technische universität dortmund

Lehrstuhl für Experimentelle Physik 5

SFB 876 Verfügbarkeit von Information durch Analyse unter Ressourcenbeschränkung

IceCube South Pole Neutrino Observatory

Unfolding the neutrino energy spectrum

Leonora Kardum

on behalf of Lehrstuhl für Experimentelle Physik 5, TU Dortmund

SFB 1491 Kick-off meeting

June 2022

Why neutrinos?

- Small but nonvanishing mass
- No charge
- Not susceptible to the strong force
- Interact only via weak force
- Can travel galactic distances without changing their direction
- Second most abundant particle in the Universe
- Over 300 neutrinos per cubic centimeter
- Flavor changing (oscillating)
- Many unresolved questions

Neutrino sources

- Many different neutrino sources, either terrestrial or astrophysical
- The energy of a neutrino points to the means of its production

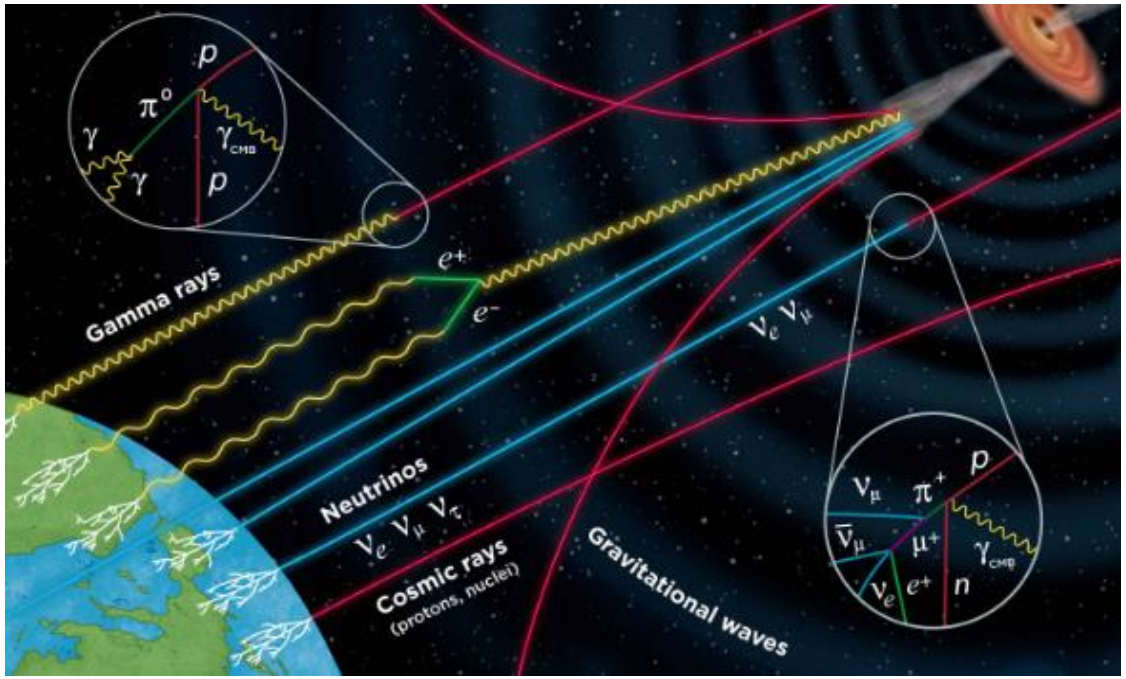


Image credit: GRAND (Giant Radio Array for Neutrino Detection)

Neutrino sources

- cosmic neutrino background (CNB)
- nuclear processes (solar, supernova...)

low energy

- cosmic rays collision with Earth's atmosphere

high energy

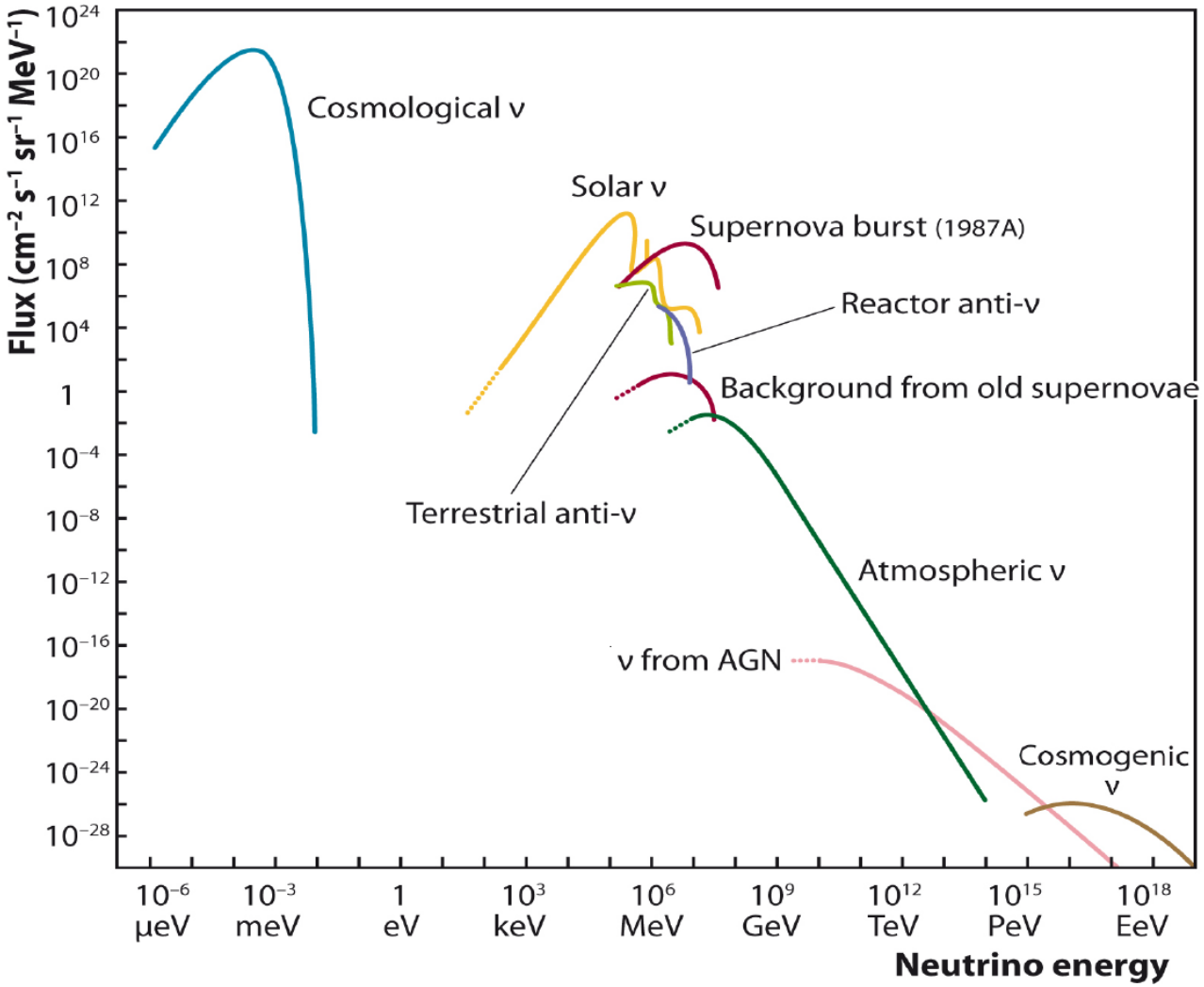
Detection in IceCube

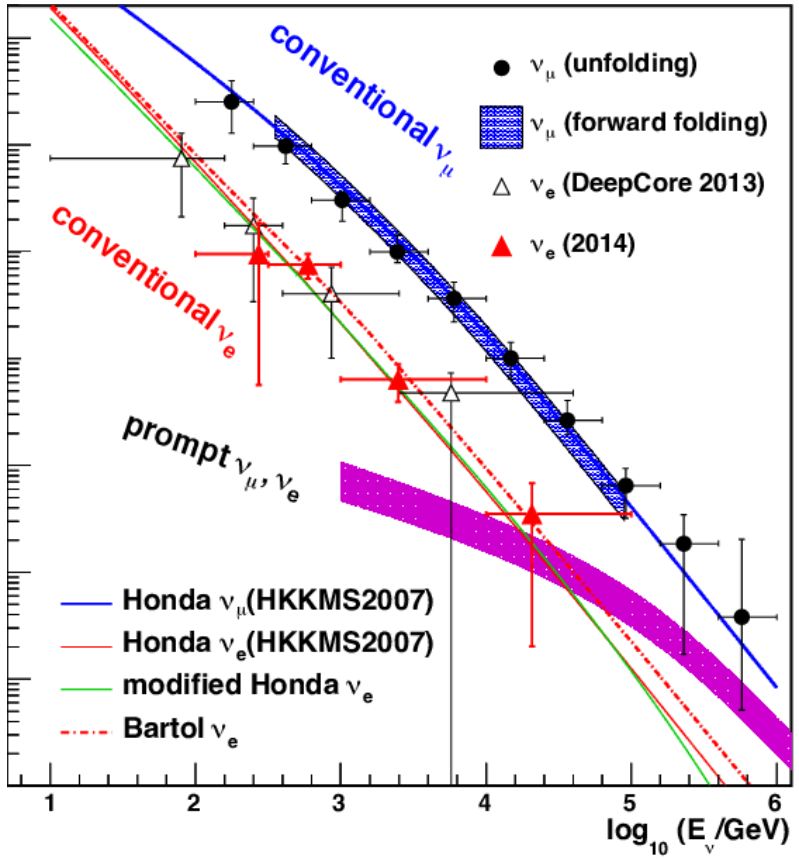
- extreme objects (neutron stars...)

very high energy

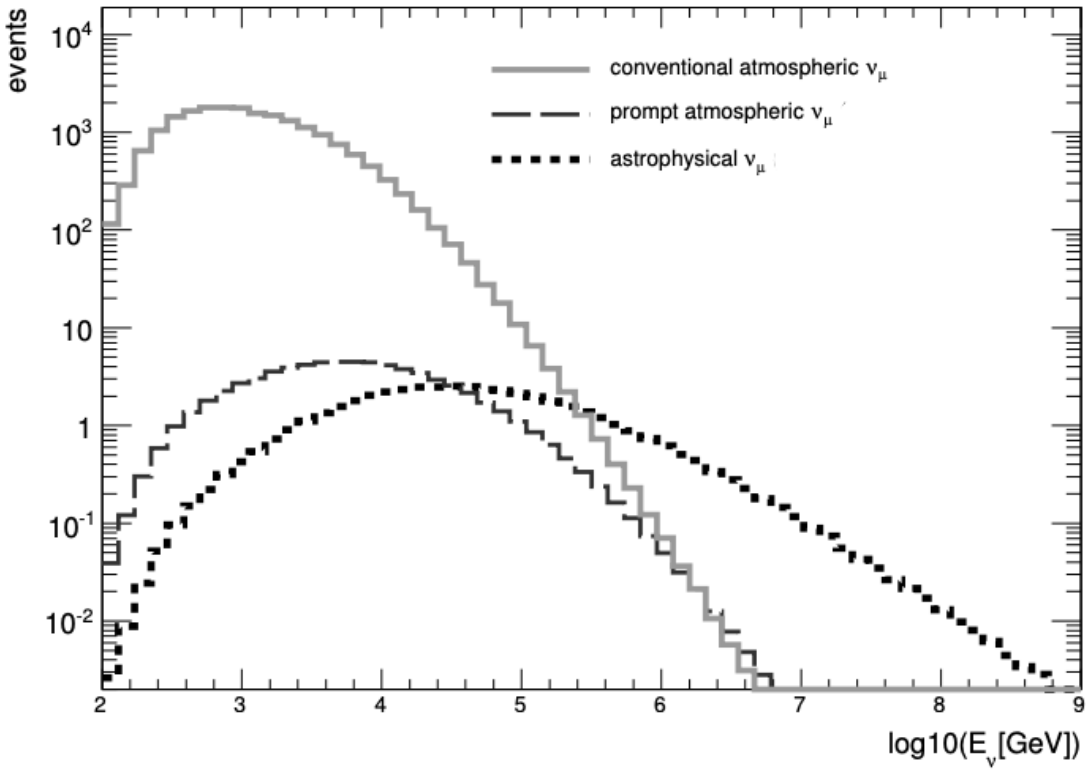
- cosmogenic neutrinos

ultra high energy


Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

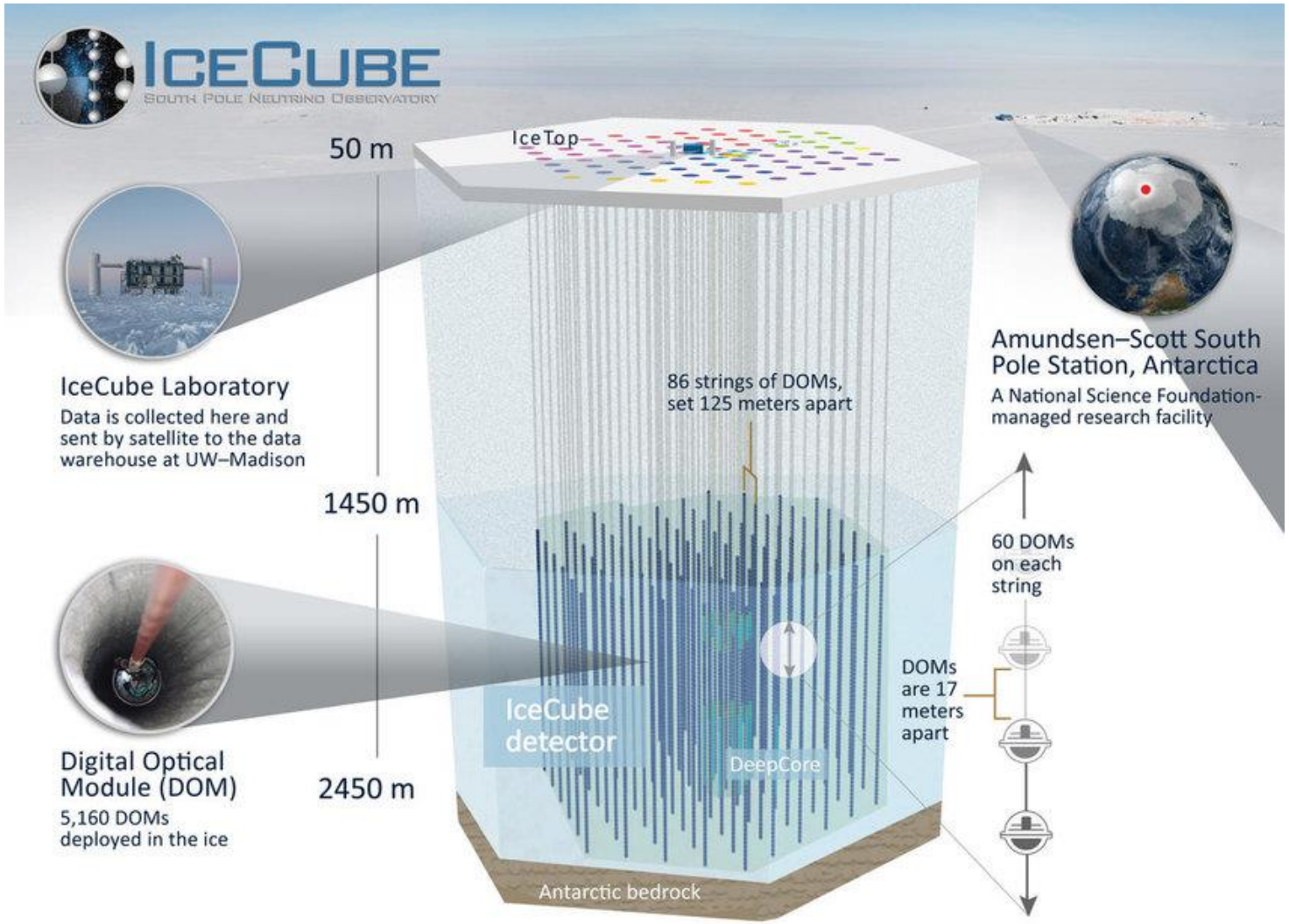


Aartsen, M.G. et al. (2017). Astrophysical Neutrinos and Cosmic Rays Observed by IceCube. Advances in Space Research. 62. 10.1016/j.asr.2017.05.030.

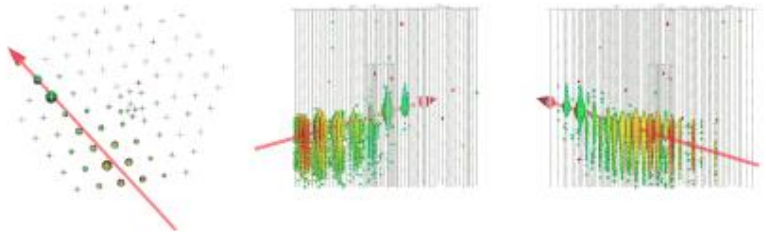


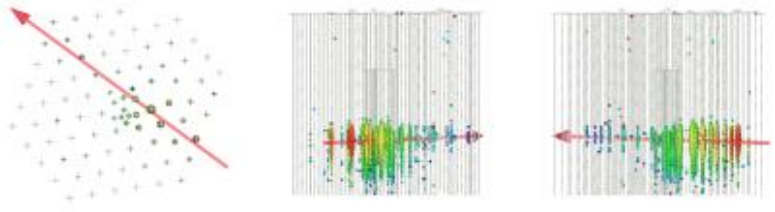
Schukraft, A. (2013). A view of prompt atmospheric neutrinos with IceCube. Nuclear Physics B (Proceedings Supplements) (2013), pp. 266-268

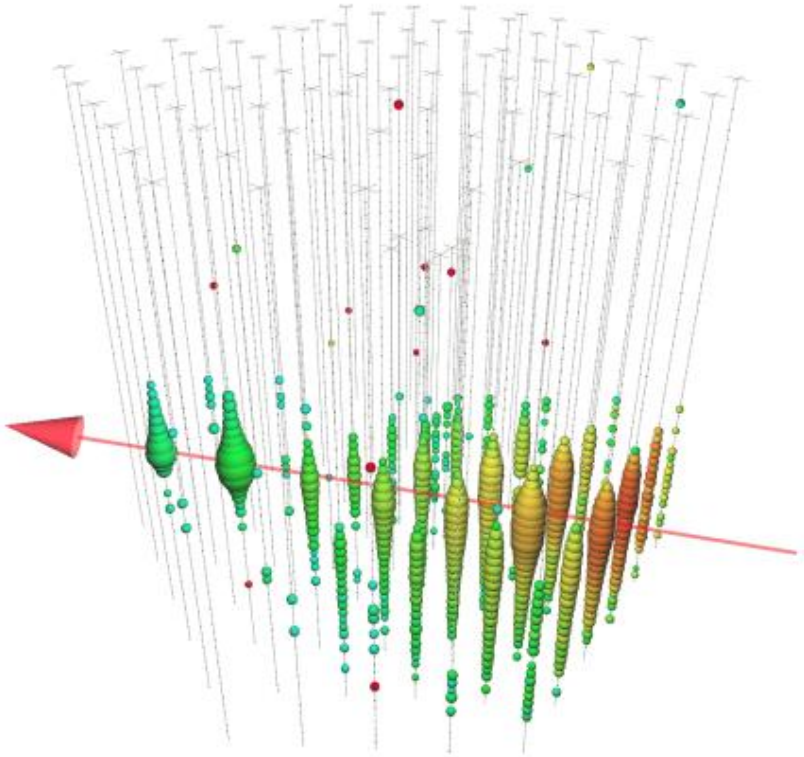
Detection in IceCube

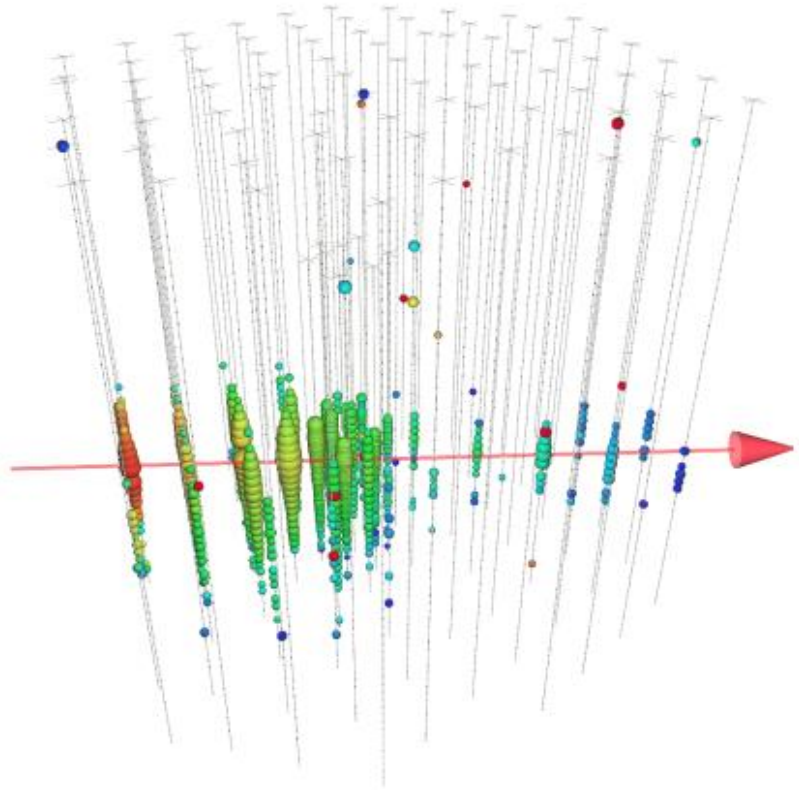


Detection in IceCube



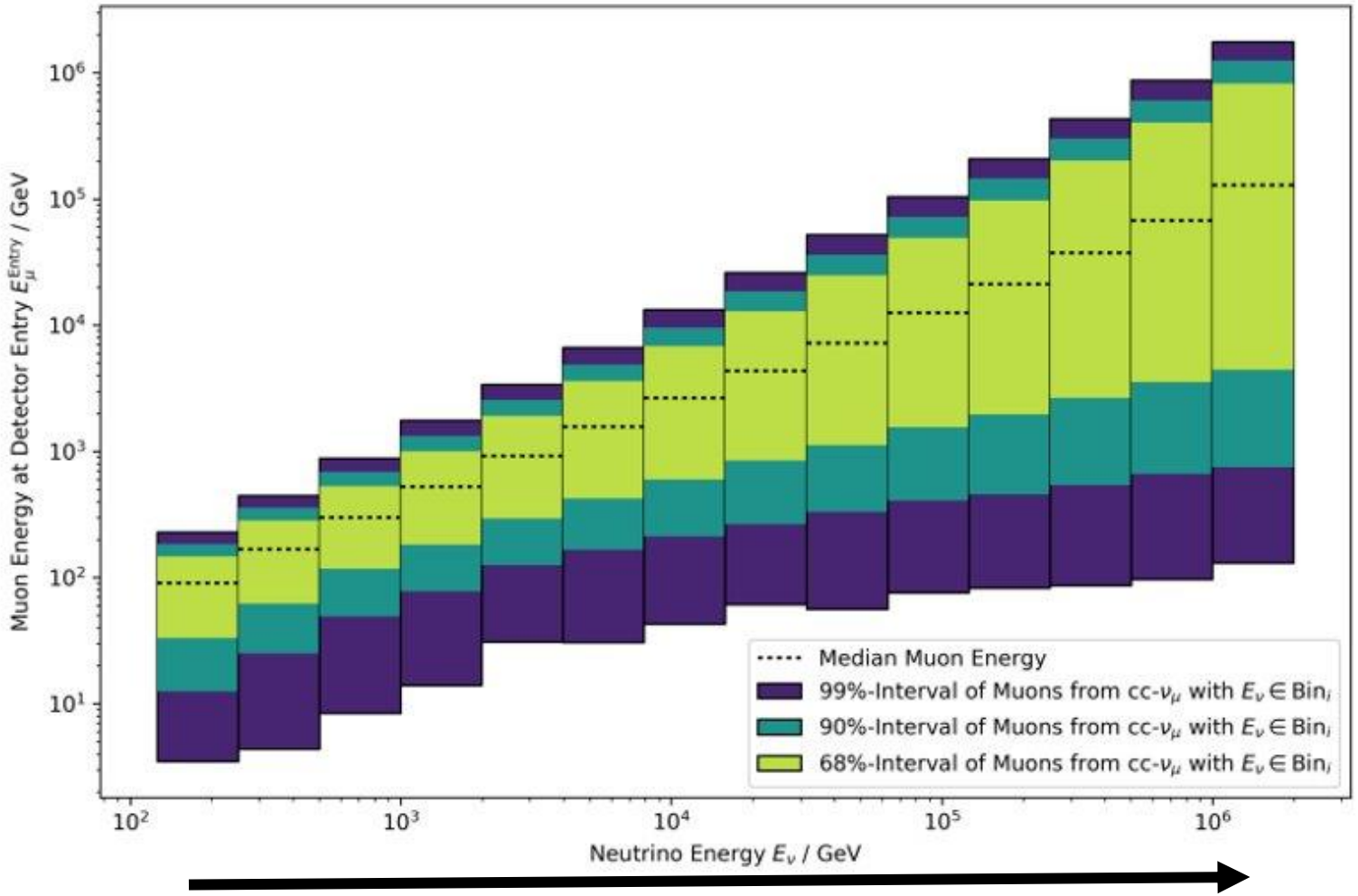






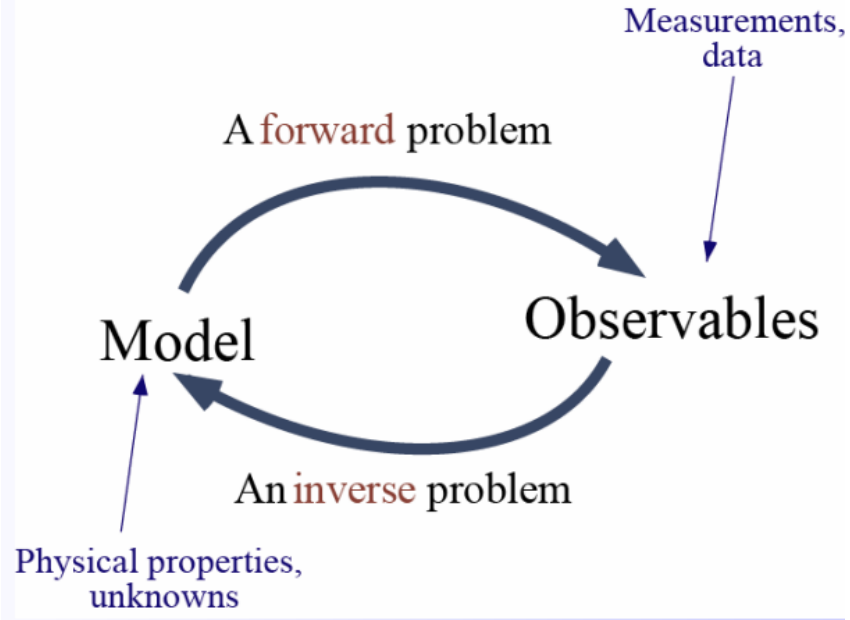
Detection in IceCube

Energy smearing gets progressively strong with raising energy in the region of interest



What is Unfolding?

To understand Unfolding, first we need to define Inverse problems:



$$g(y) = \int A(x,y)\, f(x)\, \mathrm{d}x + b(y)$$

Detection process

Background

Observables

Property of interest

Image credit: Research School of Earth Sciences, Australian National University

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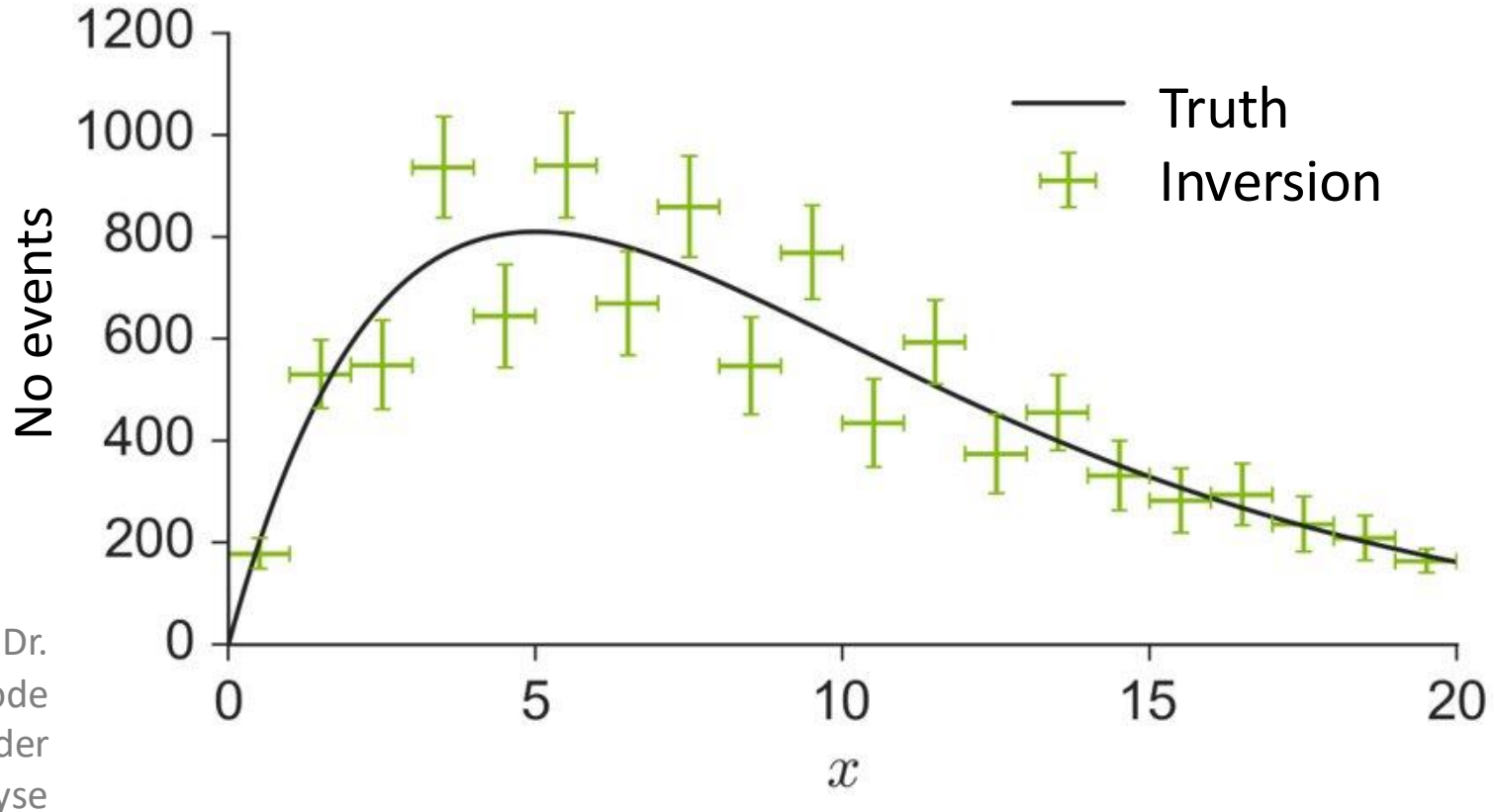
To understand Unfolding, first we need to define Inverse problems:

$$\vec{g} = \mathbf{A}\vec{f} \not\longrightarrow \vec{f} = \mathbf{A}^{-1}\vec{g}$$

Leads to large uncertainties if the problem is ill-conditioned!



Credit: Prof. Dr. Dr. Wolfgang Rhode Statistische Methoden der Datenanalyse

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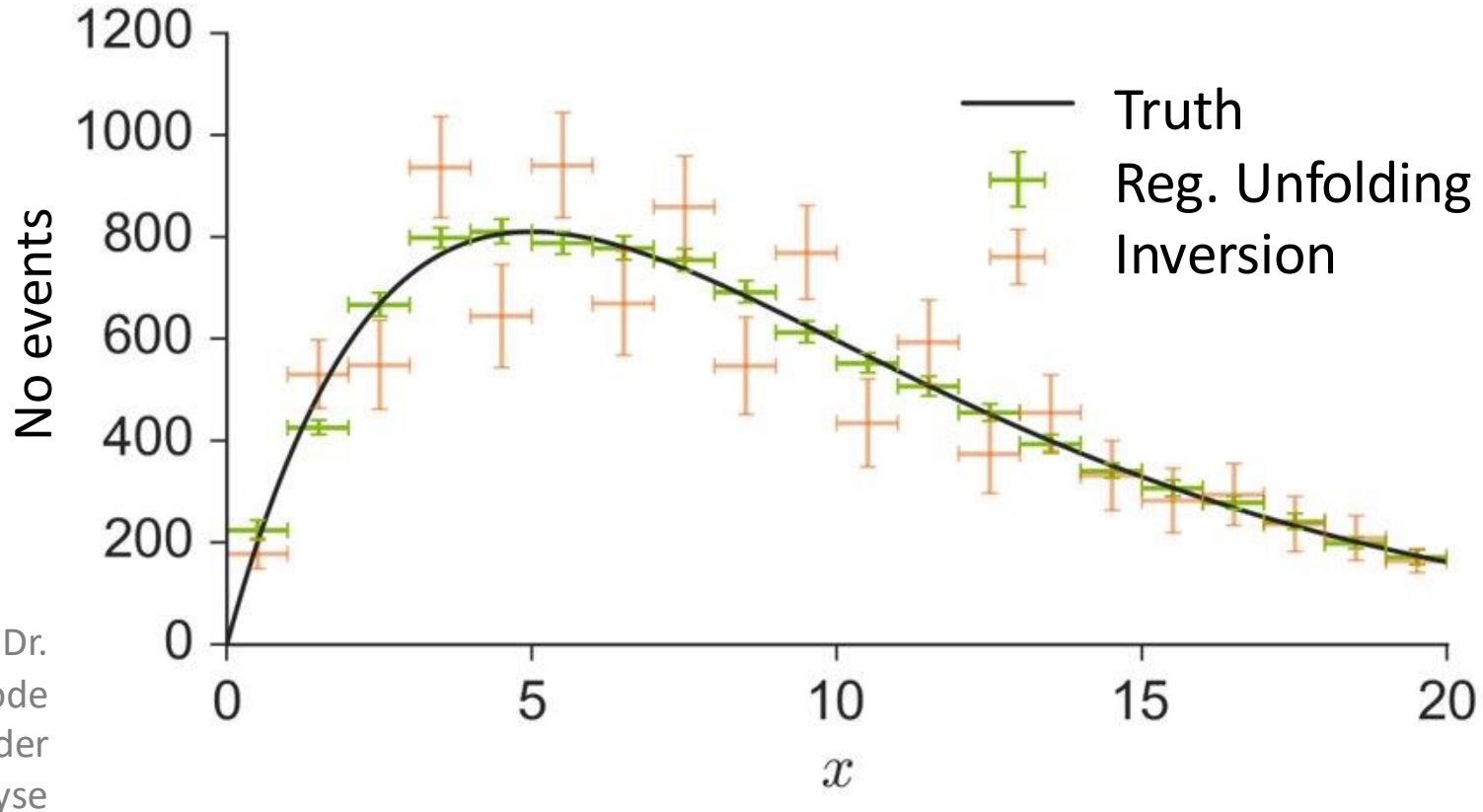
→ Regularization is required!



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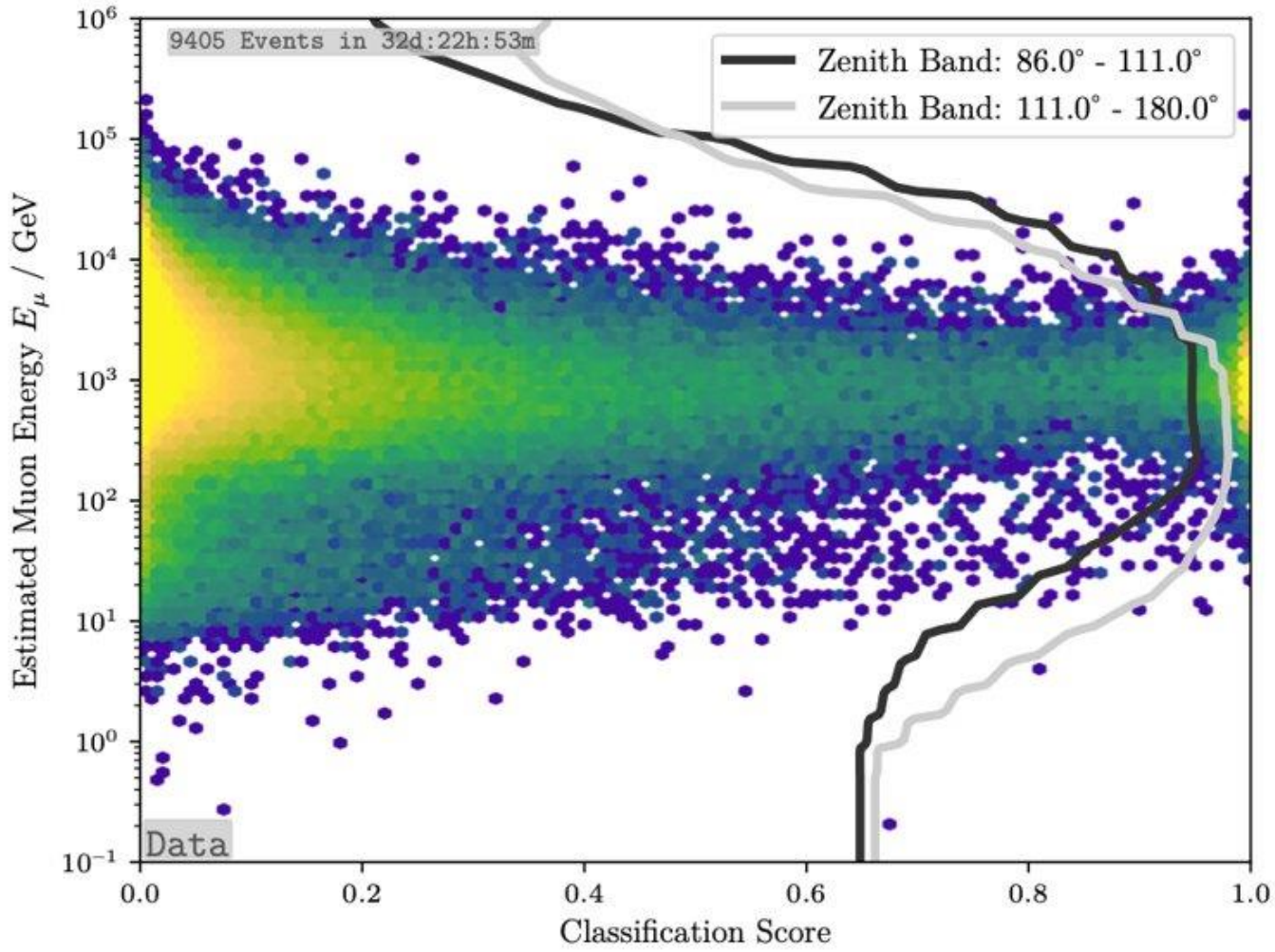
What is Unfolding?

Special attention is given to Sample cleaning (so the Background dropping can be justified)

- Sample with purity of 99.7% was achieved with our approach



What is Unfolding?

Two approaches to Unfolding:

- Poisson Likelihood Unfolding

`funfolding`

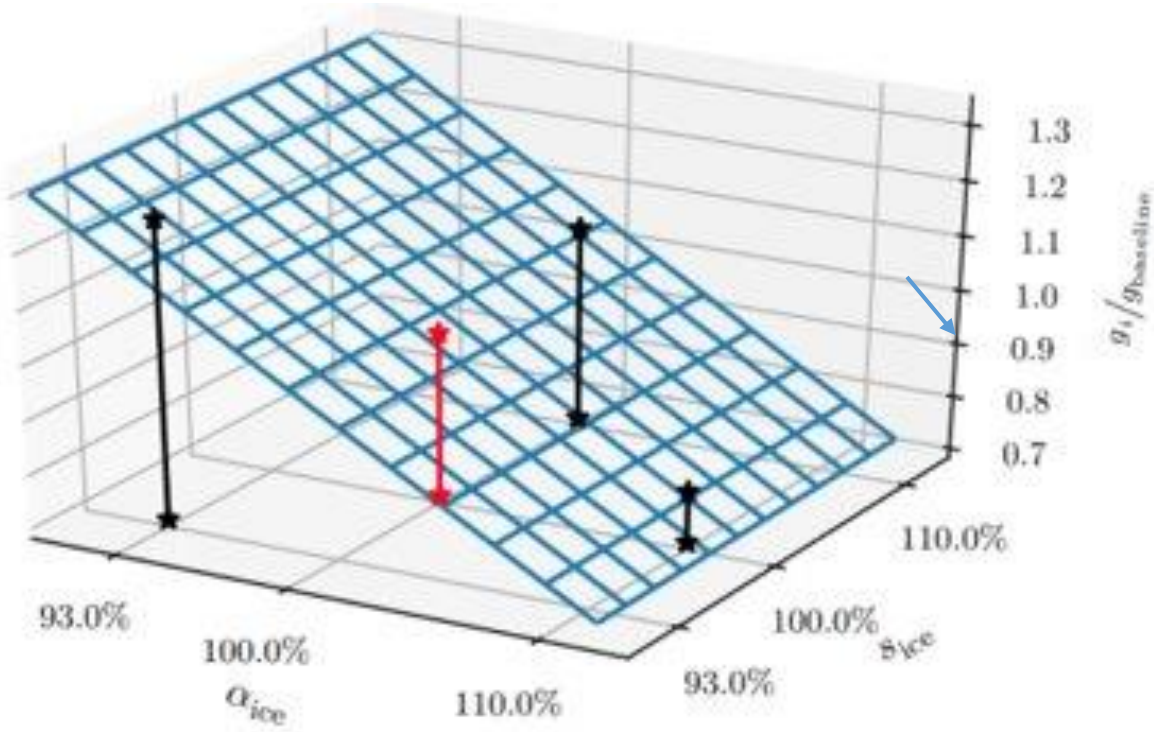
- Iterative probabilistic Unfolding

Dortmund Spectrum Estimation Algorithm (DSEA+)

funfolding

Systematics:

$\rightarrow \mathbf{A}(\vec{\xi})$

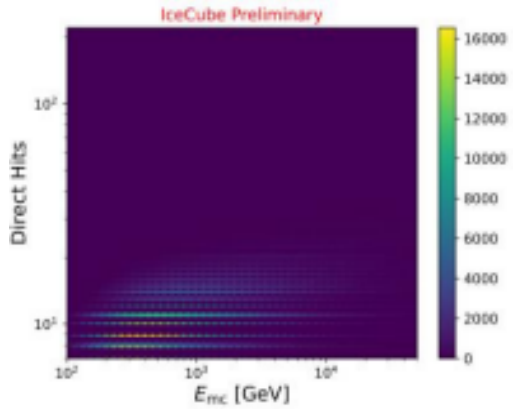


Likelihood based Unfolding:

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

$$- \frac{1}{2} \tau^{-1} \log_{10} \left(\mathbf{A}_{\text{eff}}^{-1} \left(\vec{f} + d \cdot \vec{1} \right) \right)^{\mathsf{T}} \mathbf{C}^2 \log_{10} \left(\mathbf{A}_{\text{eff}}^{-1} \left(\vec{f} + d \cdot \vec{1} \right) \right)$$

Dortmund Spectrum Estimation Algorithm (DSEA+)



Energy proxies

Random Forest

Prior

Regularization

DSEA+

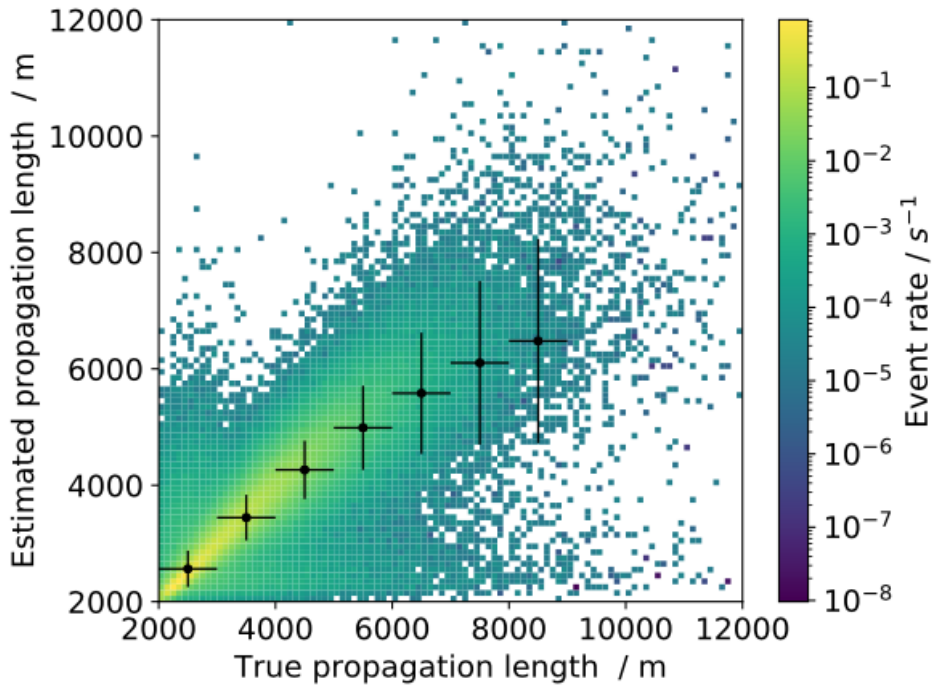
repeat for *k* iterations

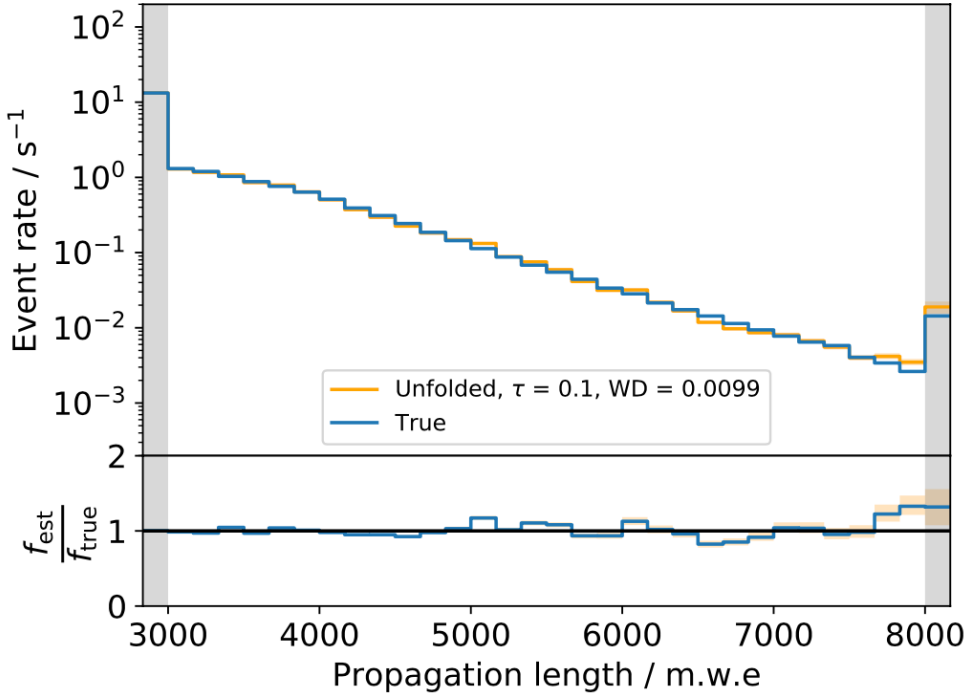
$$\hat{f}_i^{(k)} = \frac{1}{N} \sum_{n=1}^{N_{\text{events}}} c_M(i \mid x_n) \qquad \forall 1 \le i \le I$$

What is Unfolding?

Different approaches to Unfolding based on the chosen Proxy:

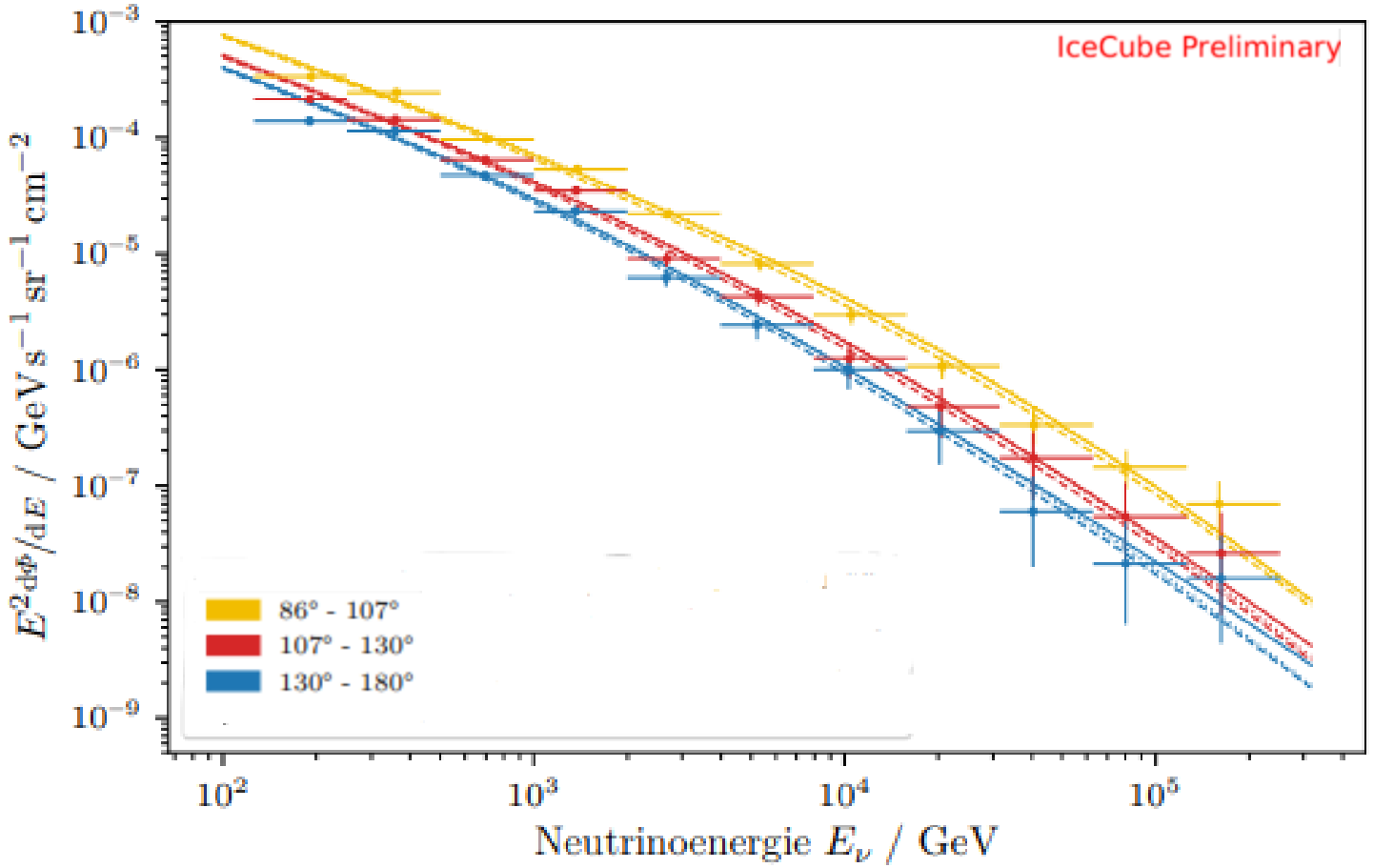
- e.g. Stopping Muon Unfolding



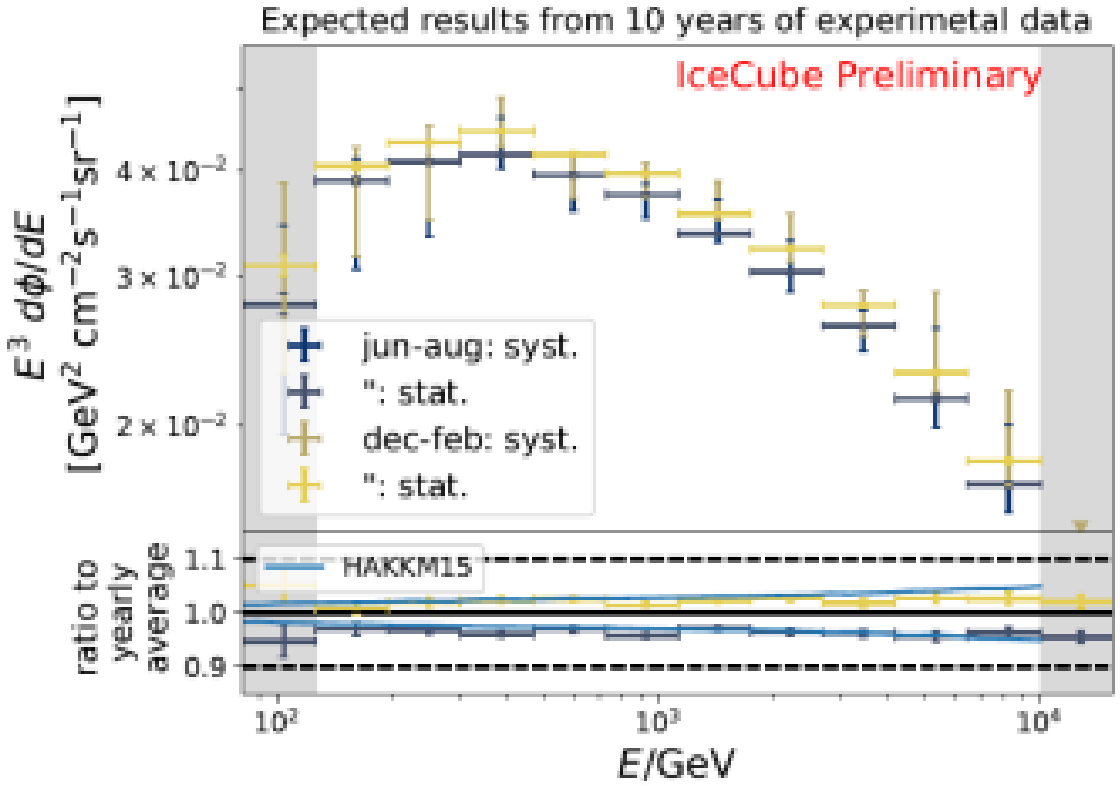


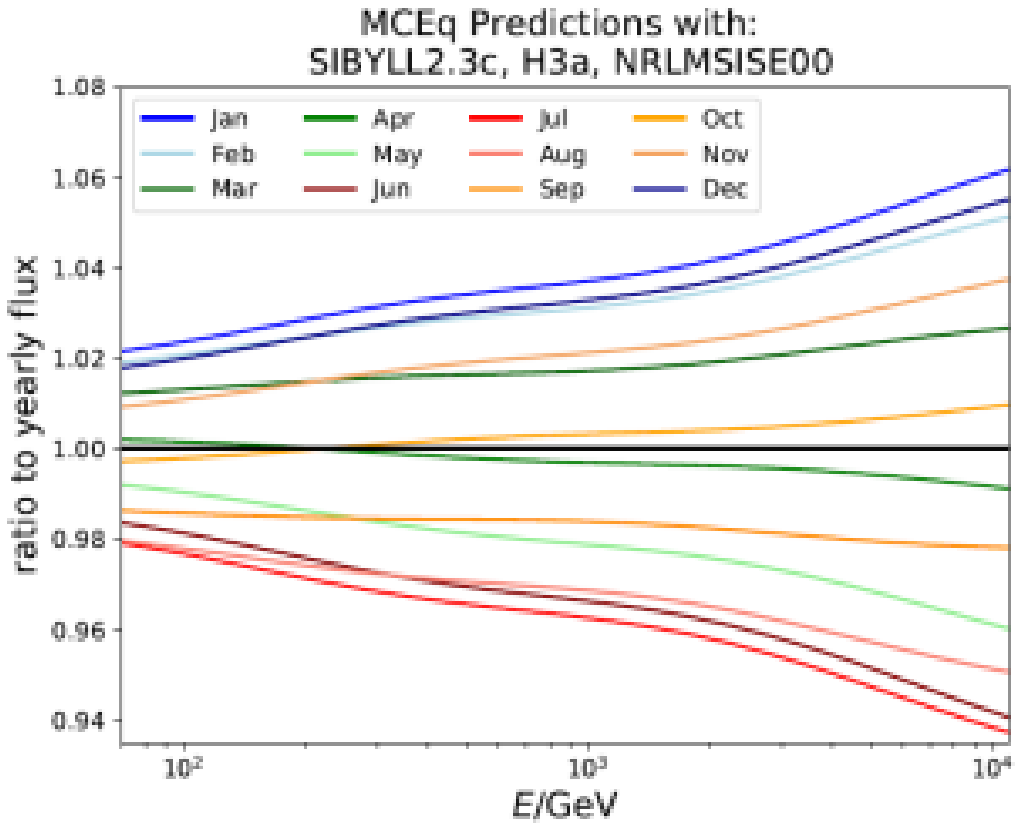
Zenith dependance

Unfolding in different zenith bands can unveil the expected flux dependance to zenith degree

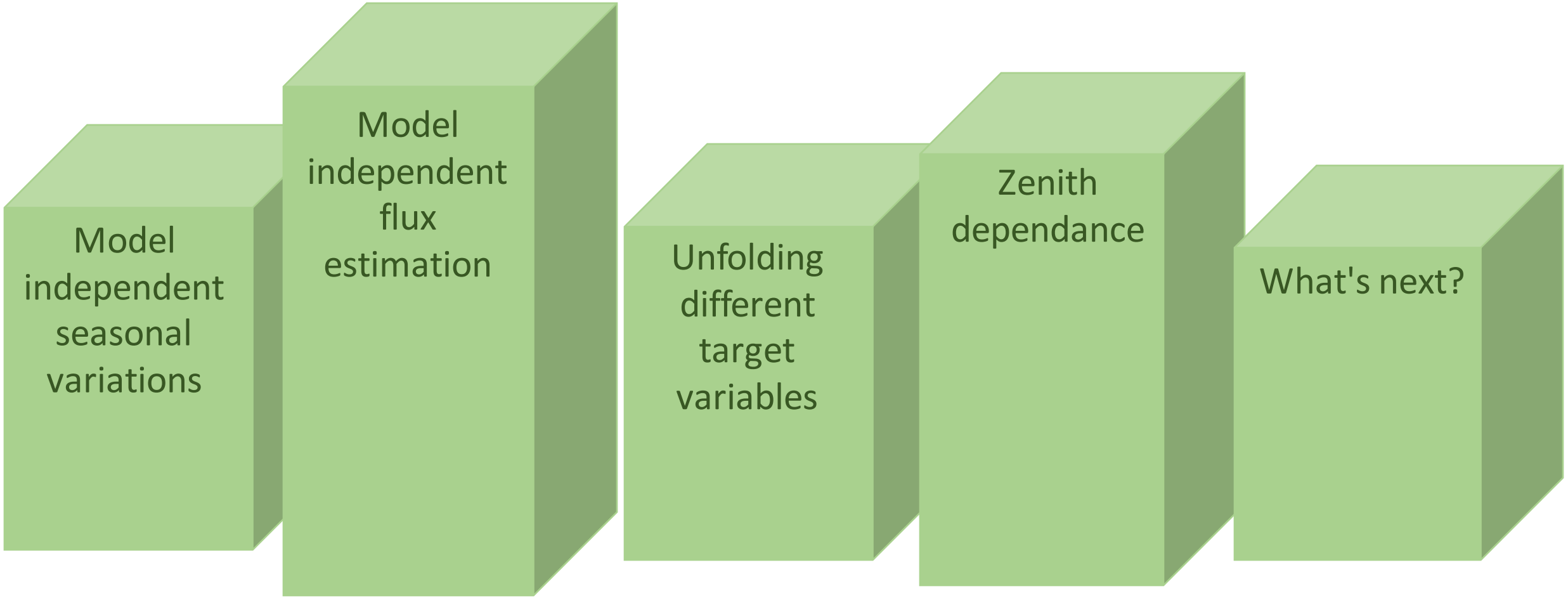


Seasonal variations





Conclusion


Model independent seasonal variations
Model independent flux estimation
Unfolding different target variables
Zenith dependance
What's next?

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