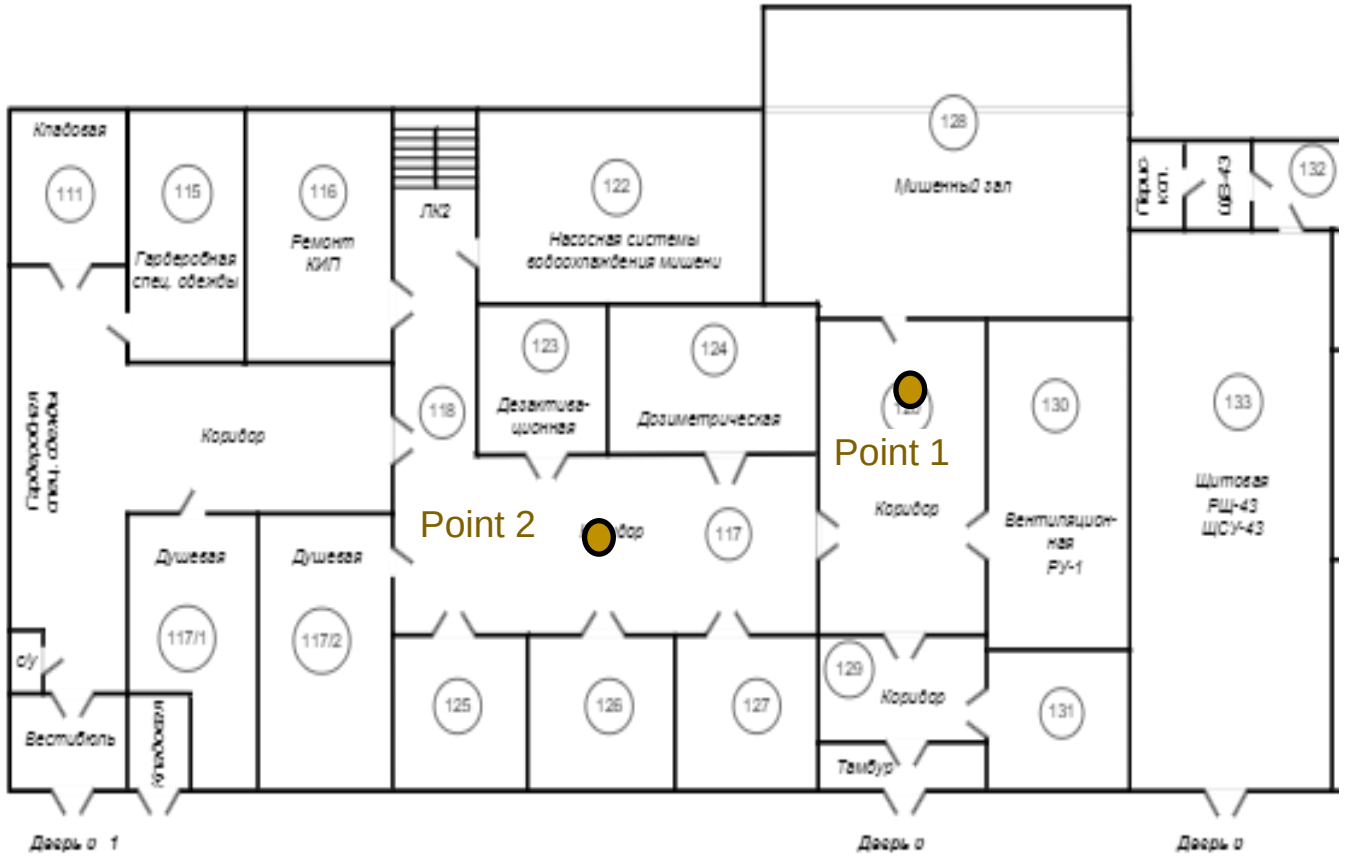


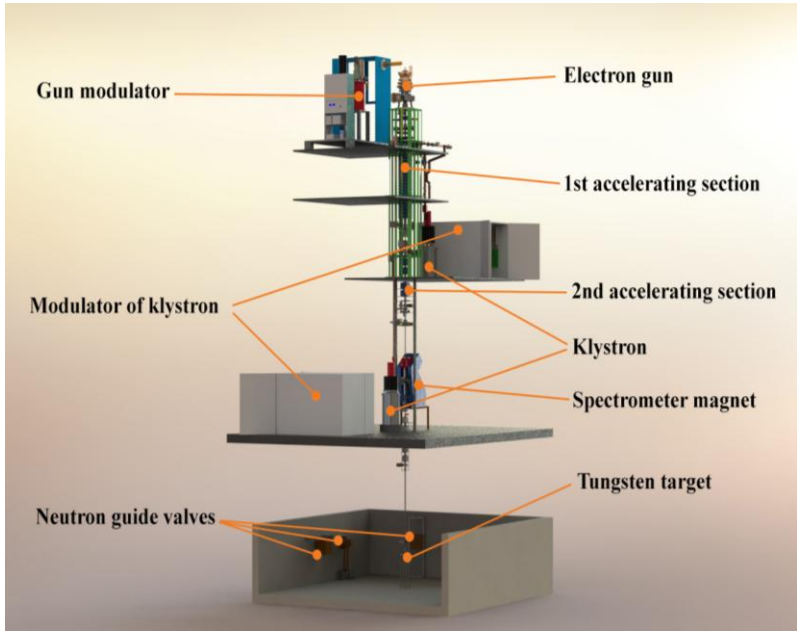

Monte-Carlo calculated spectra from GSF realistic neutron field facility (GRENF), for position C that corresponds to a specific physical placement of the dosimeter relative to the plutonium source with significant scattering from surrounding materials.

*Compendium of Neutron Spectra and Detector Response for Radiation Protection Purposes: Technical Report Series. Vienna: IAEA, 2001. No. 403.*

# Results for IREN facility (Intense Resonance Neutron Source)

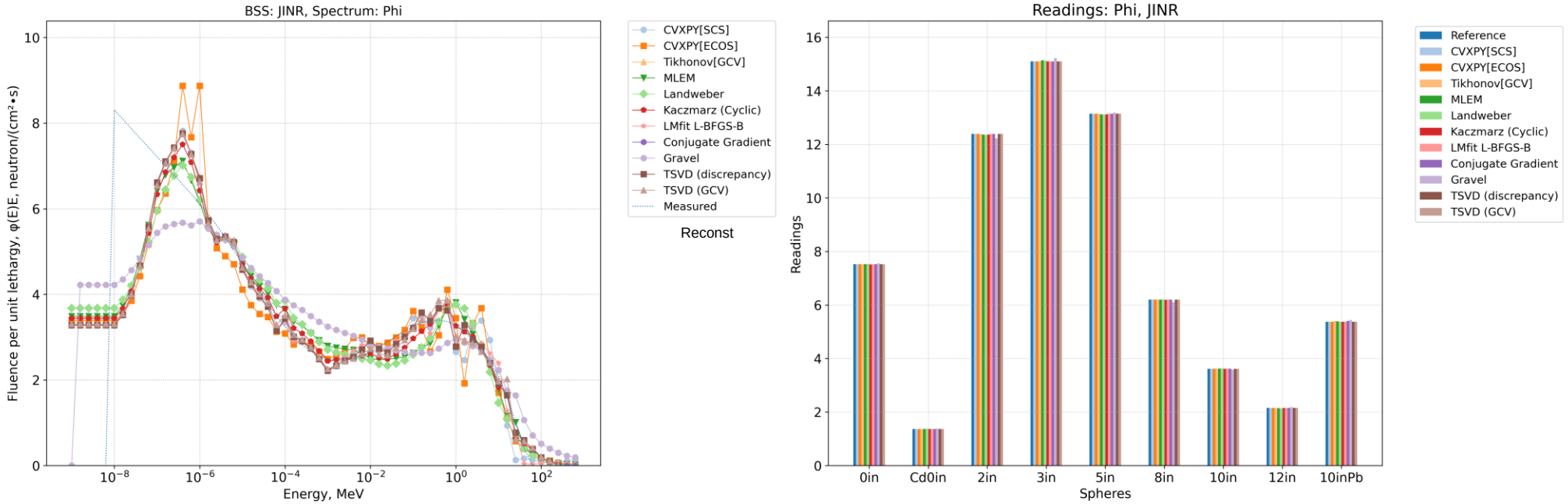
General schematic of the IREN facility accelerator and target halls.

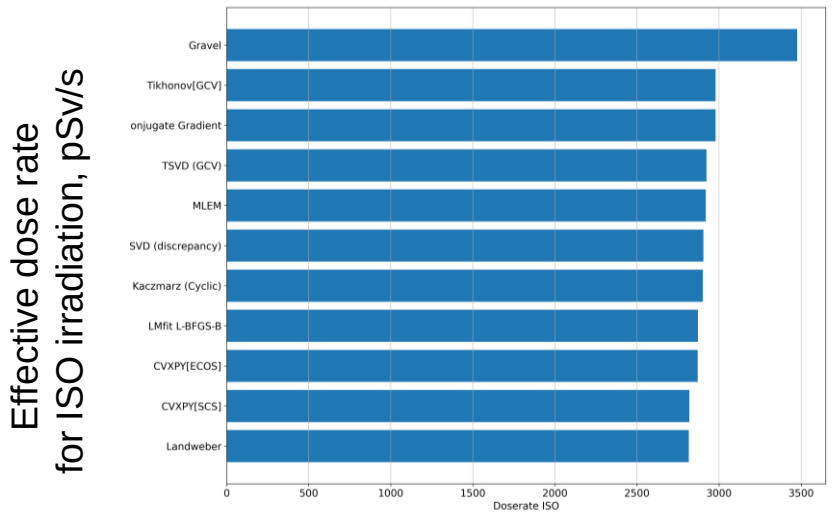


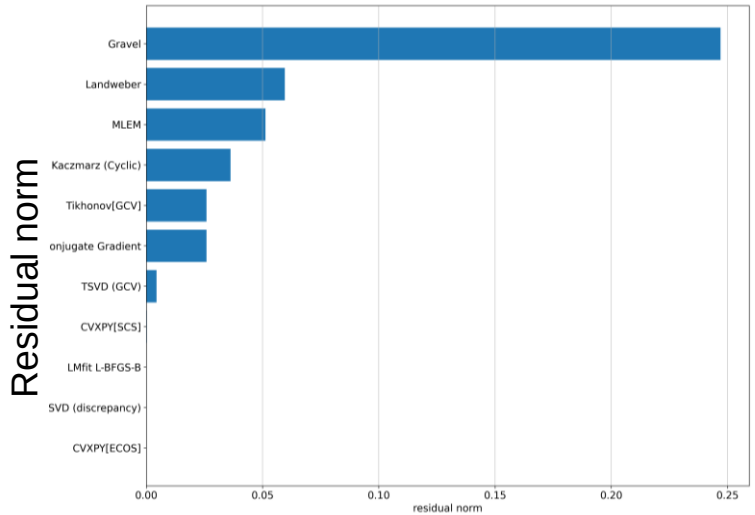




*https://flnp.jinr.int/en-us/main/facilities/iren*

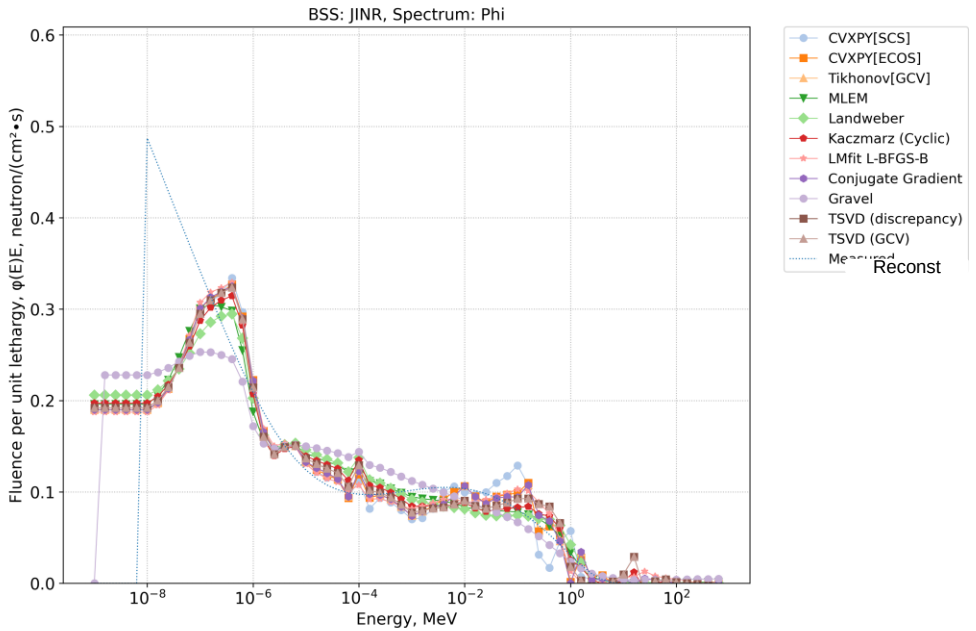
# Results for IREN point 1

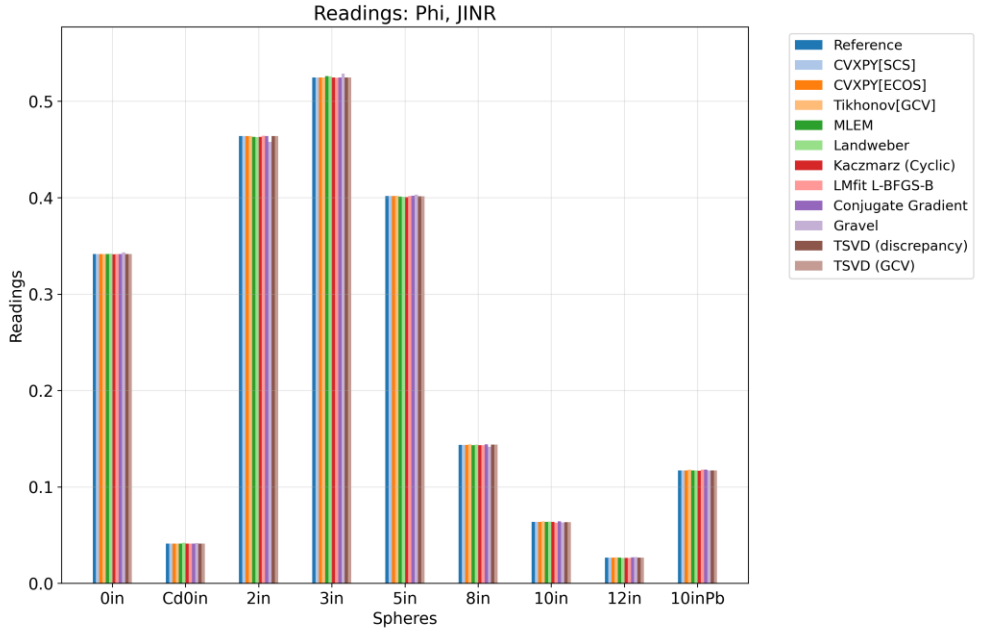


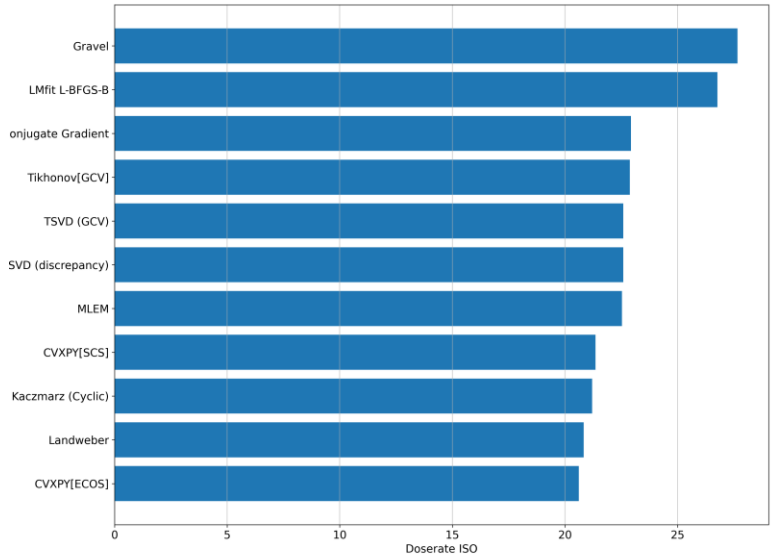



# Results for IREN point 2

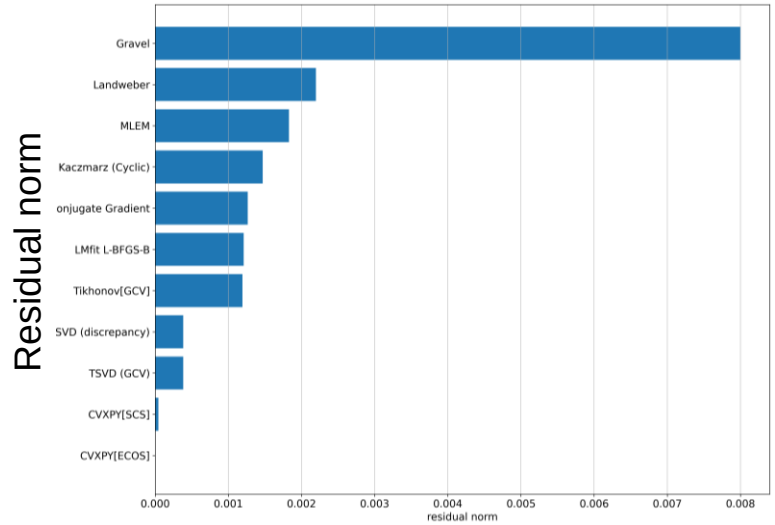



Effective dose rate
for ISO irradiation, pSv/s




Residual norm



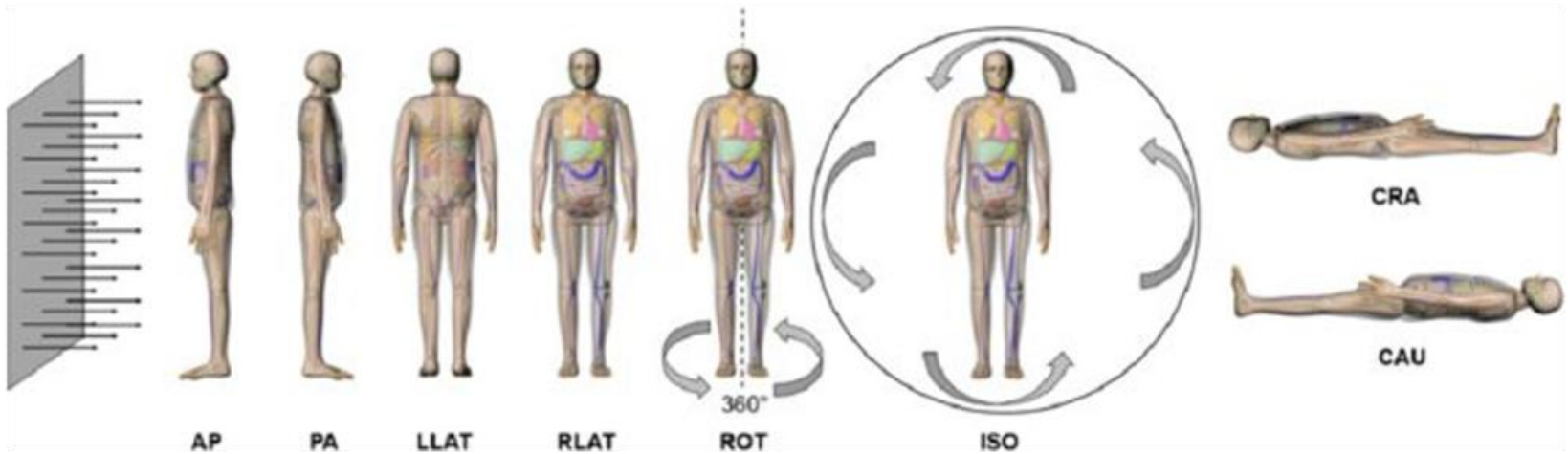
# Dose estimation for spectrum

The Bonner multi-sphere spectrometer is used to measure neutron spectra in stationary fields to assess irradiation of personnel.

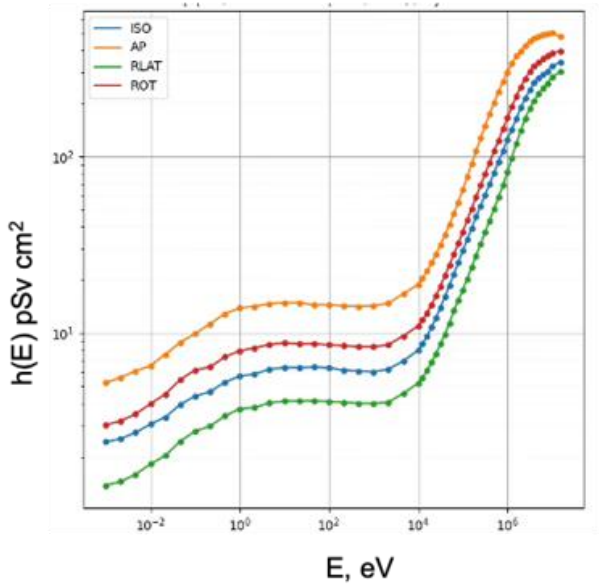
$$\dot{H} = \int_{Emin}^{Emax} \varphi(E) \cdot h(E) dE$$

$\dot{H}$ – dose rate ($\dot{H}_{\text{eff_AP}}$,$\dot{H}_{\text{eff_ISO}}$, $\dot{H}^*(10)$, $\dot{H}_p(10,0^\circ)$)

*h(w)* – corresponding conversion factor [pSv·cm²] for monoenergetic particles in different irradiation geometries, ICRP Publication 116[1].

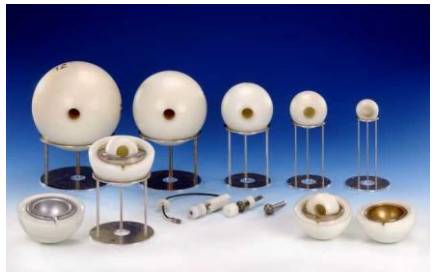



https://dceg.cancer.gov/tools/radiation-dosimetry-tools/phantoms-library

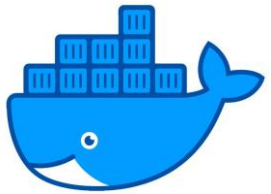


# Implementation & restrictions

- The method is suitable for unfolding spectra in stationary neutron fields.
- Used set of Bonner spectrometer spheres limits the energy range of unfolded spectrum.
- The uncertainty of sensitivity functions is not taken into account.
- It is necessary to prepare a ML model for each BSS detector and set of moderator spheres.
- ML models were converted to ONNX file format for better implementation on various computer systems.
- The app uses many dependencies, it is necessary to run in a virtual environment or container.
- The client-server implementation will allow access to spectrum analysis from different devices.







Neutron spektrometer NEMUS, https://www.ptb.de/cms/en/ptb/fachabteilungen/abt6/fb-64/643-neutron-spectrometry/nemus/neutron-spektrometer-nemus-neutron-multisphere-spectrometer.html

# Python package: bssunfold

https://github.com/Radiationsafety/bssunfold

**pip** install bssunfold

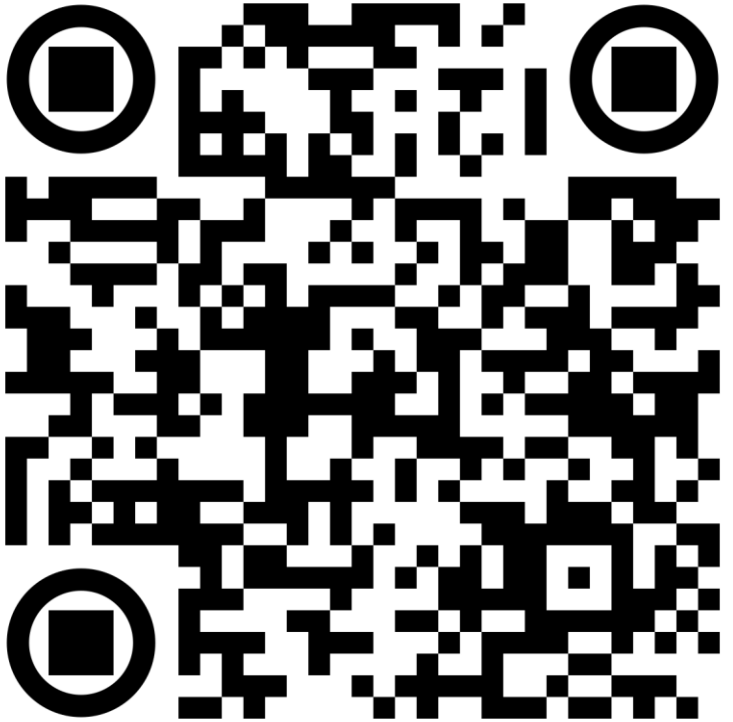
**uv** add bssunfold

**conda** install conda-forge::bssunfold

**git clone** https://github.com/radiationsafety/bssunfold.git
**cd** bssunfold

**pip** install -e .

https://sourcecraft.dev/radiationsafety/bssunfold
https://gitverse.ru/radiationsafety/bssunfold



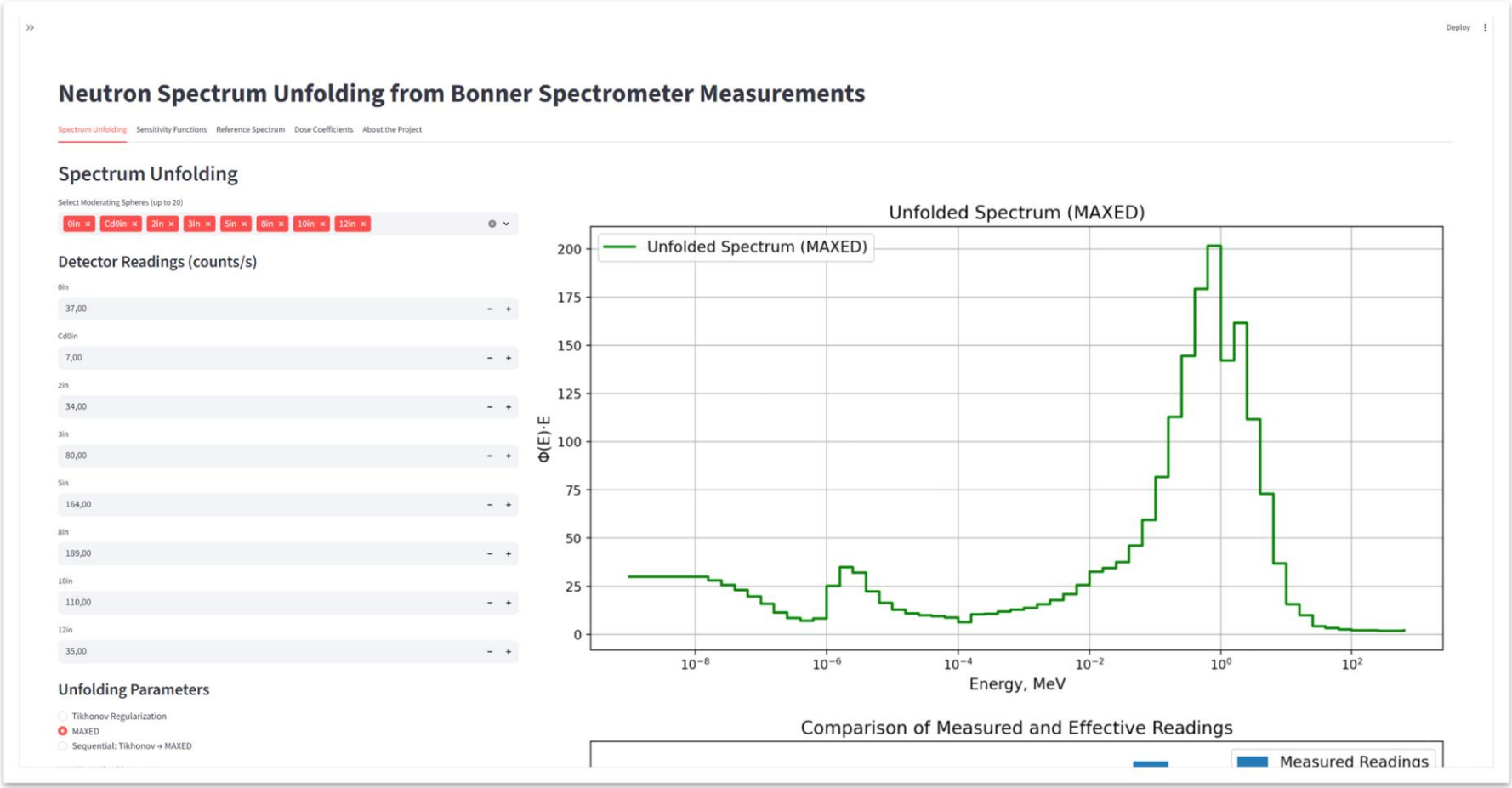
4.9K downloads since December 2025

https://clickpy.clickhouse.com
/dashboard/bssunfold

https://doi.org/10.5281/zenodo.18230507

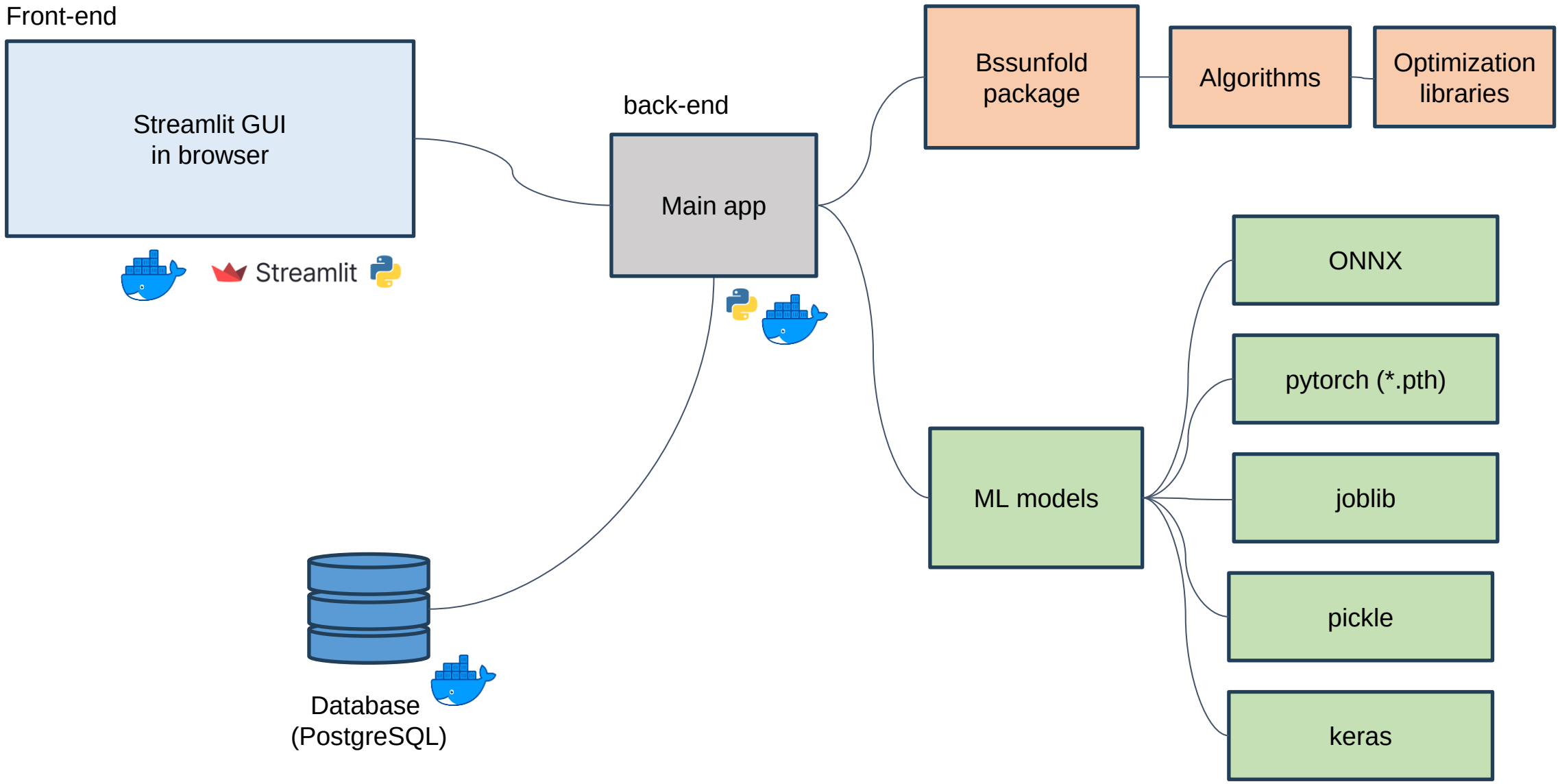
# Web-application

- Web-application based on Streamlit framework and docker container is developed;
- Work is in progress to integrate the developed methods and trained neural network models into the interface.






# Scheme


Front-end
Streamlit GUI
in browser
Streamlit
back-end
Main app
Bssunfold
package
Algorithms
Optimization
libraries
ONNX
pytorch (*.pth)
ML models
joblib
pickle
keras
Database
(PostgreSQL)

# Conclusions

1. A set of algorithms for neutron spectrum unfolding have been developed in python: Tikhonov regularization, quadratic programming solvers, TSVD, iterative algorithms (Landweber, MLEM, Conjugate gradients, L-BFGS-B, Kaczmarz).
2. Machine learning models trained on synthetic dataset are developed to unfold the spectra.
3. The web-application is developed as a docker container.
4. The python package is developed and available in repositories.
5. This work establishes a practical and effective pipeline for spectra unfolding with machine learning and inverse problem solvers. The proposed method could be used for improving radiation protection in high-energy neutron fields.

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# Thank you!

Publications:

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