technische universität dortmund

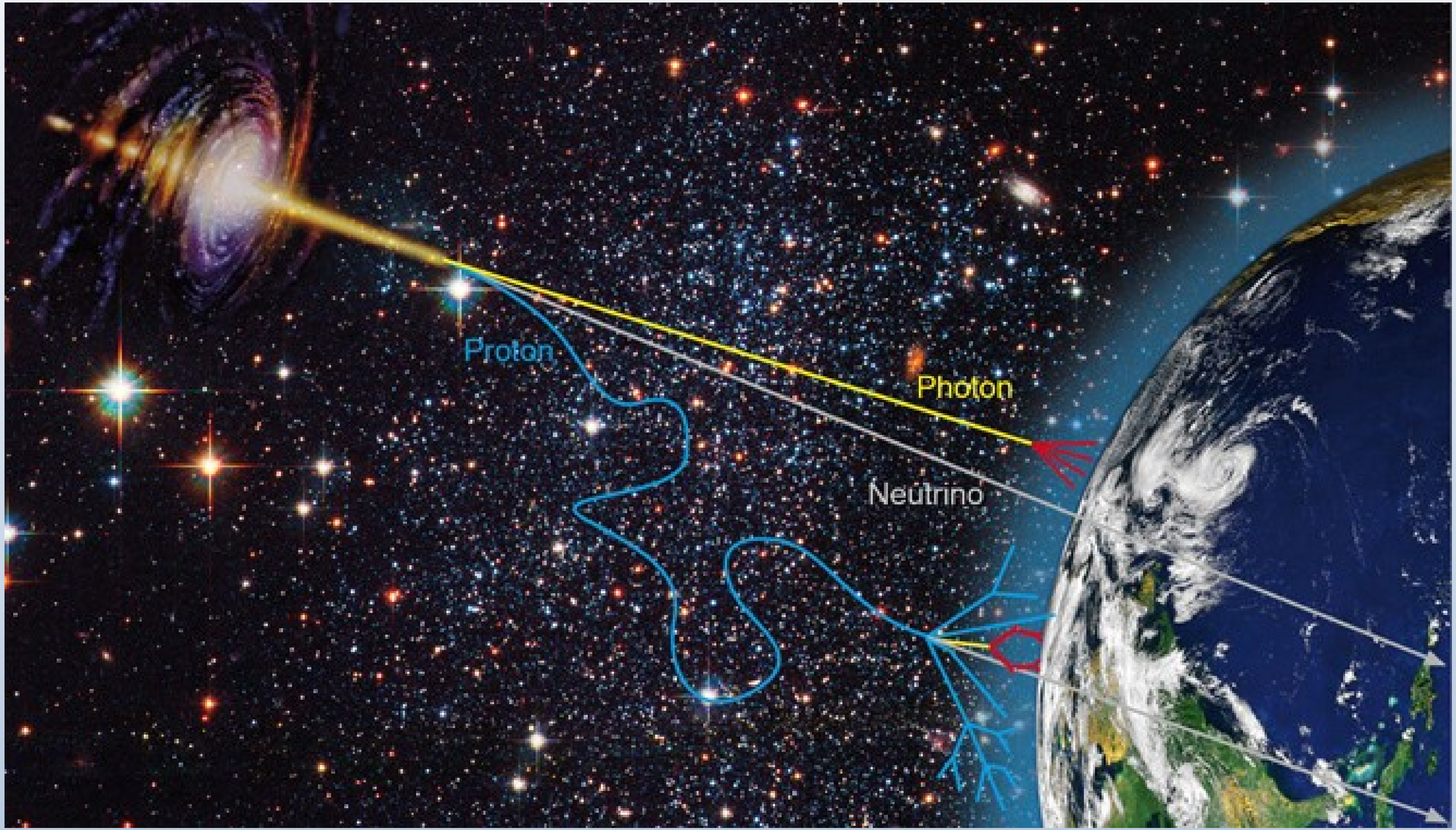
Leonora Kardum

# Unfolding in Astroparticle physics

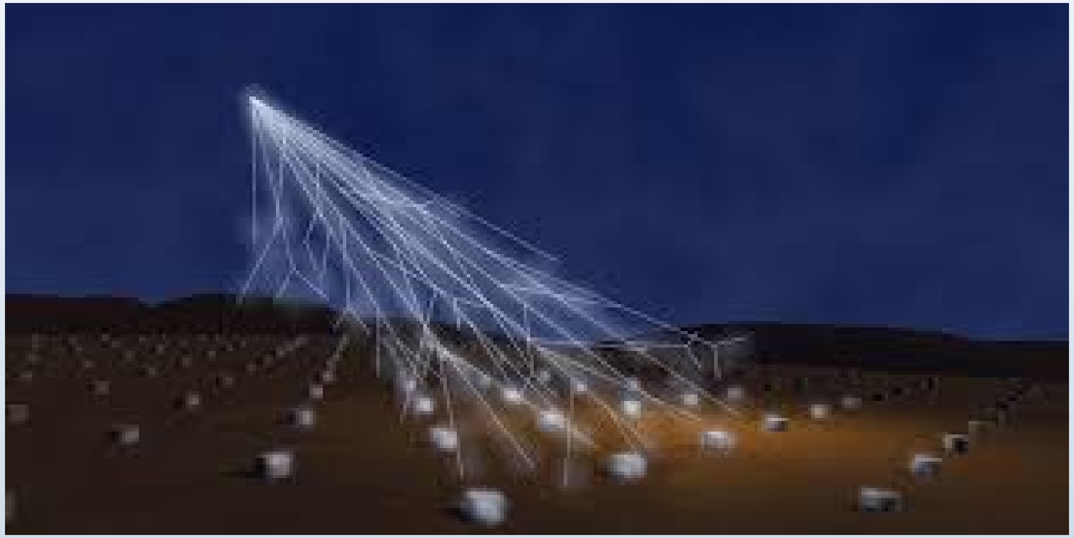
LAMARR

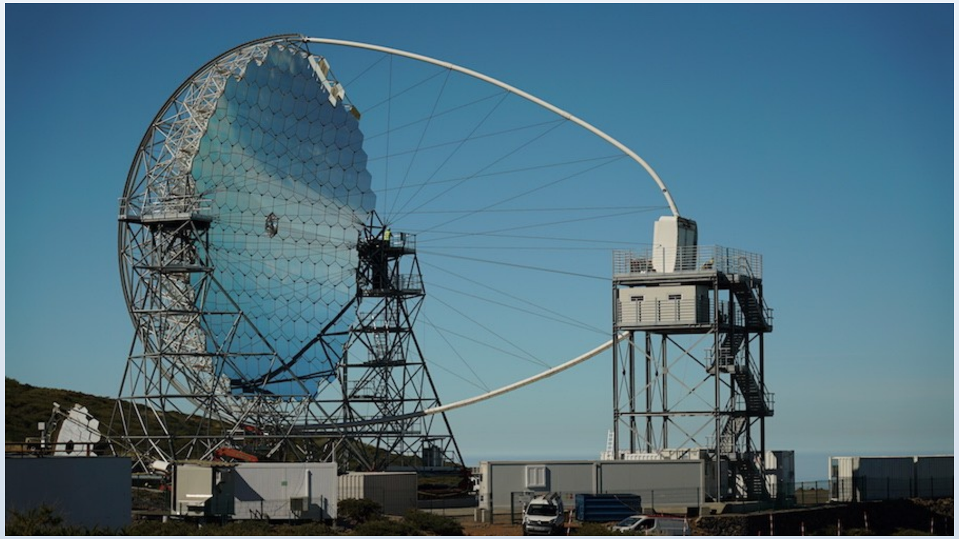
INSTITUTE FOR MACHINE LEARNING AND ARTIFICIAL INTELLIGENCE

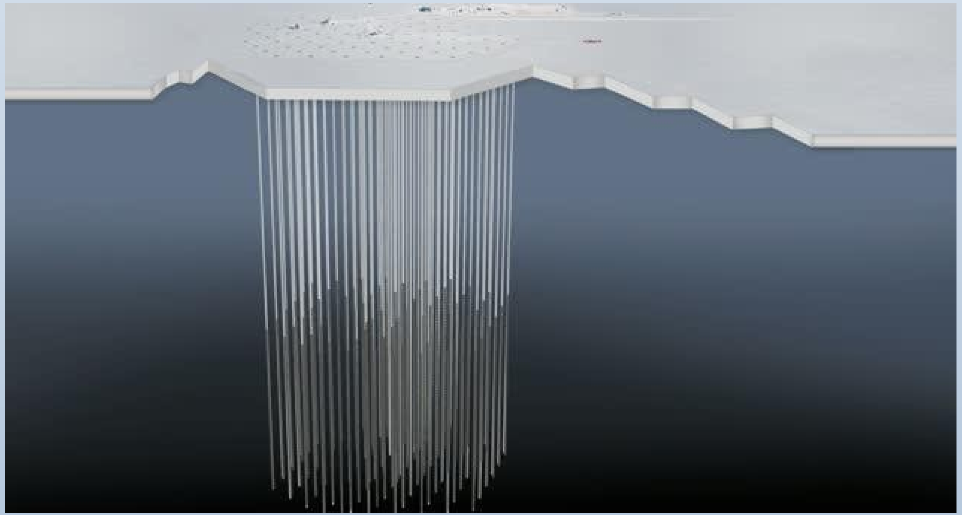
# Astroparticle physics



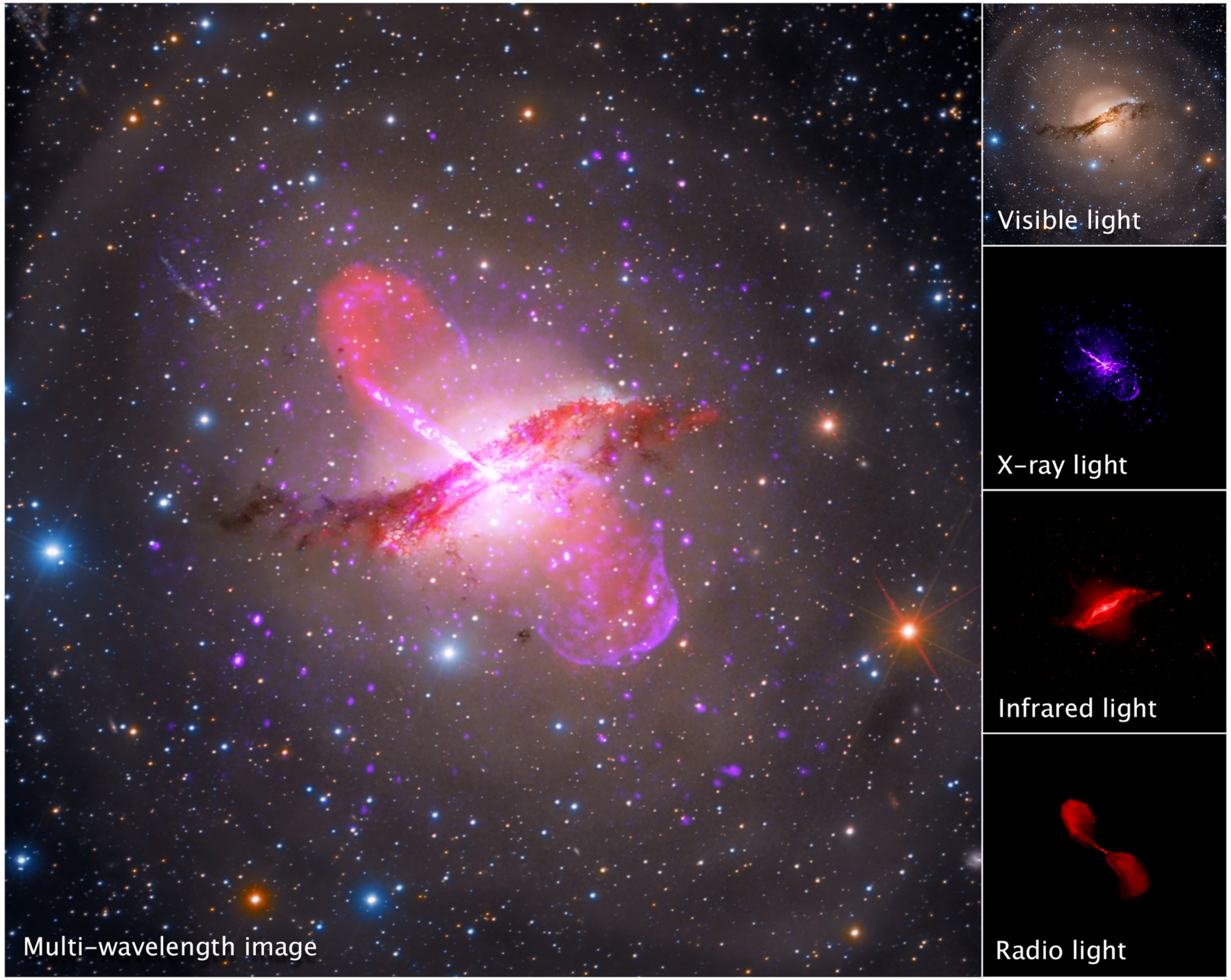
# Astroparticle physics

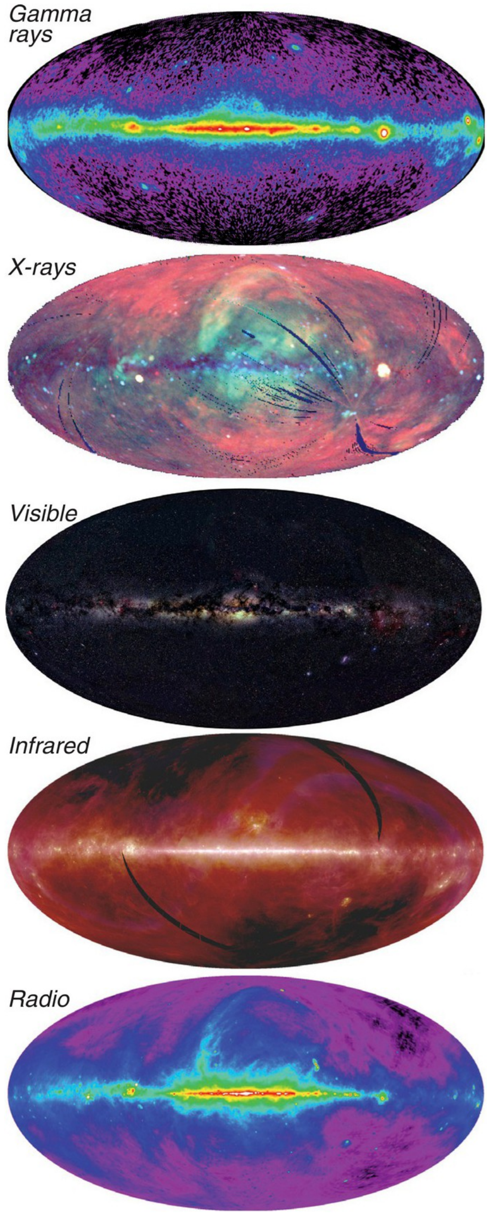




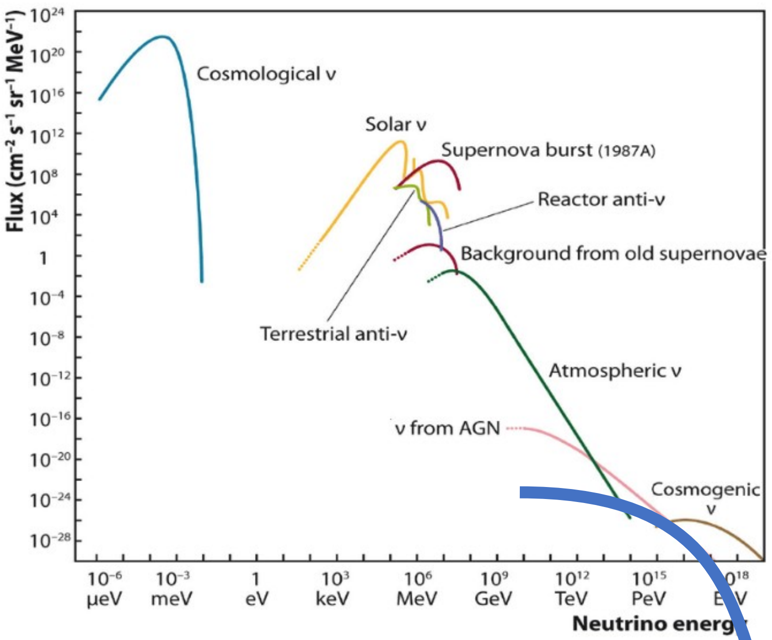


# Astroparticle physics

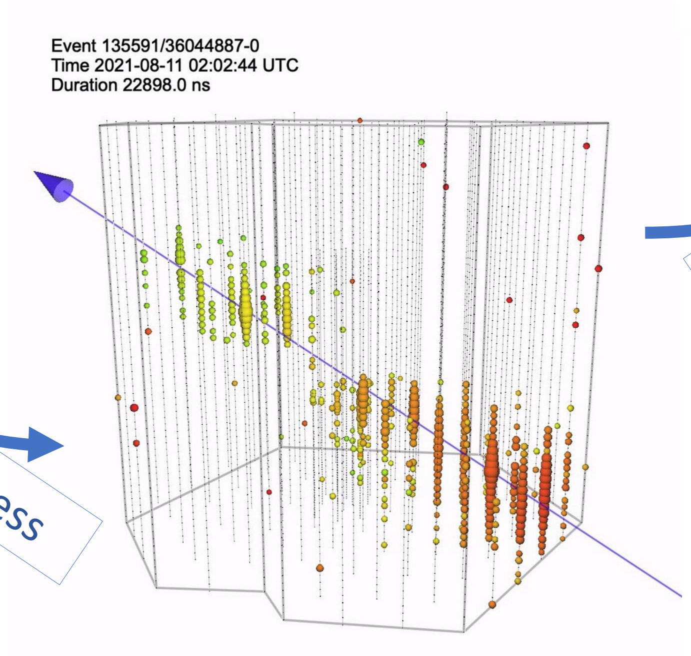


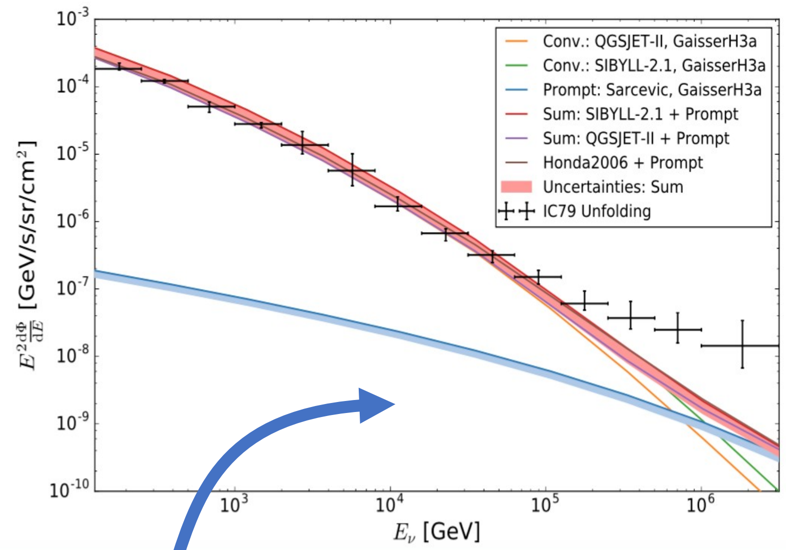
# Astroparticle physics




Detection process




Unfolding



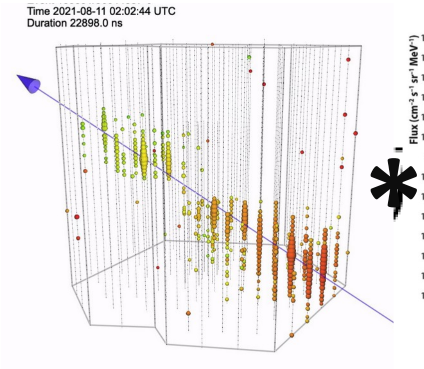
# Unfolding

## Fredholm's Integral equation of the second kind

Measurements — Migration matrix — Function of interest — Noise

$$g(y) = \int_c^d A(y,x) f(x) dx + b(y),$$

$$= \int_c^d$$

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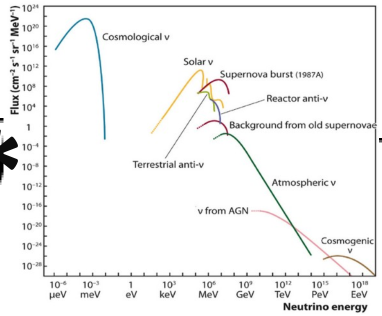



$+$

# Unfolding

Problem cannot be solved by simply working backwards...

Ill-conditioned problems contain matrices with a high condition number

$$\vec{f}_{unreg.} = \mathbf{A}^{-1}\vec{g}$$

Matrix with small values and large uncertainties

$\mathbf{A}$

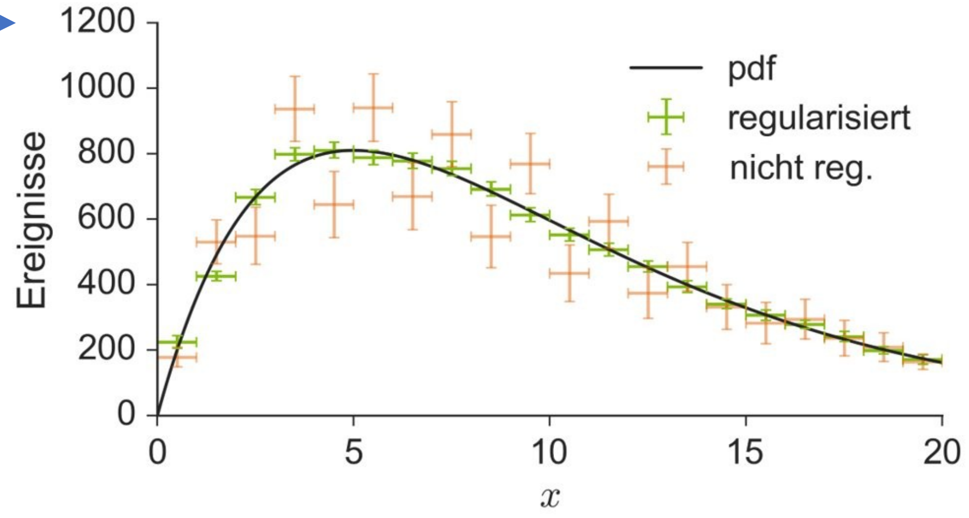
inversion →

Matrix with large values and large uncertainties

$\mathbf{A}^{-1}$

→

Unstable (oscillating) solution



# Unfolding

Problem cannot be solved by simply working backwards...

$$\vec{f}_{unreg.} = \mathbf{A}^{-1}\vec{g}$$

Regularized unfolding

$$\vec{f}_R = \mathbf{A}^{-1}\vec{g} + R(\vec{f})$$

Poisson (likelihood) unfolding

$$\alpha(\vec{g}|\vec{f}) = \prod_{u=1}^{m} \frac{(A\vec{f})^{g_u}}{g_u!} \cdot exp(-(A\vec{f})_u)$$

$$l(\vec{g}\,|\,\vec{f}) = \sum_{u=1}^{m}\left(g_u \ln\left((\mathbf{A}\vec{f})_u\right) - (\mathbf{A}\vec{f})_u\right) + R(\vec{f})$$

Probability unfolding

$$\vec{f}_i = \frac{1}{N}\sum_{n=1}^{N} c_{\mathcal{M}}(i\,|\,\mathbf{x}_n)$$

Probability unfolding (Bayesian iterative unfolding)

$$\vec{f}\,{}_i^1 = \sum_{j}^{N} \frac{1}{\epsilon_i} P(i\,|\,E_j)$$

# Unfolding

*T. Ruhe, M. Börner, M. Wornowizki et al., "Mining for spectra - the Dortmund spectrum estimation algorithm," in Astronomical Data Analysis Software and Systems. XXVI. Astronomical Society of the Pacific, 2016*

*M. Bunse, DSEA Rock-Solid, Regularization and Comparison with other Deconvolution Algorithms*

RUN

TRUEE

funfolding

DSEA / DSEA+

RooUnfold

IBU

SVD

…. many more

## DSEA

**for** $k \in \{1, 2, \dots, K\}$ **do**

$\forall\, 1 \leq n \leq N' : \; w_n^{(k)} \leftarrow \hat{\mathbf{f}}_{i(n)}^{(k-1)}$

Infer $\mathcal{M}$ from $\mathcal{D}_{\text{train}}$ weighted by $w_n^{(k)}$

$\forall\, 1 \leq i \leq I : \quad \hat{\mathbf{f}}_i^{(k)} \leftarrow \frac{1}{N} \sum_{n=1}^{N} c_{\mathcal{M}}(i \,|\, \mathbf{x}_n)$

## DSEA+

$k \leftarrow 0$

**repeat**

$k \leftarrow k + 1$

$\forall\, 1 \leq n \leq N' : \; w_n^{(k)+} \leftarrow \hat{\mathbf{f}}_{i(n)}^{(k-1)} \,/\, \mathbf{f}_{i(n)}^{t}$

Infer $\mathcal{M}$ from $\mathcal{D}_{\text{train}}$ weighted by $w_n^{(k)+}$

$\forall\, 1 \leq i \leq I : \; p_i^{(k)} \leftarrow \frac{1}{N} \sum_{n=1}^{N} c_{\mathcal{M}}(i \,|\, \mathbf{x}_n) - \hat{\mathbf{f}}_i^{(k-1)}$

$\alpha_{\text{RUN}}^{(k)} \leftarrow \arg\min_{\alpha \geq 0} \ell_r \left( \hat{\mathbf{f}}^{(k-1)} + \alpha \cdot p^{(k)} \right)$

$\hat{\mathbf{f}}_i^{(k)+} \leftarrow \hat{\mathbf{f}}^{(k-1)} + \alpha_{\text{RUN}}^{(k)} \cdot p^{(k)}$

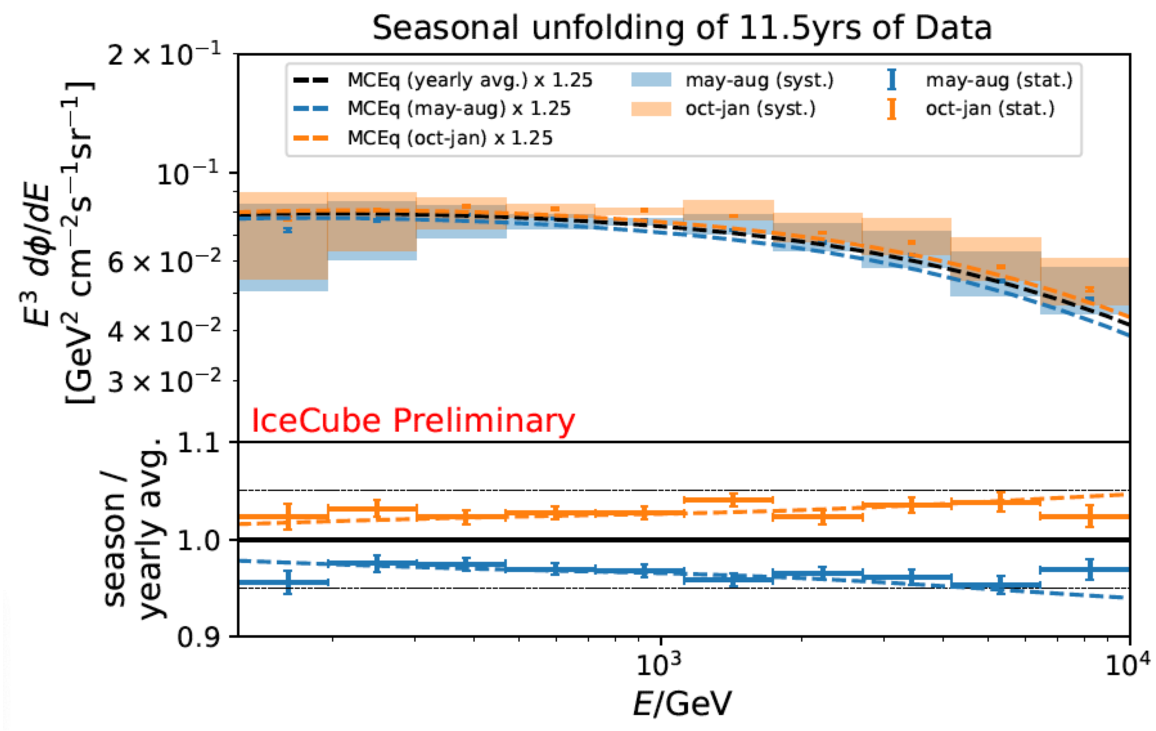
**until** $\chi^2_{\text{Sym}}(\hat{\mathbf{f}}^{(k)}, \hat{\mathbf{f}}^{(k-1)}) \leq \epsilon$

**return** $\hat{\mathbf{f}} \leftarrow \hat{\mathbf{f}}^{(k)}$

# Unfolding examples

- Unfolding seasonal variations (K. Hymon)

$$\Phi_\nu(E_\nu,\Theta,X) = \Phi_{\mathrm{N}}(E_\nu)\cdot \int_0^{X_{\mathrm{ground}}} \left( \frac{A_{\pi\to\nu}(X)}{1 + B_{\pi\to\nu}(X)\cdot \frac{E_\nu \cos(\Theta^\star)}{\epsilon_\pi(T(X))}} + \frac{A_{K\to\nu}(X)}{1 + B_{K\to\nu}(X)\cdot \frac{E_\nu \cos(\Theta^\star)}{\epsilon_K(T(X))}} \right) \mathrm{d}X,$$




*Seasonal Variations of the Atmospheric Neutrino Flux measured in IceCube, the 38th International Cosmic Ray Conference (ICRC2023), arXiv:2307.14724*

- First proton spectrum measurement with MAGIC (A. Fattorini)

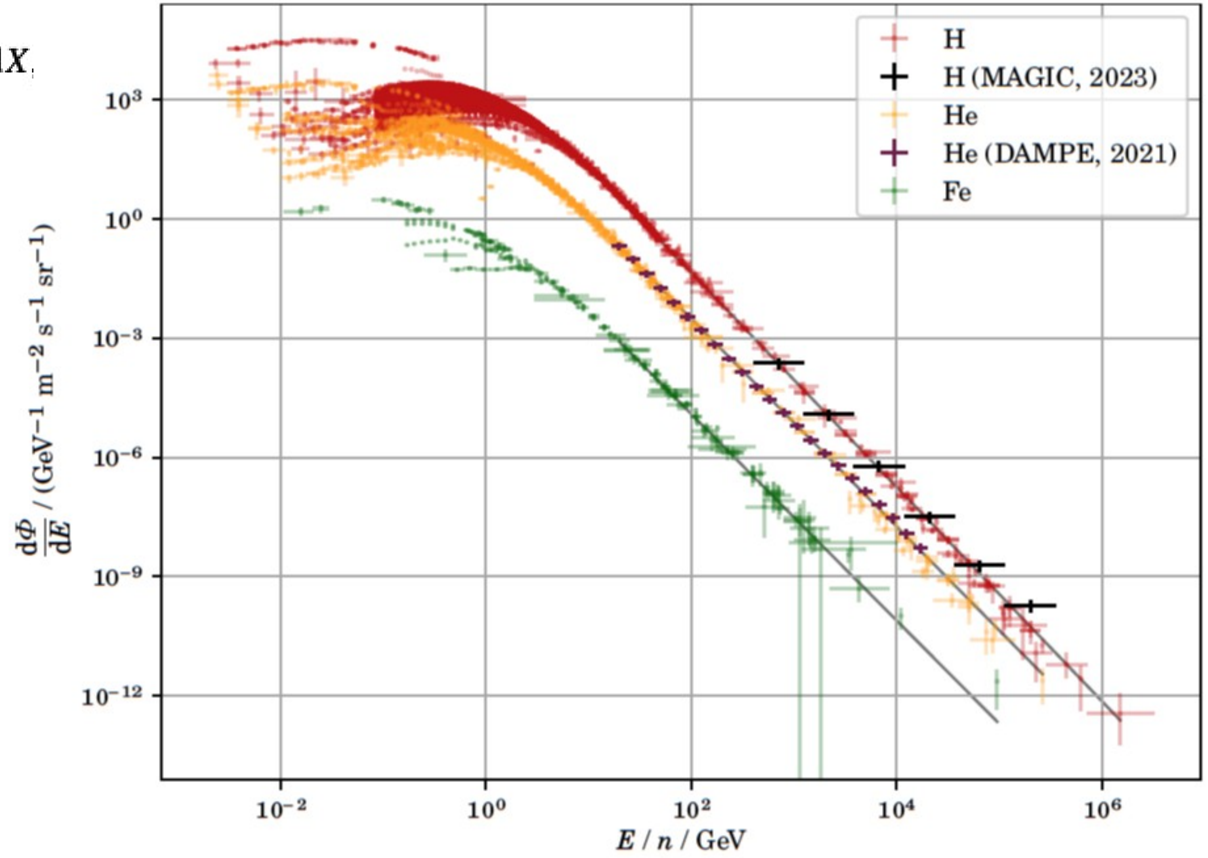
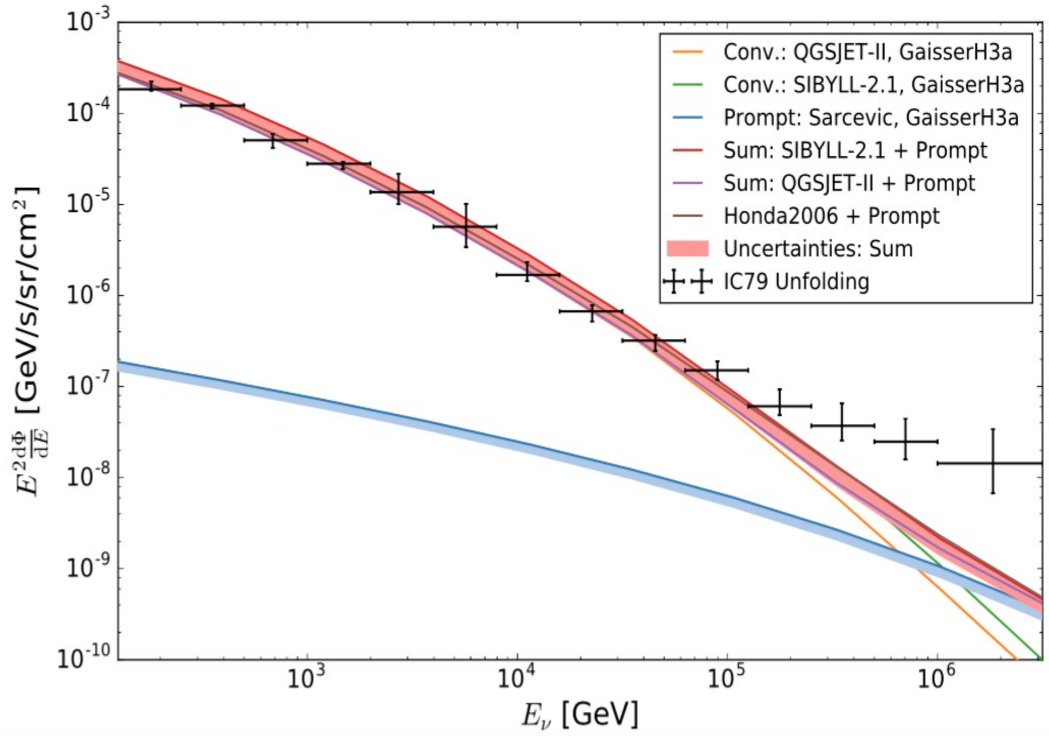
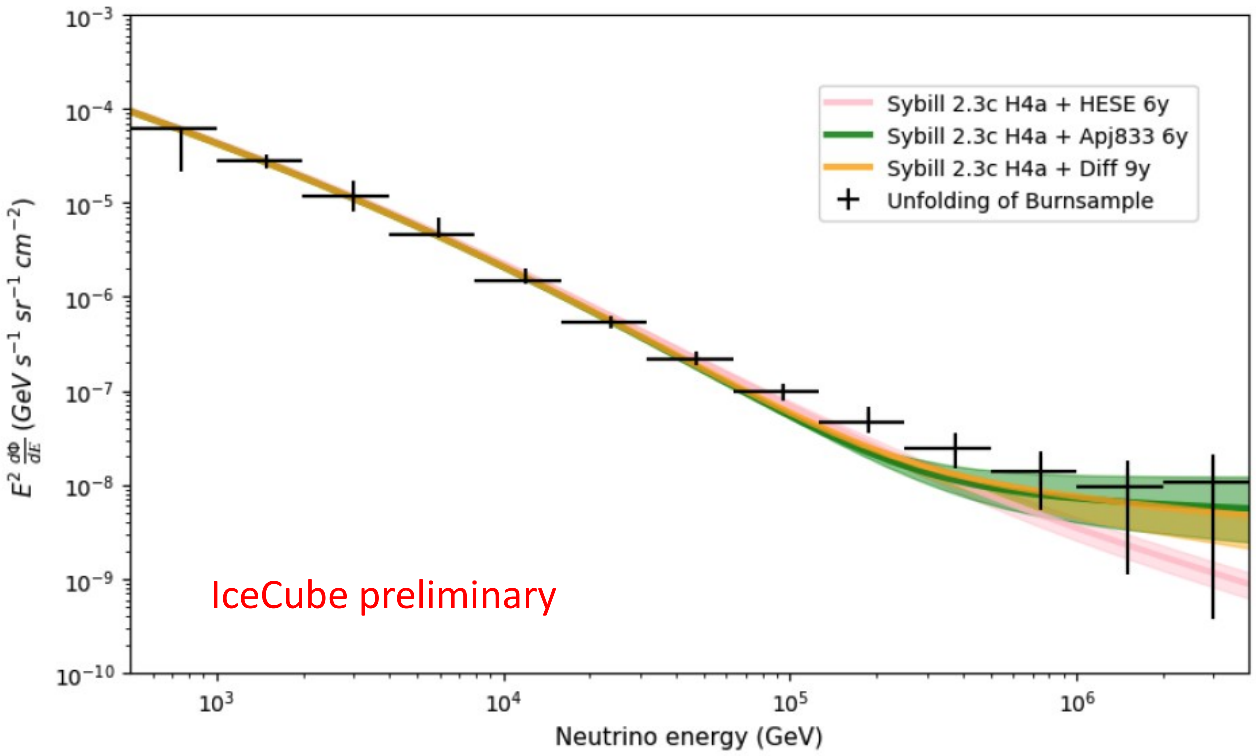



**Figure 8.12:** Cosmic-ray spectra of measurements with different experiments during the last decades including this work: the first proton spectrum of the MAGIC experiment (black).

# Unfolding examples

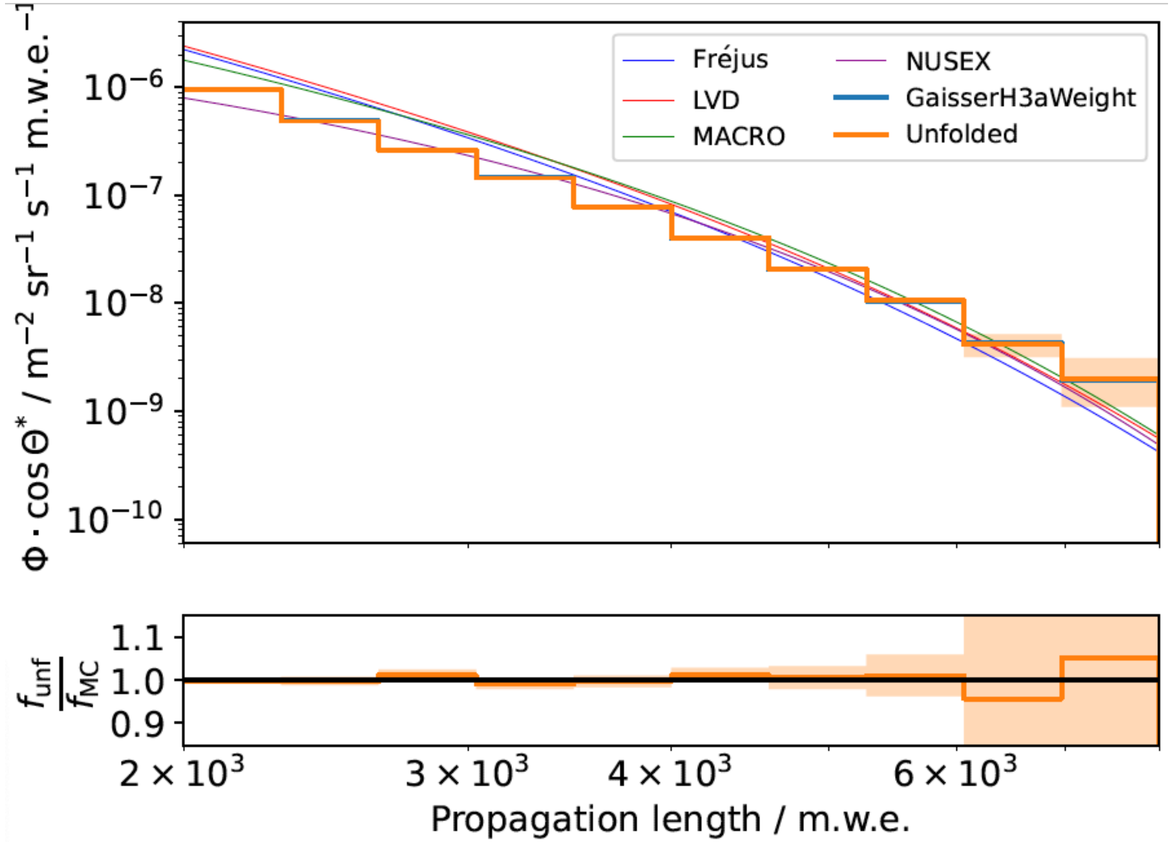
- Unfolding the total neutrino flux (L. Kardum, T. Ruhe)

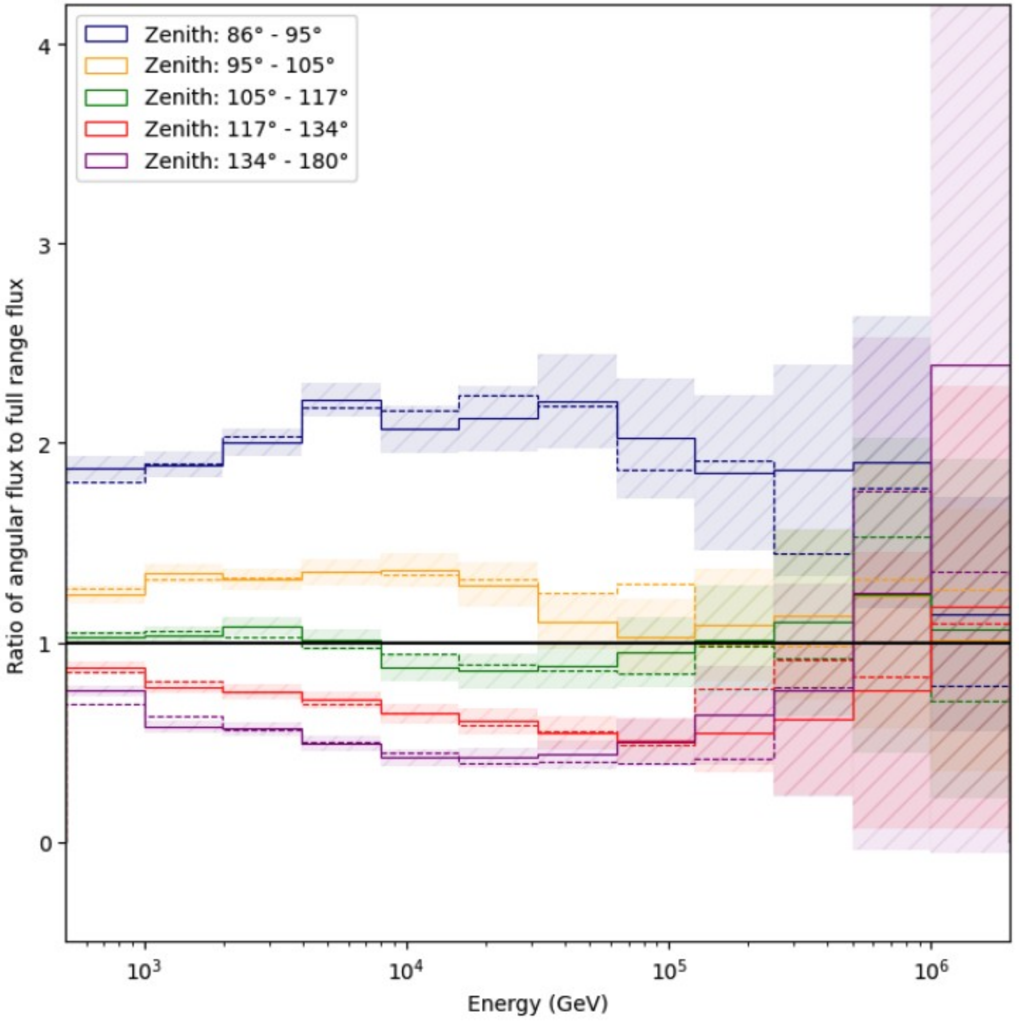


# Unfolding examples

- Unfolding angular variations (L. Kardum)
- Unfolding the stopping depth (L. Witthaus)




*Angular dependence of the atmospheric neutrino flux with IceCube data, 38th International Cosmic Ray Conference (ICRC2023), arXiv:2307.14728*

# Solution of Inverse Problems and Research Data Management

Experiments produce an abundant amount of raw data

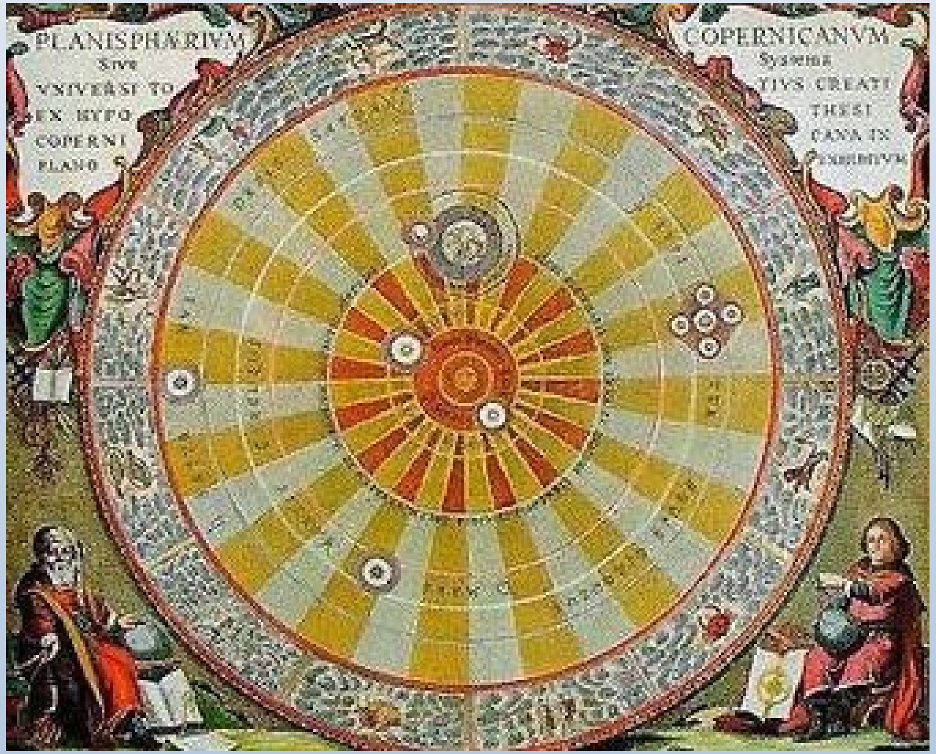
→ Only accessible with highly speacialized read-out and analysis programs

→ Understanding dependant on Monte Carlo simulations

→ Dependence on hardware and software properties

How do we keep access to this data alive so that it can be used ten years after the experiment is finished and all people left science and forgot everything?

**Unfolded results can be used for eternity and require comparably few resources**



# Unfolding – future plans

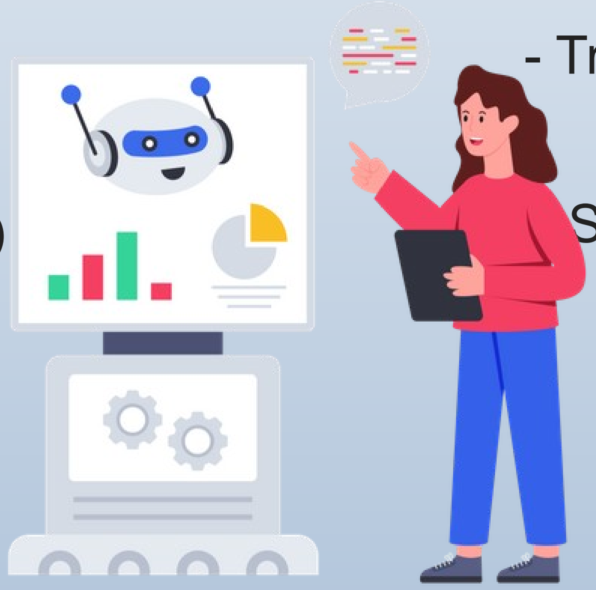
- Improve Robustness (against regularization strength and training assumptions)

- Automatic proof of the independence from Monte Carlo and / or automatic information on the properties (energy resolution, sensitivity for sharp changes of the spectrum) of the solution

- Multidimensional input

(treatment and optimization)

- Multidimensional output



- Automatic optimization of the regularization strength

- Automatic Background subtraction

- Automatic efficiency correction

- Treatment of systematic effects

Studies on statistical uncertainty

# Thank you for your attention!

Leonora Kardum, Technical University Dortmund